Basic Problems and Techniques in Range Research (1962)

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Basic Problems and Techniques in Range Research

A REPORT OF A JOINT COMMITTEE OF THE AMERICAN SOCIETY OF RANGE MANAGEMENT AND THE AGRICULTURAL BOARD

Prepared by the
Subcommittee on Range Research Methods
of the Agricultural Board

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FOREWORD

RANGE RESEARCH deals with plants, the animals grazing them, and the land producing them. The difficult problems involved, dissatisfaction with available methods, and the natural bent of humans toward inventiveness have resulted in development of a wide variety of research methodology. Often these methods are uncorrelated.

No comprehensive listing of available range research methods has ever been made. Even the experienced research worker seldom understands fully the limitations and suitabilities of all methods. As a result, new methods may be devised for situations where suitable techniques are already available. Methods may be applied to situations for which they are not suitable. Errors may be repeated, unwittingly. Data derived from studies under similar situations may not be comparable because of differences in methods employed. Needlessly conflicting evidence and conclusions may arise.

Complete standardization of methods, even if possible, is not suggested here. This would presume that fully satisfactory techniques were available to meet each objective. Nevertheless, improvement and unification of methods is a goal to be sought if the various range research programs are to yield comparable and consistent results.

The objectives of this book are to discuss the problems inherent to range research; to assemble the various methods used for different phases of range research; and to describe their use, limitations, and suitabilities.

This book is the product of many years of effort on the part of the American Society of Range Management and the Committee on Range and Pasture Problems of the Agricultural Board of the National Academy of Sciences—National Research Council. Through cooperative efforts each group has established a research methods committee of identical membership. This committee organized the subject matter herein, assigned various phases to be written by recognized specialists in the field, and compiled and edited the material produced. The Committee is indebted to the specialists listed on the following pages who also contributed material for this book.

It is hoped that the book will serve as a reference guide to those interested in range research methodology and as a textbook for advanced students who anticipate careers in this increasingly important field.

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Basic Problems and Techniques in Range Research

Chapter 1
Introduction to Range Research

NATURAL pasturage is produced on nearly half the land area of the United States and is grazed by livestock and wildlife. Range management is the science of economic improvement, maintenance, and efficient use of the forage on these rangelands for the production of animals and animal products. This use must be consistent with the perpetuation and wise use of other resources of the land. Such a definition envisions the full application of measures for improving range forage production to, or in some cases beyond, their original state. It implies planning and directing use of forage resources to obtain maximum sustained production. It implies planning and directing use of forage by big game, and correlating such use with livestock use. It implies consideration of other uses of the land, such as for watershed, recreation, and timber production. Above all, it implies improvement and maintenance of the basic resource of rangelands—the soil.

To achieve these objectives actions must be based on sound knowledge of range plants, soil, climate, livestock nutrition and management, wildlife needs for forage and habitat, associated uses of the land, and economic soundness of the practices employed.

Range research is the quest for basic information about rangelands and the development of guides and procedures for their management, improvement, and efficient use. Its primary function is to provide a firm foundation for range management.

Rangelands frequently have products other than livestock which must be considered in range research. Many ranges are important sources of water vital to irrigated agriculture, to city water supplies, and to industry. They may provide game and fish for the sportsman, recreation for campers and sightseers, and timber and minerals for commercial production. Range research must consider these multiple uses where they are implicated and develop management techniques advantageous to all land functions. This may involve team work with specialists in hydrology, wildlife, forestry, engineering, soils, animal husbandry, ecology, plant physiology, agronomy, pathology, entomology, economics, sociology, and in other fields.

Biological research is most often directed toward what can be done on rangeland. Often such research should be accompanied by economics research which more frequently is directed toward determining what we choose to do on rangeland. Economics research tries to explore the cost and returns of alternative lines of action to arrive at the most rational practices or management techniques.

A Rational Approach in Range Research

A systematic approach should characterize research procedures. These procedures involve logical and methodical breaking down of broad problems into component parts, solving the parts, and from these synthesizing the solution of the broader problems. Even with restricted problems, thorough analysis and planning of work are conducive to the most efficient and fruitful research.

Selecting the Research Problem

Range problems needing solution are wide and varied. From these, a work program can be chosen, using several of the following factors in making the choice: importance of the problem and need for solution; training and aptitude of the personnel; time available; facilities and budget; local, regional, or national demand; and potential cooperation in the form of funds, materials, and assistance.

The graduate student commencing research for his thesis will be primarily concerned with the first four, especially the time element. Many range problems require several years to span a representative climatic period, or to show successional response of vegetation, reproduction rate of grazing animals, or permanency of establishment of seeded grasses. Students on a one- or two-year program obviously are restricted to research which is likely to produce results in a shorter period of time. Moreover, their classroom study program may require the selection of problems that do not require observations at specific seasons or on special days.

Even experienced men sometimes tend to avoid basic or fundamental research under the premise that it is impractical or that its application will not be evident to practical ranchers whose support is desired. Formulation of management principles and techniques is hampered by lack of knowledge in vitally important fundamentals such as plant growth physiology and ecology. Sound research on basic biological phenomena is needed to develop the science of range management.

Most beginners tend to choose a research field far too broad for the time and budget available. Research in broad generalities seldom is profitable. Research problems generally should be chosen to direct efforts along narrow lines and toward a specific objective. Research should be purposeful, and once a subject is chosen, direction of efforts toward the objective is desirable regardless of side interests which seem inevitably to arise. This does not imply that change in objective is necessarily undesirable, but such change should be the result of planned reorganization.

A graduate student must demonstrate ability to do precise and intensive research on a specific subject. He can expect to become an authority on his subject only by virtue of its restricted nature. Obviously, a subject of broad scope involves a lifetime of work. Even a professional research man can expect maximum productivity only by directing his efforts to restricted phases when dealing with a broad and intricate subject such as range management.

Defining and Appraising the Problem and Research Project

Selection of the problem is the first of several steps in good research procedure. The sequence of subsequent steps will depend, in part, on the type of problem selected. Wilm (1952) outlines a pattern of scientific inquiry for applied range management research. The steps he suggests apply equally well to the solution of most biological research problems of fundamental nature.

Following selection of the problem the research worker should delineate and define it precisely. This is essential to efficient thought and action. In defining the scope of the project consideration must be given to manpower, facilities, money, and time available for obtaining the solution. For example, the research worker is concerned with the problem of how to establish bitterbrush (*Purshia tridentata* Pursh) artificially on depleted western ranges. Since natural distribution of this browse is from southern British Columbia to northern Arizona, and from near the Pacific Coast to central Colorado, total solution of this problem is impossible without a major regionwide project of long duration. To reduce the problem, it may be limited to southwestern Idaho.

Even with this limitation, the project has many ramifications which require research. Some phases may be of higher priority than others. Some may need solution before others can be attacked. Further definition and analysis are necessary. The research worker should begin his consideration of variables which may be encountered by a complete and thorough review of literature. This is essential to determine what already is recorded pertaining to the problem or to closely related ones. He may find from what is already known a basis to reject some variables and to select others for study. He may even find that a satisfactory solution to his problem already has been found, in which case he will want to select another.

Preliminary field surveys also may be helpful in the analysis of some problems. In these surveys the research worker can learn more about the exact nature of the problem and the conditions under which it exists. Climatic conditions, soil types, vegetation cover, use of land, kinds of animals grazing, and previous treatment of the range can be considered.

Discussions with stockmen, range technicians, or others closely acquainted with the problem to get their ideas on its extent and the specific conditions under which it is most acute are extremely valuable.

The information gained through literature review, preliminary surveys, and consultation with others may be crystallized in written form. Generally the research worker will find it desirable to incorporate this material into a written project analysis (U.S. Forest Service 1939, pp. 43-63). This will be valuable in the selection of successive studies and will facilitate technical and administrative review. It will also aid in preparation and proper orientation of reports. A suggested outline for such a written analysis is as follows:

(1) Scope and objectives. Definition of the field encompassed by the problem.
(2) Pertinent background data. Facts and figures that demonstrate the seriousness of the problem. Social and economic data which may be used in justifying the work. Information on land ownership, past use, present condition, range operation, or other facts is important.
(3) Specific problems presented. Review of past and current research. Research aspects of the major variables, significance of solving them, and susceptibility to solution.
(4) Relative importance and urgency. Funds, personnel, facilities, experimental materials needed, and availability of these.
(5) Selected specific problems or phases listed by priority for solution.

Analysis of the project on artificially establishing bitterbrush in southwestern Idaho may show the research worker that experiments dealing with rate, depth, and season of seeding bitterbrush under complete protection from grazing, in the absence of competing plant species and rodents, on ranges having soils of granitic origin, and in locations where bitterbrush once grew abundantly will be the most productive.

The project analysis need not be static. There should be a periodic reappraisal, evaluation, and selection of specific lines of attack. Skill and judgment are essential in choosing those phases which contribute the most for the effort and funds expended.

Planning the Investigation

It is at this point, usually, that the research worker develops a written plan for his experiment outlining procedural detail. The purposes of the plan are (1) to insure a clear understanding of the problem, a precise statement of objectives, and carefully considered methods for attaining them; (2) to facilitate technical and administrative review; and (3) in the case of long-term studies, to make certain that time and changes in personnel do not obscure original objectives and proposed methodology. The more comprehensive the planning at the outset, the more efficient will be the collection of data and the more consistent the analysis and interpretation. Moreover, a good study plan will aid materially in the preparation of final reports.

A suggested outline for such a plan follows (U.S. Forest Service 1939, pp. 67-74, 91-95):

(1) The problem. A clear, precise, and specific statement of the problem and justification for the study.

(2) Literature. A review of pertinent literature and applicable current research.

(3) Objectives. A listing of specific objectives to be attained. General topics on which the study may cast light can be discussed separately.

(4) Experimental design and field methods. Criteria to be measured, procedures in imposing treatments, design, techniques for collecting data, and sampling procedures.

(5) Analyses of results. Where statistical analyses are to be employed, appropriate dummy analyses should be developed or appropriate techniques specified for each type of data to be collected. Moreover, probability levels and magnitude of least significant differences, regressions, or other statistics to be attained should be specified.

(6) Kind of tabulations and charts contemplated for presentation of final data. This is important in order to avoid needless detail or over refinement as well as to assure completeness. Anticipated scope of application of results should also be shown.

(7) Manpower and costs involved, time of completion, and personnel assignments.

(8) Appendix. Here should be included such items as detailed instructions for various techniques of measurement to be employed, schedule of work to be done from year to year, choice of instruments, locations of study areas, details of plot arrangements, and handling of experimental animals.

Before the plan for the experiment is completed it is essential to know that experimental materials or facilities needed (land, livestock, seed) will be avaliable. In some cases, unavailability of experimental materials needed may necessitate changes in definition or design of the problem.

The plan should be viewed as a guide for the conduct of the work, not so inflexible that it cannot be changed if developments point to the need.

When the magnitudes of errors for techniques and sampling procedure being employed are not known, it is desirable to conduct preliminary trials to determine the errors. Change in techniques or improvement in sampling procedures may be necessary. All too often a technique is used without proper regard to its accuracy. The research worker may complete the study only to find that technique or sampling errors prohibit statistical measurement of real effects. The longer the study, the more serious this can become.

It is desirable to compile and tabulate the data at the end of each working season for careful observation before commencing another field year. Change in design and technique may be desirable for increased analytical efficiency.

Often there is pressure for early results that may seem to force the research worker to rush ahead without adequate preparatory thought, skillful planning, and careful preparation. Time spent in preliminary phases of research, however, may mean the difference between solution of the problem or costly failure.

The Experimental Solution

When the research worker has completed the study, analyzed the data, and interpreted the results, he can evaluate them with his objectives. He may find that the treatments selected were not satisfactory, that techniques employed were not sufficiently accurate, that variables he had not anticipated were more important than those he included, or that experimental or sampling errors were too great for reliable conclusions.

To aid in judging accuracy of conclusions drawn from his data he selects a probability level which indicates chances or odds that the solution may be correct. The probability level selected should be in relation to how vital the outcome of the study is or the consequences of an erroneous conclusion.

During the conduct of the study, new variables or new problems may have been discovered. Some may be more important than the one under study. Thus, the conduct and completion of the study may emphasize the need for revision of the project analysis and initiation of research on new phases.

Extension of Solution by Pilot Project

When dealing with rangelands, the researcher is faced with variable factors such as soil, weather, diseases, and insect and rodent populations. Although he tries to control and evaluate as many variables as possible, he can hope to handle only a small portion in one study. Consequently, his results often need further testing on a larger scale for better evaluation of their application in practical management. This is commonly done on a pilot test.

It is still research and it calls for use of sound scientific method, even if the evaluation is only through critical observation.

The initial pilot test should be under conditions as near as possible to those in the first experiment. If the solution proves sound and practical under these restricted conditions, additional pilot projects may be warranted under increasingly different conditions to determine how widely the data apply.

Failure of the pilot projects to confirm the initial results may indicate variables not adequately treated in the initial study. This may or may not mean that the original solution was invalid, but it would certainly call for re-examination of both the original experiment and the pilot project. Perhaps a too low or too high probability level used in judging the significance of results led to illogical conclusions. Perhaps factors considered of minor importance in the original experiment proved to have a dominant influence in practical application. Whatever the cause of the discrepancy, the researcher will best resolve it by again following through the steps of logical research procedure—beginning with a new study plan or perhaps a revised project analysis.

In addition to the research aspect, pilot projects have an advantage in demonstrating results to the range user.

Demonstration and Extension

The ultimate value of research is realized only when results become part of practice. Even though research is of a high order and the results widely applicable, the stockman or range administrator may not adopt the results readily. In the absence of demonstration trials the value of research may be lost or only slowly accepted.

Demonstration of the practical value or applicability of an experimental solution at widespread points is important. The experiment itself may demonstrate the superiority of one treatment over another, and pilot projects provide broader demonstrations. But, in addition to these, it often is necessary to plan for more extensive, larger-scale, practical applications of the experimental solution to achieve the necessary link between research and practice. Here, economics research is of value. Research on the cost-and-return aspects of various action policies is important in interpreting the results of biological experiments to ranchers.

Complexities in Range Research

Many variations in ranges, grazing animals, climate, and other features characterize the materials with which the range man works. Ranges differ widely in vegetation, topography, and soils. Range condition, and thus the expected response, may vary within a tract of a few hundred acres. The flora may be made up of a hundred or more species of grasses, forbs, shrubs, and trees. Soil depth, salinity, slope, and exposure may change in short distances and may confuse results.

Grazing animals are a part of the range and are vital in the range plant's environment. Conversely, the range is the animal's environment. In many types of range research the effects of treatment are measured in terms of both animal and plant response.

The grazing animal is often the harvesting mechanism in range research. Just as the range is subject to large variation so is the grazing animal. Even under a fixed and constant grazing environment, production differs with species, breeding, sex, age, maturity, class, condition, and temperament of the grazing animal. Diseases, insects, and breeding cycles influence animal production. Maintenance of uniform grazing use over all parts of a range is difficult because animals tend to concentrate near water or supplemental feed, in shade, on well fertilized areas, or in areas of easily accessible topography. The palatability of a plant and also the parts of the plant eaten will vary with different animal species and different seasons of the year.

Climates in different portions of the rangelands differ. Within a single location weather may vary widely from year to year or from season to season. Climate is an uncontrollable variable of such magnitude that its effects on both the range and the grazing animal are often greater than those of the treatment imposed. Its effects on production and behavior of the animal and on production and nature of range vegetation are frequently difficult to separate from treatment effects. These variations constantly harass the range investigator, increasing the required time and effort to obtain significant results and confusing the analysis of his data.

Responses to treatments occur slowly in many types of range research. Unless treatments are drastically different, significantly measurable effects on animal or range forage production may not be found for 8 to 10 years.

These many variables necessitate skill in the design of research projects. They influence selection of experimental materials, replication and duration needed, and the scope of application of results. Ways in which the research worker may overcome some of these are discussed later in this book.

Selection of Experimental Facilities

The criteria to be used in the selection of facilities for use in research vary with the kind of studies contemplated. Some of the major criteria are representativeness, suitability for study purposes, accessibility, feasibility of control, possibility of obtaining support and cooperation from other groups, and demonstrational possibilities.

The relative importance of these criteria will vary with the type of study. At one extreme may be laboratory or greenhouse study where complete control and uniformity can be approached. Here the investigator still must be concerned with representativeness of soil, seed source, suitability of the facility for the type and size of study to be conducted, and its accessibility.

In selecting an experimental range which is to constitute an outdoor laboratory for a long-time research program, all of the criteria mentioned above and others must be considered (U.S. Forest Service 1939, pp. 53-59, 62). This task is one of the most exacting that a range research worker faces.

In the selection of experimental facilities it must be remembered that scope of direct application is thereby determined. Results from greenhouse or laboratory studies may be used to develop principles whose range application may involve further research under field conditions. In field research, minimizing extent of variability in areas, grazing animals, or plants may prevent direct application of results to highly variable conditions found on other ranges. Conversely, failure to control or eliminate great variability may result in failure to identify and evaluate treatment effects.

In general, in field research, the land, the animals, and the plants should be typical of large areas in order that results will have broad application. Obviously, research is too expensive to permit separate investigations for small areas and localized problems. Much applied research depends upon public support, which in turn depends upon broad and practical application.

It is important to keep accurate record of conditions existing at the start of research. Land, vegetation, and animals should be described in detail. Past treatment or prior use of land may influence its responses. Exact genetical nature of plant materials is important. Specimens should be collected and placed in a permanent herbarium for future reference.

Methods in Range Research

Methods used in range research have changed radically since its initiation. Observation was the mainstay of the early research worker. Later, more objective and exact techniques from plant ecology, physiology, soils, and other sciences were introduced. Frequently these had to be changed to adapt them to the new needs. The application of statistical methods to the analysis of data, and the concepts of efficient sampling procedures and experimental design brought still further refinements.

The range research worker will find that each of the methods available has strong and weak points for his particular purpose. The validity of results and the efficiency of the experiment will depend upon his skill and judgment in selecting and applying techniques.

The wide variety of methods used, and the variation in the type of data they produce, is a source of major difficulty to those seeking to integrate the results from many separate investigations to obtain solutions to broad regional problems. This is also a source of difficulty to those engaged in the economic analysis of data derived from applied range research. As a result, standardization is often urged.

Complete standardization at the present time is neither possible nor desirable. Ultimately, more uniformity in routine techniques must be sought, but the utmost freedom must be maintained in developing ideas and better methodology.

It is not the purpose of this book to effect complete uniformity of research methodology. For many investigations, several methods may be equally effective. Various range conditions, individuals, and budgets may require different techniques. It is not desirable to standardize to the degree that all investigators accept a method without question. Such a practice would prevent progress and improvement in methods as well as impair high-grade scientific work and individual efficiency. Minor details, especially, should be determined by the judgment and experience of the individual research worker (Amer. Soc. Agron., 1952).

This book will present numerous commonly accepted methods. The inclusion or exclusion of any technique is not intended to indicate its acceptability or value. It is the desire of the American Society of Range Management and the Academy—Research Council to provide research workers with examples of fundamental methodology which can be applied, sometimes with modifications, to suit particular demands.

Advantages and disadvantages of various techniques will be presented in the hope that the best research practice for each particular situation will be followed. Insofar as possible, unification of approach is desirable. Results obtained by similar methods are more readily comparable. Deviations from commonly accepted methodology should be avoided except where advantages are clearly evident.

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Chapter 2
Assessment and Control of Habitat Factors

MUCH variability of habitat is encountered in range research. This variability stems from the large units of land involved and the inherent diversity on western ranges where extensive artificial control of factors is impossible.

It becomes necessary to control or minimize the natural variables, to determine what variables remain, and to design the experiment to equalize their effects as far as possible. This chapter will treat problems of determining, measuring, and controlling habitat factors to aid in designing experiments and interpreting and applying results.

FIELD VERSUS LABORATORY STUDIES

The study of range management is a study of the relations between cause and effect. Attention is focused upon the habitat as the cause and the plant or plant community as the effect. Because the plant in turn modifies the habitat, the plant may also be looked upon as a cause and the habitat, through reaction, as an effect.

Range researchers of course wish to develop general principles but have to deal largely with local situations. Usually the work is conducted in the field under natural situations. Although this is a practical approach, results often are difficult to apply to other areas and other conditions. Furthermore, many years may be necessary to encounter extremes of environment necessary for a complete view of the problem. The field environment is variable and complex. Even careful assessment and control of habitat variables may not be completely satisfactory because we do not know how to use such measurements precisely in connection with predicting vegetation and animal behavior. It is not enough merely to record the circumstances under which experimental data were gathered. Such information must be accompanied by an interpretation of the significance of the habitat variations and an appraisal of their effects.

Many fundamental principles of range management can be investigated better under greenhouse conditions, and the value of field investigations can be enhanced by adding growth chamber or greenhouse studies. Here, plants can be grown in a simplified environment with the possibility that any of the factors may be held constant. By thus minimizing variation, it is possible to isolate single factors or to establish given combinations of factors that would be impossible under natural conditions. Laboratory and greenhouse studies may speed up research. For example, by artificial drought or freezing, certain grasses may be eliminated from further study, whereas naturally the drought or frost test might not occur in 10 years. An investigator provided with both field and greenhouse conditions is best equipped to develop basic principles.

ECOLOGICAL FACTORS INFLUENCING RANGE RESEARCH DATA

Climatic Factors

Climate is the primary factor determining range forage production. Field studies of forage production and use by grazing animals must recognize and evaluate climate, which may vary widely with geographic area and season. An appraisal of the microclimate is particularly essential to an understanding of the ecological life history of the individual range plants and animals and of the community.

Techniques for control of climatic factors in research are limited largely to the greenhouse, although irrigation may make the project somewhat independent of precipitation variation in the field. Use of extreme methods for control, such as are used in the phytotron, may make possible an almost complete control of climatic factors. Statistical methods are required to isolate the importance of individual factors in the climatic complex.

Characterization of Regional or Areal Climates

The macroclimate associated with range types may be characterized by groupings or summations of important climatic variables such as precipitation, temperature, and evaporation. Monthly values of precipitation and temperature based on Weather Bureau records presented in either tabular or graphic form or as climatographs or hythergraphs (Smith 1940) provide useful tools in portraying generalized climatic patterns of unit areas. Although the value of such summaries for determining relations between climate and vegetation is limited, climatographs have proved useful in the prediction of successful introduction of game species into new areas (Odum 1959) and this may apply to plant introductions as well.

Classifications such as that of Thornthwaite (1948), based on summations or efficiencies of temperature and moisture and their seasonal variations, may serve to delimit climates. In this classification, the moisture efficiency scale is based on precipitation and potential evapotranspiration. This makes it a useful tool in presenting average climates and year-to-year variation in moisture and temperature conditions.

Climatic cycles, particularly the incidence of drought, are known to affect range and animal production. Yearly and seasonal departures from precipitation values, and the frequency and severity of departure have been used to characterize regional climates. In Texas, rainfall less than three fourths of normal was considered critical in maintaining forage production (Texas A. & M. College, Dept. of Range & Forestry 1953). In Arizona, Reynolds (1954a) has distinguished three categories of drought severity based on summated departures of below-average rainfall: slight-departures between 0 and 40 percent of average rainfall; moderate-departures between 41 and 70 percent of average rainfall; severe-departures in excess of 70 percent of average rainfall. Unfortunately, we know too little of how various magnitudes and distributions of climatic factors actually interact and ultimately influence vegetation and livestock production (see also Smoliak 1956).

Microclimate

Until recently the microclimate of the specific habitat within which the range plant, the animal, or the community develops has received relatively little attention. Climatic variations within the plant cover near the ground surface may be more or less extreme than those of the macroclimate. Also, for the individual plant, climate may be greatly influenced by the characteristics of the total vegetation. Measurements of the microclimate are essential for a thorough appraisal of the range environment.

General concepts of the microclimate are reviewed by Geiger (1950) and Wolfe *et al.* (1949). Instrumentation and techniques for analysis of individual factors are specialized. Standardization of methods has not yet been effected (Brooks and Kelly 1951).

Instrumentation and Sampling

The kind, number, and location of climatic instruments to be employed in the measurement of macro- or microclimates will depend on several factors: (1) nature, objective, and relative importance of the study; (2) variability as expressed by micro- or site climates; (3) physiography and extent of the area. Comprehensive range investigations should have at least one station equipped to measure such climatic factors as precipitation intensity, air temperature, wind velocity, evaporativity, and humidity (Middleton and Spilhaus 1953). Radiant energy and dew also may be important.

In areas with variable topography, attention should be given to the proper location of sampling stations to obtain representative data. Intensive sampling of widely variable climatic factors such as precipitation may be efficiently carried out by a combination of short period areal- and time-stratified observations coupled with fixed station measurements (Wilm 1943).

Precipitation: Instruments for measurement of rainfall include the standard 8-inch Weather Bureau rain gauge; the weighing type, such as the Ferfusson self-registering gauge; and the tipping-bucket gauge with electrically recording instruments for the determination of period and intensity of precipitation. Less expensive devices can be made in various ways, such as from a small gasoline can with a funnel equipped with a flange soldered into the top. By using oil to prevent evaporation, these may be left for long periods of time in inaccessible parts of a range. In regions of rugged topography, errors in measurement caused by slope and prevailing winds may be corrected by using gauges with sloping orifices oriented parallel to the slope or directed into the prevailing wind (Hamilton 1954).

Rain gauges may be modified by using shields to permit measurement of snowfall (Kittredge 1955). Core sampling, as employed in snow surveys, gives a more satisfactory measure of precipitation in regions of heavy snowfall.

Daily and monthly records of precipitation are valuable in analyzing factors affecting forage production. Knowledge of the frequency and intensity of droughts and of high-precipitation storms is important to the watershed manager. Soil moisture availability is a more readily interpreted index to effectiveness of precipitation than is the precipitation record itself (Lull and Reinhart 1955).

Humidity and vapor pressure deficit: Field instruments for measurement of humidity include the psychrometer for measure of wet and dry bulb temperatures and the hygrometer or hygrothermograph for continuous readings of relative humidity. Other instruments for laboratory use in measuring the amount of water vapor in the air are based on chemical absorption and determination of dew point temperatures.

Psychrometric data on wet and dry bulb temperatures may be used in the determination of relative humidity and of vapor pressure deficit. Vapor pressure deficit is a direct indication of atmospheric moisture independent of temperature and its use is preferable in ecological studies to that of relative humidity.

Humidity data may be expressed as maximum and minimum values derived from hygrometer records or as instantaneous values from psychrometric determinations.

Evaporation: Evaporating power of the air is determined by temperature, vapor pressure gradient, wind velocity, and barometric pressure. Evaporation from a land surface is regulated by evaporation opportunity or the ratio of actual water loss under existing atmospheric, soil, and vegetational conditions to the potential rate of evaporation from a free water surface.

Evaporativity may be measured by tanks or pans, or by porous porcelain or Piche wet-paper atmometers which record the amount of water loss from a water surface or film. Evaporation from land surfaces can be evaluated by: (1) direct measurement of water loss from soil blocks in containers or lysimeters; (2) measurement of vapor pressure gradient from continuous records of air temperature, specific humidity, and wind velocity at two levels above the ground surface (Thornthwaite and Holzman 1942); (3) direct measurement of radiation and calculation by difference in the hydrologic equation for water intake and water outgo (including evaporation combined with transpiration).

Evaporativity measurements are of importance in analyzing the habitat, and evaporation opportunity measurements provide criteria related to soil moisture availability. Studies on potential and actual evapotranspiration by Thornthwaite (1948) show the importance of the latter type of measurement.

Evaporation from a vegetated surface includes the interception loss or that portion of the rainfall which is retained by the aerial portion of the vegetation and is either absorbed by it or is returned to the atmosphere in vapor form. Interception losses vary with rainfall intensity, foliage cover, and other environmental conditions and may constitute an important reduction in effective precipitation (Clarke 1940).

Temperature: Instruments for the measurement of air temperature include maximum and minimum thermometers, thermographs for continuous records, and thermocouples or thermistors for microenvironmental studies.

Temperature data of value in characterizing climatic areas include average monthly maximum, minimum, and mean temperatures; duration of frost-free period; and temperature summation or efficiency indices (Klages 1942). Significant diurnal and seasonal variations in temperature regulating plant growth and animal activity should be portrayed. Time and duration of extremes are important.

Variations in air and soil temperature with slope, exposure, altitude, and character of vegetation may influence or determine the intensity and nature of temperature measurements. Microclimatic studies involving air and soil temperatures related to various densities and types of cover may be conducted efficiently with thermistors.

Temperature data, like many other climatic records, are difficult to interpret in range research. Temperature directly influences both plant and animal activity, but too high as well as too low temperatures restrict activity. Also, the optimum and suitable range of temperature varies with the type of organism studied. Extremes do not tell the whole story, and there are definite limitations imposed upon the use of maximum and minimum temperatures alone. Yet our knowledge is incomplete as to such things as effect of duration of given temperatures, the relative effects of day-time and night-time temperatures, and the interrelations between temperature and other factors, such as soil moisture.

Radiation: Solar radiation and light are important climatic factors. Duration may be studied with a Marvin sunshine duration recorder, which employs a differential air thermometer, or by self-recording devices containing sensitized paper. Intensity and quality measurements may be conducted with photoelectric meters or radiometers (Middleton and Spilhaus 1953).

Few studies have been made of the effect of light upon range plants. Duration or photoperiod is significant in regulating the vegetative and reproductive growth of most forage plants. Light intensity may have pronounced effects on seed germination, plant development, and nutrient content of forage, and may influence range livestock directly through activation of toxic substances causing photosensitization.

Evaluation of the light factor may involve intensity, quantity, and quality. Control of light by shading, filtering, or modification of day length may provide a more convenient analysis of cause and effect than sampling natural environments. Ordinary electric lights and reflectors producing 100-180 foot-candles of light, as measured by a Weston sunlight meter, are satisfactory for increasing day length (Olmsted 1944).

Wind: Wind velocity may be measured with some form of anemometer such as the rotating cup, vane, pressure plate, or pressure tube.

Wind movements are important in relation to evaporation and transpiration, movements of range livestock, wind erosion and shelterbelt effects, and in detailed ecological studies of seed dissemination and mechanical effects on plant tissue.

In measurement of wind velocity, consideration should be given to topography, character of vegetation, major paths of wind movement, and other physical factors. Wind profile studies, especially within woody vegetation types, may demonstrate wide differences as influenced by plant cover.

Soil Moisture Measurement

Soil moisture is measured to determine: (1) the amount of water that is available to range plants; (2) the distribution of rainfall into the soil; (3) the rate and depth to which soil dries; and (4) the amount of water that is evaporated and transpired from the soil.

There are many ways of measuring soil moisture, but the most commonly used are the gravimetric and electrical resistance methods. A third, the nuclear method, holds considerable promise of solving instrumentation problems.

Gravimetric Method

The gravimetric method consists of obtaining a soil sample, weighing it, oven-drying the sample for 24 hours at 105° C., reweighing, and expressing its moisture content as a percentage of the dry weight. To reach the sampling depth desired may require pick and shovel. A soil tube or post-hole digger may be used if the soil is not too rocky.

Gravimetric sampling is arduous and time-consuming, and its frequency should be directed by weather and soil moisture conditions. Another inherent disadvantage, this method destroys the sampling point so that moisture contents determined over a period of time possess location as well as time variation. Despite these disadvantages, the gravimetric method is the only one that gives a direct, quantitative measurement. Other methods require calibration in order to transform electrical resistance or other types of data into moisture contents.

Electrical Method

The electrical resistance method involves inserting into the soil a small unit composed of electrodes surrounded by porous material. As the surrounding soil wets and dries, the porous material wets and dries, thereby changing its electrical resistance. These changes are measured with a portable meter. Units must be calibrated—i.e., resistance readings related to actual soil moisture content—in the laboratory or, preferably, in the field. For accurate records, resistance must be adjusted to a common temperature.

Careful installation of units is crucial. They should be installed when the soil is moist enough to pack well and the excavated soil repacked.

Nuclear Method

The nuclear method is based on detection of the slowing down and deflection of neutrons by water in the soil. This method measures the amount of water per unit volume of soil. Since the relation between neutron count and moisture content is largely independent of the character of the soil, one calibration curve may suffice for all locations. The nuclear instrument has advantages of speed and ease of operation. It does not give accurate values for the upper six inches of soil. It is expensive and experience so far has indicated that it is subject to frequent breakdown in field use.

Choosing the Method

Choice of methods depends, to a great extent, on the measurements desired and on the kind of soil. If, for instance, only infrequent measurements are required, such as at the beginning and end of the growing season, the gravimetric method is indicated. Where daily or weekly measurements are recorded over a period of several seasons, the electrical resistance method seems preferable. Where soils are stony, gravimetric sampling must be done with a pick and shovel. In stonefree soils, gravimetric sampling with a soil tube may reach depths of 10 to 15 feet. Field calibration of resistance units is difficult in coarse or stony soils and laboratory calibration may be necessary. Salt concentration of the soil solution, though not affecting the gravimetric or nuclear methods, may dictate the type of electrical units used.

Using Soil Moisture Data

Samples are often taken by consecutive one-foot depths throughout the depth of soil drying. Frequent sampling is not required when the soil is continuously wet or dry. To define summer soil drying curves, daily samples may be taken for a few days after the soil has become wet. As it dries, the rate of change decreases and sampling may be less frequent.

Soil moisture content values on a percent dry-weight basis do not indicate how much water is in the soil and can be used for relative comparisons only when soils of similar bulk densities are compared. Soil moisture contents on a volume basis are necessary if absolute quantities are required. They are useful in hydrologic studies where soil moisture, precipitation, and streamflow are expressed volumetrically. Per cent-by-volume values, however, possess an added source of error over per cent-by-weight because measurements of soil volume are also involved.

Soil moisture measurements, to have meaning, must be interpreted in relation to soil moisture constants under wet and dry conditions. Field capacity is the amount of water which can be stored in the soil. It is the moisture content that exists when, after the soil is thoroughly wetted, there is little further downward movement of soil moisture. Two or three days are required for medium-textured soils to drain to field capacity. The amount of soil moisture at field capacity ranges from about one to four inches of water per foot depth of soil for very coarse and fine-textured soils, respectively.

Permanent wilting point marks the low end of the moisture scale. It is that moisture content below which plants wilt. It ranges from less than one-half inch to more than two inches of water per foot depth of soil, increasing with increasing fineness in soil texture.

Storage capacity for different soil texture classes is given on page 19 in inches of water per foot depth of soil (U.S. Army Corps of Engineers 1956).

Subtracting the permanent wilting percentage from the field capacity percentage will give an approximate measure of the soil moisture available for transpiration.

A discussion of methods of soil moisture measurement, their advantages

Texture class	*Field capacity*	*Permanent wilting point*
Sand	1.2	0.3
Fine sand	1.4	0.4
Sandy loams	1.9	0.6
Fine sandy loams	2.6	0.8
Loams	3.2	1.2
Silt loams	3.4	1.4
Light clay loam	3.6	1.6
Clay loam	3.8	1.8
Heavy clay loam	3.9	2.1
Clay	3.9	2.5

and disadvantages, instrumentation, and costs is given by Olson and Hoover (1954) and Lull and Reinhart (1955).

Soil Characteristics and Qualities

In this discussion on soils, emphasis is given to soil characteristics and qualities and to certain principles that should prove useful to the range scientist. Soil science is a complex field in itself, although closely allied with plant science and an integral part of ecology. For this reason, the range scientist is well advised to consult with a soil scientist in carrying out research involving the recognition and measurement of soil differences.

Factors of Soil Formation

Range lands are characterized by a great diversity of soils, which is to be expected because of wide differences in the *natural factors of soil formation*, including climate, living matter, parent material, relief, and time (Jenny 1941, U.S. Dept. Agr. 1938). The natural characteristics of a soil at any one place are the result of the integrated effect of climate and living matter, acting on soil parent material, as conditioned by relief, over a period of time (U.S. Dept. Agr. Soil Survey Staff 1951).

Rangeland in general cannot be characterized by any one combination of the factors of soil formation. There are as many combinations as there are soils. Climate and living matter vary from those characteristic of the hot deserts of the Southwest to those of near tundra conditions in the high Rocky Mountains, or to those of high rainfall areas along the Pacific Coast. Soil parent material is highly variable in composition as well as mode of formation. Relief varies from nearly flat plains to perpendicular cliffs. The time factor in the formation of soils varies from almost zero, as for soils of recent alluvium, to many thousands of years.

Range soils cannot be differentiated on the basis of soil formation factors alone. Too little is known about variation in soil characteristics as related to the tremendous number of significant combinations of soil-forming factors. Nevertheless, these factors should be appreciated. This is particularly true in making appraisals of areas for experimental work since the more uniform the natural factors of soil formation the more uniform the natural characteristics of soil.

In addition to natural factors, man's activity also must be considered as a significant modifying factor. Soil changes brought about by man-induced erosion, severe soil compaction from livestock trampling or use of equipment, soil moisture changes from gullying and drainage, and plant-nutrient changes through fertilization may be of great significance in relation to kind and amount of forage production.

Differentiation of Soils

Soils may be differentiated in several ways, depending on objectives. Three commonly used ways, actually interconnected, are: (1) soils classed simply according to differences in one property, such as texture, color, or reaction; (2) soils classed according to their qualities or attributes as manifest in behavior or performance, such as erodibility, moisture retentivity, permeability, fertility, or productivity; (3) soils existing as natural units of the landscape classed according to distinctive and relevant combinations of a number of soil characteristics, as is done in natural classification of soil.

The broad objective of natural systems of soil classification is to provide means of organizing knowledge of soils. The principles of classification are as applicable in range areas as in cultivated areas, and one of the chief uses is for predicting soil behavior or performance. The *soil series* is a group of soils with horizons similar in differentiating characteristics and arrangement in the soil profile, except for the texture of the surface soil, and developed from a particular type of parent material. In the soil series, emphasis is on the characteristics of the horizons. Some soils, such as those of recent stratified aluvium, may have distinct layers but no evident soil horizons, since the characteristics of the strata are not the result of soil-forming processes. In such cases, characteristics of the soil layers are used for classification purposes. Soil series are usually given geographic place names where first recognized.

The *soil type* is a subdivision of the soil series based on the texture of the surface soil. The type name consists of the series name plus the textural class name of the surface soil, such as Vista sandy loam.

The *soil phase* is a subdivision of the soil type or soil series based on characteristics potentially significant to man's use or management not otherwise covered by the classification unit. Subdivisions based on significant differences in slope, soil depth, erosion, or rockiness are common phases of soil types or series.

Common Differentiating Characteristics

The following characteristics include those commonly used in developing criteria for differentiating soils at and below the soil series level (U.S. Dept. Agr. Soil Survey Staff 1951). Most behavior and performance characteristics of soils can be related to, or identified with, soils differentiated on the basis of combinations of these characteristics.

Thickness of horizons and soil depth: Thickness of horizons is usually measured in inches and perpendicular to the soil surface. Thickness of soil is the summation of the thickness of horizons regardless of ease or suitability for root growth and penetration. The term *soil depth* commonly has a more practical meaning and refers to that portion of the soil from the surface downward to underlying bedrock, hardpan, consolidated substratum, or other material that would greatly restrict root distribution, soil moisture, or nutrient supply.

Arrangement and number of horizons: The number and relative position of the horizons in the profile as well as the degree of gradation from one horizon to the adjacent horizon below are all important characteristics.

Structure of horizons: Soil structure refers to the aggregation of primary soil particles into compound particles or clusters. Soil structure classes are based on shape, such as granular, blocky, prismatic, or platy, and on size and distinctness or durability of visible aggregates. Structure is an extremely important characteristic of soils because of its influence on permeability, erodibility, and productivity. No other management problem pertaining to soils in range areas is so important as the maintenance, restoration, or improvement of structure at the soil surface.

Color of horizons: Color is the most obvious characteristic of soils. It has little to do with behavior, but may be indicative of important quality differences. Dark-colored soils normally are higher in organic-matter than light-colored soils; uniformly colored soils, particularly those of reddish hues, are usually well-drained and well-aerated; and mottled soils, where color differences are not due simply to differences in decomposing rock fragments, are usually indicative of imperfectly or poorly drained and less completely aerated conditions.

Soil color is measured according to the Munsell system (hue, value, and chroma) and usually by comparisions of dry and moist soil samples with standardized color chips. Soil color class names, such as grayish brown or reddish brown, are based on limits within the Munsell system.

Texture of horizons: Soil texture refers to the relative proportions of the various size groups of individual soil grains: clay, silt, sand, and gravel. Texture is one of the less easily changed characteristics of soil and has an important influence on behavior. Differences in moisture retentivity, permeability, erodibility by wind, and workability are commonly related to texture.

Textural classes, such as sandy loam and clay loam, are based on amounts of the soil grains in each size group below 2 millimeters in diameter. The amount in each is determined by mechanical analysis, either by hydrometer or pipette methods. Experienced men can make close estimates simply by feeling well-moistened soil between the fingers. Coarse fragments (above 2 mm. in size) are important to recognize, both as to amount and predominant size, because of their influence on moisture retentivity and workability. Terms such as "gravelly" and "cobbly" for coarse fragments are used to modify textural class names.

Consistence of horizons: Soil consistence refers to the degree of cohesion and adhesion or the resistance to deformation or rupture. Terms such as cemented, compact, hard, soft, loose, friable, firm, plastic, and sticky, are used. Consistence of most soils varies with moisture; a particular kind of clay soil may be extremely hard when dry, firm when moist, and sticky when wet. Change in consistence of the soil surface may have an important influence on soil behavior.

Soil consistence is usually expressed qualitatively rather than quantitatively. Classes are not rigidly defined, and yet they are described in sufficient detail to be expressive of soil differences (U.S. Dept. Agr. Soil Survey Staff 1951). For certain purposes, empirical quantitative determinations, such as plasticity limits and sticky point, may be needed.

Reaction and base status of horizons: Soil reaction refers to the degree of active acidity or alkalinity. It is probably the most important single chemical test that is made of soils because of its general importance in connection with plant growth. It is measured according to pH values, usually by colorimetric method in the field and by electrometric method (glass electrode) in the laboratory. In the laboratory, tests are usually made on a saturated soil paste or a 1:1 soil-water mixture. Since the pH scale is logarithmic, it should be kept in mind that a difference of one unit is a 10-fold difference in hydrogen ion activity. A pH of 7.0 is neutral. For example, a soil sample with a pH of 5.0 is 10 times more acid than one of pH 6.0; or one of 8.5 is 10 times more alkaline than one of 7.5 (Wherry 1927). Reaction classes are commonly used, such as slightly acid or moderately alkaline. Soil reaction classes and corresponding ranges in pH values are reviewed by the Soil Survey Staff of the U.S. Department of Agriculture. (1951, p. 235).

The pH value of a soil is a fairly good indication of its base status, that is, the relative amount of active base cations (exchangeable bases). Acid reactions in general indicate a degree of base unsaturation, and usually the more acid the soil the lower the base status. Alkaline reactions indicate a high base status or a saturation of the exchange complex with base cations, commonly Ca, Mg, Na, and K. Soils with pH values of about 7.8 or above are commonly, but not always, calcareous, and soils with pH values above 8.5

normally are high in exchangeable sodium, although the reverse of this does not necessarily hold. Calcareous soils can be identified by effervescence with dilute (0.1N) hydrochloric acid.

Although pH indicates base status, it does not indicate the proportions of exchangeable bases. A soil with a pH of 7.5, well within the optimum range for the growth of many forage plants, may be exceedingly low in calcium and high in magnesium; or it may be high in sodium relative to other bases. In both cases there is a nutritional unbalance that would affect plant growth.

Soluble salts in horizons: Excesses of soluble salts, which characterize saline soils and which commonly occur in alkali soils, influence the kind and amount of plant growth. Some of the early classical studies of soil-vegetation associations were on saline and alkali soils in relation to plant communities (Hilgard 1906). Content of soluble salts is usually determined by electrical conductivity methods, either with saturated soil paste or with a solution extracted from saturated soil (U.S. Salinity Laboratory 1954; U.S. Dept. Agr. Soil Survey Staff 1951).

A *saline soil* contains enough soluble salts so distributed in the profile that they impair productivity. It is not strongly alkaline nor otherwise an alkali soil. A saline soil sample has a conductivity of its saturation extract greater than 4 millimhos per centimeter at 25° C., or a content of soluble salts greater than 1.15 percent (dry soil basis). An *alkali soil* has either so high a degree of alkalinity or so high a content of exchangeable sodium, or both, as to impair its productivity. An alkali soil has a pH of 8.5 or higher, or an exchangeable sodium percentage of 15 per cent or higher, or both. A *saline-alkali* soil fulfills the requirements of both a saline soil and an alkali soil.

The kinds and amounts of salts are also important in their influence on plant growth, and the characteristics of the soil. For example, some alkali soils containing sodium carbonate and bicarbonate are not only strongly alkaline in reaction but commonly tend to disperse on wetting and to become compact and hard on drying.

Organic matter in horizons: Organic matter is important usually in the upper horizons. It includes freshly fallen litter as well as decomposed matter. Organic soils contain 30 per cent or more organic matter. Relative differences in organic matter content of mineral soil horizons usually can be detected mainly by differences in color. Quantitative differences must be determined in the laboratory, usually by organic carbon determinations. Total nitrogen content of the soil is also commonly determined since the carbon-nitrogen ratio of organic matter is an important characteristic of soils as well as an indicator of fertility.

Mineralogical composition of horizons: The mineralogical composition of soil horizons is in part dependent on the mineralogical composition of the soil parent material. It is also dependent on processes of soil formation and the length of time these processes have gone on. The kind of silicate clay resulting from decomposition of clay-forming minerals, such as the feldspars, has an important influence on soil behavior. Clay soils with expanding lattice-type clay (montmorillonitic) are much more "clayey" in the sense of stickiness and in expansion and contraction than soils with the same amount of non-expanding lattice-type clay (kaolinitic), and there are other important differences of fundamental nature.

Kind of silicate clay is usually determined by X-ray diffraction pattern or by differential thermal analysis. Coarser minerals are determined by microscopic techniques.

Character and geology of parent material: Certain soil qualities are more readily inferred from type of parent material or parent rock than from any other characteristic. For example, some soils contain sufficient selenium to produce troublesome concentrations in certain forage plants (Byers *et al.* 1935-1948). Other differences, such as abnormally low or high base status and certain mineral nutritional deficiencies or toxicities in some soils are traceable to the character of parent material or of underlying parent rock. The low calcium and high magnesium content and other differences of certain soils formed from the decomposition of serpentine are directly traceable to the characteristic chemical nature of this rock.

Slope: Although slope gradient is the most common basis for differentiation, other characteristics of slope, such as shape and length, may be important. Slope is of particular importance in connection with surface run-off and erodibility. The relative influence of slope on erodibility, however, is dependent on other characteristics of the soil.

Erosion: As a differentiating soil characteristic, erosion refers to soil change that has occurred through accelerated erosion, not to the eroded material. It should not be confused with erodibility of a soil, since some soils relatively resistant to erosion may be severely eroded whereas other highly erodible soils may not be eroded at all. It is important to distinguish between past and active erosion. Usually active erosion manifests itself by observable changes at the soil surface, even though total soil loss from an area may be slight (Gleason 1953). Erosion of one soil may damage production far more than the same amount of erosion of another kind of soil.

Drainage: Differences in drainage are reflected in other characteristics such as organic-matter content and color pattern. Some soils, however, must be differentiated solely by observed differences in drainage, such as frequency and duration of overflow or duration and height of water table. Some soils may have formed under poorly drained conditions and have become better drained through gully development.

Differences in soil drainage are important because of the close relation of drainage to the moisture regime of soils and its effect on plant growth. Caution is needed, however, in making generalizations on soil behavior and plant growth on the basis of drainage alone. All poorly drained soils do not behave the same way any more than do well drained soils.

Rockiness and stoniness: Rock outcrops and stones larger than 10 inches in diameter are not considered part of the soil. They may be, however, of great importance in the use of soils. Although degrees of surface stoniness ordinarily have less or different significance in range areas than in cultivated areas, they should be considered.

There are other characteristics of soils, such as temperature, moisture, bulk density, and porosity, that are important in connection with certain experimental work. Soil temperature and moisture, particularly near the surface, are highly variable. Soil behavior may change rapidly because of fire or artificial removal of vegetation. Bulk density determinations are particularly important in studies on moisture retention as related to soil and water volumes. Porosity, especially size, shape, and continuity of pores, is significant in permeability studies.

Some Important Soil Qualities

Soil qualities are behavior characteristics inferred from the previously discussed differentiating characteristics or attributed to a particular kind of soil. Such qualities can be predicted only to the degree that soil behavior is known and related to the differentiating characteristics. Also, these predictions can only be as accurate as the relationships established are accurate. With such information, different kinds of soils can be grouped into a number of interpretive classes of direct value in use and management decisions (Gardner & Retzer 1949).

Range research involving soils is usually for a better understanding of soil qualities important to range use. Also, the variation of some soil quality is studied in relation to variations of selected soil characteristics, as in variations in compactibility of soil surface as related to variations in texture and organic-matter content. The results of such studies can be extremely useful provided the following principle is understood and adhered to: *The influence on soil behavior of any one characteristic depends upon the others in the combination* (U.S. Dept. Agr. Soil Survey Staff 1951).

Soil qualities of particular importance in range research include erodibility, moisture retentivity, permeability, fertility, and productivity.

Erodibility: Erodibility refers to the relative susceptibility of a soil to erosion. In considering erodibility, two aspects are necessarily involved: (1) Characteristics of soils that pertain to their stability, and (2) the degree of soil or vegetation disturbance that would accelerate erosion.

Erodibility is not easy to measure nor to express quantitatively. Usually, measurements are based on the amount of soil lost per unit of area under specified conditions. Behavior of a soil in a small experimental plot, however, may be quite different from its behavior in larger units.

Moisture retentivity: Moisture retentivity refers to the moisture retaining power of soil at specified levels of moisture tension. Three levels are commonly used: saturation, field capacity, and permanent wilting point. Field capacity formerly was approximated by moisture equivalent determinations. Recently the pressure plate method with tensions at 1/3 or 1/10 atmospheres has come into greater use (U.S. Salinity Laboratory 1954). Permanent wilting point is determined through growing sunflowers in a sample of soil under standardized procedure. A close approximation of moisture content of a soil at this point is obtained by the pressure plate method with tension at 15 atmospheres. Available soil moisture ordinarily refers to the amount of moisture a soil can contain between its permanent wilting point and field capacity. Soil texture (as well as content of coarse fragments) has a greater influence on moisture retentivity of mineral soils than other characteristics, although in some soils organic-matter content or kind of silicate clay may have important influences.

Permeability: This quality of soil relates to the readiness with which it conducts or transmits fluids. Ordinarily it refers to a quality of soil horizons, but for some purposes the permeability of the least permeable horizon of a soil (except for the immediate surface layer) is used to denote permeability of the whole soil. In the field, estimates of permeability are made usually by considering structure and texture although other characteristics may be important. For example, strongly alkaline soils tend to disperse on wetting and become nearly impermeable.

Infiltration rate, or the rate of surface water entry into a soil, is governed by the least permeable layer of the wet soil. Frequently in range soils, the limiting layer is at the immediate surface, where permeability can be greatly influenced by changes in structure and compaction (see Chapter 7).

Laboratory measurements meaningful in terms of field behavior have been difficult to devise. One method is the measure, under standardized conditions, of the water flow rate through relatively undisturbed core samples from a soil horizon. Since one large, continuous pore in a sample may have a tremendous effect on rate, it is usually necessary to collect several core samples from each horizon.

Fertility: Fertility is the quality that enables a soil to provide the proper kinds and amounts of nutrients for the growth of specified plants. Three general methods for testing soil fertility are in common use: (1) Chemical analyses of soil samples (Peach *et al.* 1947); (2) chemical analyses of plant foliage (Ulrich 1952); (3) determining in the greenhouse the growth response of plants in soils to which different kinds and amounts of fertilizer have been applied (Jenny *et al.* 1950). Nitrogen, phosphorus, and potassium are most commonly determined; sulfur, calcium, and minor elements less commonly determined. Soils react differently to fertilizers. Some fix significant amounts of phosphate, others fix little or none. Continued applications of sodium nitrate to alkaline soils that already contain appreciable exchangeable sodium can increase the sodium to harmful amounts. Soil fertility may have an important bearing on quality as well as amount of forage.

Productivity: Soil productivity pertains to the capability to produce specified plants under given management practices. The distinction between soil fertility and soil productivity needs to be clearly understood. A soil only a few inches deep may be fertile and yet nonproductive. A fertile soil may become so compacted that its productivity is lowered. Management affects productivity. A soil may have one productivity where there is little control of livestock, another where there is careful control, another where fertilized, another where both seeded and fertilized, and still another where seeded, fertilized, and irrigated. The other side of the management picture must also be considered—those practices which reduce productivity and may in time permanently damage forage production capacity. General discussions of soils in relation to grass production are given by Kellogg (1948) and by Thorp (1948).

Soils in Relation to Range Experimental Areas

Ideally a site selected for experimental work should be representative of fairly extensive areas. Experimental plots in some places have been located on soils of minor extent, which differed uniquely in behavior from predominating soils. Soil surveys or soil-vegetation surveys can be of direct aid in locating experimental areas on representative soils and associated vegetation. Unfortunately, most rangeland at present lacks such surveys, and the lack may restrict the reliable extension of experimental results (Gardner 1955 and Burcham *et al.* 1957).

Another consideration in selecting a site is the variability of soils within the experimental area itself. No soil in a sizeable experimental area can be expected to be entirely uniform. It may be an advantage to have several contrasting soils to determine the influences of soil differences. It is important, however, that these different soils occur in large enough bodies for experimental work. Each block of replicate plots should be on a single kind of soil. Consequently, areas having a complex and intricate pattern of soils, ordinarily should be avoided. There are two main reasons for selecting a single kind of soil: (1) Less chance for soil differences to affect the significance of results, consequently an opportunity of using a minimum of replications, and (2) more precise interpretations of results, involving only a single kind of soil rather than a compounding of two or more different soils (See also Selection of Experimental Facilities, Chapter 1).

In summation, it is most desirable for a soil scientist and a plant scientist working together to classify and map both soils and vegetation of an area being considered for range experimental purposes for (1) representativeness of the area, (2) variability within the area, (3) a better understanding of the soils and vegetation, and (4) an adequate basis for interpreting and extending the results of experiments.

Physiographic Factors

Physiographic factors include topography, exposure, elevation, and rock ledges. These vitally affect the environment of plants and, to a lesser extent, of animals.

Topography affects uniformity of grazing. Steep slopes, large rivers, and rock ledges may restrict use of one area and cause overuse of another. Equal quantities of forage can be grazed by more stock on level land than on rough land. Likewise, a given amount of range water will serve more stock on level land. Various kinds of animals will utilize various topographies in different manners.

Low-lying valleys may have deep and sub-irrigated soils and be highly productive. They may accumulate soil salts and be unproductive. Ridges and slopes may lose water by runoff or blowing snow. Evaporation is greater if they are in the path of hot, drying winds.

Plant and animal distribution responds sharply to direction of exposure and elevation above sea-level. An entirely different flora may occur, the change often strikingly sharp, as a result of slope and exposure. Changes with elevation generally are more gradual. Exposure and elevation are interrelated. Thus, in the northern hemisphere, a given species will occur on south-facing slopes at higher elevation and north-facing slopes at lower elevation.

North-facing slopes are cooler and more moist, permitting a higher vegetation density. In consequence, soils become more fertile and deep which encourages still more dense vegetation. Snow tends to accumulate on north slopes resulting in later spring growth, less freezing and thawing of soil, and increased soil moisture. South-facing slopes have wide variation in soil temperature, shallower soil, and higher evaporation rate.

Exposed forage is more leafy, higher in sugar, and lower in protein (Cook and Harris 1950). Shaded vegetation is more stemmy and higher in undigestible carbohydrates. Exposed ridges may be swept free of snow in winter to provide good feed conditions but cold winds may shorten the duration of grazing. Deep snow and lack of warming sunshine may prevent winter use of north slopes.

Range readiness may be delayed several weeks on north slopes and at higher elevations (Costello and Price 1939), and climate, especially temperature and precipitation (Lull and Ellison 1950) may vary rapidly with change in elevation.

Physiographic variation can be eliminated on an experimental range only by careful selection of area. Selecting similar pastures or planting areas generally is not as difficult on level or rolling plains. However, in mountains where exposure, water drainage, wind prevalence, soil type, and vegetation characteristics occur in a multiplicity of variations and combinations, selecting experimental areas is most difficult.

Measurement of microclimate in a large number of subareas and careful study of soil and vegetation are necessary in selection of study areas and in subsequent interpretation of data.

Plant Competition

Competition occurs when an inadequate supply of a necessary resource is being used by a number of plants, either of the same or different species. Each plant, species, or population of plants affects the other by its utilization of light, water, nutrients, living space, or any other factor essential to unimpeded plant growth. Competition, although usually detrimental to best plant growth, is natural. Beneficial effects may occur such as when one species shades or protects another from wind. Generally, attempts in research to remove this factor artificially, as by cultivation, create a condition unnatural to the range. For example, studies of range plants should be conducted in an environment where competition simulates the natural condition.

Most plot research recognizes the role of competition in creating border effects. A common practice is to place buffer strips around plots to provide normal competition.

There are two approaches to the problem of measuring competition between plants. The first of these has emphasis on the effects of the environment on the plants and the reciprocal effect of the plants on the environment. If adjacent plants A and B are utilizing the same facet of the physical environment, of which there is a limited amount, competition will be exerted between plant A and plant B for that element. Because of its size and growth habit, plant A may attain dominance over plant B and therefore plant B must depend upon the amount (or quality) of the element that is residual after utilization by plant A. Evaluation of the limiting factors and their significance to individual plants as well as the intra and interspecific populations of plants may be involved in studies of this nature.

A second approach to the problem is related to measurement of competition without regard to the environment. This approach is a short-cut modification of the first, wherein the investigator establishes merely the relationships between the occurrence, abundance, or vigor of plants A and B without regard to cause and effect, which can be determined only through approach number one.

If an experiment purports to show how a species may be favored or discouraged by management of associated species, both approaches are necessary. To find the best competitor or the species least susceptible to crowding out, a thorough study of underlying causes may be far more economical than the long-favored trial-and-error methods. The following exposition on the techniques of studying plant competition considers both methods of attack.

Qualitative Aspects of Plant Competition

Many observations that help in understanding the interaction of plants can be made which cannot gainfully be expressed in quantitative terms or which do not lend themselves to statistical analysis. Such observations need not lack objectivity.

Bisects and root studies: Enough studies have been made to show that while there is considerable genetic variation in root behavior within a species, differences in environment, especially soil, account for much of the variation in a particular population. It is also indicated that variation in root morphology between closely related species is greater than within a species when soil differences are eliminated. If this is generally true for range plants, such work should be encouraged even when masses of data are impossible to collect.

For competition studies, pertinent root data to collect may be listed as:

- Distribution of roots in the various horizons of the soil profile.
- Extent of root system and extent of branching (Pavlychenko 1937).
- Growth rates of roots of different species.
- Seasonal development of roots (Robertson 1943).
- Interaction of roots in a natural community—the bisect (Weaver 1919).

Phenological observations: To learn how to control or increase competition, certain phenological data about the species often are useful. These may include:

- Time of seeding and seed dormancy in relation to suitable germinating conditions.
- Time of germination and emergence.
- Relative growth rates during particular stages of development or seasons.
- Differential seasonal susceptibility to grazing, chemicals, fire, or drought.
- Differential seasonal uptake of plant nutrients and growth responses.

Species lists: The presence or abundance of one group of species often is associated with absence or infrequent occurrence of another by the test of random distribution. Species list quadrats can be used, in a rough way, to determine competitive rank among range plants, providing soil conditions are uniform.

Quantitative Aspects of Plant Competition

Quantitative studies of competition are usually concerned with relative abundance or vigor. Abundance may be measured by basal or foliar cover, weight, number of culms, or number of plants. Vigor may be determined by size of plant or certain organs, color, rate of water and nutrient use, or by amount of proteins, sugars, or other compounds produced. Such studies can be made *in situ* in native populations but will here be treated as experiments designed for statistical analysis.

Measurements of vegetation influences: The effects of vegetation on habitat are a result of the functional responses of individual plants. Examples of influences are absorption decreasing soil moisture, leaf fall improving infiltration, excretion of carbonic acid speeding up soil formation, and transpiration raising humidity. These processes and techniques are discussed under the subject of watershed management in Chapter 7. Measurement of these processes is basic to the study of competition, although all may not be limiting to plant growth.

Physiological studies of plant behavior under varying environment: Plant responses to fertilizers, water absorption and transpiration ratios, rate of photosynthesis in relation to shade tolerance, the effects of hormone inhibitors, and respiration in response to temperature changes are examples of studies that might be made to clarify competition. Such physiological studies determine within what ranges a given factor will affect the behavior of a plant. Competition occurs in that portion of the range of this factor which is jointly important to another plant in either time, amount, or quality. Such studies are incidental to the approach of controlling or measuring the effect of competition athough vital to the explanation of competition.

Studies of relations between abundance and vigor of plants: A classical experiment with sunflowers can be considered a model for most competition experiments (Weaver and Clements 1938). The effects of limited light, water, nutrients, and space were measured by height of plants, weight, leaf surface, root penetration, and relative rates of development of the plants; conversely, the effects of spacing were measured by amount of soil moisture depletion, soil fertility loss, and the amount of shading. Refinement of the technique of this model is largely limited to statistical procedures.

The simplest way to express relationships between two competing species is by use of linear or curvilinear regression equations. In order to find what the relationship is between grass density and number of brush seedlings, both are determined on many individual plots (Schultz *et al.* 1955). By the method of least squares these data are reduced to straight line regression formulas or curvilinear equations.

When two or more species of forage plants are seeded in mixtures, it may be important to know whether and to what extent they compete with each other, and at what proportions the species should be mixed to give the best yields of forage. All three questions can be answered with one experiment. One of several factorial designs can be used to test the effects of seeding rates of each species on its own yield and on the yield of other species (Schultz and Biswell 1952). An analysis of variance is used to tell whether differences in yield are truly attributable to seeding rates of another species and whether the seeding rates of one species have a greater effect than those of another on the yield of a third species.

Analysis of covariance may be valuable in studies of forage or seed production, where it is desired to eliminate the effects of competition from the effects of treatment. This is done by statistical control rather than by actually removing the competing vegetation. Treatment means are adjusted to equal densities of competing vegetation, which amounts to eliminating competition as a factor. The method has been described by Pechanec (1941).

Multiple correlation and partial regression are used to measure the combined and the independent influence of each of a number of possibly related variables on some other quantity, independent of their influence on each other. Thus it would be possible to ascertain the effects of soil fertility, soil moisture, and light intensity—which are not entirely independent of one another in stands of vegetation—and the growth of several kinds of competing plants on yields of forage of a given species when the effects of the intercorrelation of these factors are eliminated.

A technique has been applied to analysis of vegetation by Goodall (1954) that can be adapted to the problem of isolating the factors which are commonly thrown together under the collective term *competition*. It is based on this theory: positive and negative interspecific correlations from a large number of sample quadrats are due to certain relationships of the distribution of the species to environmental factors. Mathematical factors are separated from the correlation matrix and identified with the physical factors by what is known about ecological affinities and physiological tolerances of species.

Big Game

Big game animals can be an important factor in the range complex. Just as changes in the range vegetation may modify abundance and distribution of big game animals, so can changes in population levels of the larger herbivores modify the abundance and distribution of range vegetation. Not only can heavy browsing result in maintaining shrubs and small trees in open stands which otherwise would soon form a closed canopy, but selective use by big game can affect the reproduction, and hence the succession rates of vegetation.

The use of various elevational ranges by deer, elk, antelope, moose, bighorn sheep, or mountain goats usually is seasonal. Areas at lower elevations on which migrating big game is scarce or absent in summer may be subject to heavy stocking by one or more species during the spring, winter, or fall. In planning research on areas which support significant populations of big game, the researcher should decide whether the objective is to study the range as it is under existing influences or as it would be if such influences were removed. Results of studies within plots fenced securely enough to discourage entrance by deer may not apply to unfenced range on which deer are present.

Where control or elimination of big game is needed in research, the approach depends on the size of the area. On small areas, the influence of big game is best removed by fencing. The use of chemical repellents has been successful only for limited periods.

When it is desired to discourage big game animals from using larger areas, consideration should be given to the manipulation of factors which make range areas attractive to game. The influences of edges between intermixed vegetation types should be considered. The scarcity or abundance of food, water, or cover may bring about a change in the distribution of these animals. Special hunts or more liberal bag limits on the experimental area may be needed.

Effect on Utilization and Range Condition

Several approaches can be used in determining the effect of big game animals on forage utilization and range condition. Where utilization checks are wanted on ranges which do not support livestock, no special problems are involved and these surveys can be made by the same methods used to determine livestock utilization. Where livestock use a range during one season and game during another, two surveys may be necessary; one to determine the effect of livestock use, another to determine the additional use by game animals. The problem is most complicated when game and livestock use an area during the same period. Under such a condition, the separation of livestock utilization from game utilization can best be accomplished by a comparison of either livestock-free or game-free areas with those on which dual use has occurred. Where such segregation does not occur as a result of natural distribution of animals, the use of fenced exclosures is necessary.

An approximation of the quantity of forage removed by big game animals from large areas can be computed through use of census data, period of use, and known daily forage intake values. Brody determined that the forage required by a herbivorous animal is in relation to the radiating surface of the animal, rather than in direct proportion to its weight. The air-dry forage requirement is reported as proportional to the 0.73 power of the live weight of the animal (Carhart 1946). Carhart applied Brody's formula to deer and reported the daily air-dry food requirement to be:

2.80	pounds	for a	100	pound deer
3.88	"	" "	150	" "
4.78	"	" "	200	" "
5.63	"	" "	250	" "

Other workers have shown that the average daily intake of deer runs about three pounds of air-dry forage per hundredweight (Nichols 1938).

One indirect census method that includes the time value is the pellet group count (McCain 1948). It has been shown by several workers that the defecation rate of deer on winter forage is about 13 pellet groups a day (Rasmussen and Doman 1943, Dasmann and Taber 1955). Pellet group counts can serve to determine deer days use and concentration areas and hence forage type preferences where this information is needed.

Food Habits

Food habits of big game animals are not well understood. Antelope have been considered grass-eaters, but recent studies indicate that grass makes up only a small percentage of their diet. Deer have been classified as browsers, but the diet of these animals includes considerable forbs and grasses. Most game departments have conducted food habit investigations. The range manager and researcher should make use of this information.

Classifications of form and age of browse are useful in analyzing condition of ranges used by game. Form class of browse includes a composite rating of both availability of forage and degree of hedging resulting from cropping. When shrubs are not browsed or are only lightly browsed they will assume their natural growth form or shape. As intensity of browsing increases, the departure from normal shape becomes more striking. Continued heavy browsing, year after year, results in closely hedged or highlined, and dead or partly dead browse plants.

Degree of hedging may be classed into (1) hedged little or none, (2) moderately hedged, and (3) heavily hedged. Hedging is a product of past use and should not be confused with current use.

Browse may be classed for availability as (1) all available, (2) largely available, (3) mostly unavailable, and (4) unavailable. Availability may result from height, location, or density of plants. Forms of browse plants may be classified as follows:

Form class 1: All available, hedged little or none
2: All available, moderately hedged
3: All available, heavily hedged
4: Largely available, hedged little or none
5: Largely available, moderately hedged

6: Largely available, heavily hedged
7: Mostly unavailable
8: Unavailable

For age, browse plants may be classified as seedlings, young plants, mature plants, or decadent plants. The factors used for age determination of browse include size, growth rings, branching, bark, and in some cases foliage.

Survey data on age and form classes in a browse stand can be used to evaluate present condition by age structure, availability of forage, degree of past browsing pressure, and abundance of dead plants. These findings may be used also as base data from which future changes can be measured. A more detailed description of the method will be found in Dasmann (1952) and Parker (1953).

Rodents and Rabbits

Rodents and rabbits are common inhabitants on western grazing lands. They feed on many plants which are valued for livestock forage. In some cases, range investigations can be invalidated by rodent feeding pressure. In other instances, the rodent factor is inconsequential. Evaluation of the qualitative and quantitative significance of rodents requires considerable knowledge of rodent ecology, particularly the relations of various species to soil and vegetation.

Species Variability

The importance of rodents in the range complex varies with the species which are present. For example, where a range is occupied primarily by grasshopper mice, the effect is indirect and probably minor since these animals live largely upon insects (Bailey and Sperry 1929). At the other extreme, a colony of prairie dogs can sometimes cause such devastation to range vegetation as to vitiate completely any grazing treatment with domestic livestock (Taylor and Loftfield 1924).

Fitch (1946) found that the relatively small size of the Tulare kangaroo rat, together with its restriction to arid situations or shallow soils, makes competition slight between this rodent and livestock under ordinary circumstances. However, at high populations on limited areas, the same species can compete severely with cattle or sheep.

Life habits of individual species have a fundamental bearing on how rodents should be treated in investigative work. Population of rodent species is affected by condition of vegetation. Certain rodents, because of their preference for plants in a lower stage of succession, are held at low population when ranges are in high succession stages. This relation seems to hold for the California ground squirrel (Fitch 1948a), the white-throated woodrat (Vorhies and Taylor 1940), the Merriam kangaroo rat (Reynolds 1950), and pocket gophers in Oklahoma (Phillips 1936). Other species prefer and attain greater numbers in the higher stages of plant succession. Included in this group are such species as pocket mice of southern Arizona (Reynolds and Haskell 1949) and cotton rats (Phillips 1936).

The effect which rodents have upon vegetation varies with condition of the range. Moore and Reid (1951) found that where mountain meadows of Oregon were in poor condition, populations of the Dalles pocket gopher were sufficient to prevent range recovery. Rabbits and rodents of the mesquite-snakeweed type of the Southwest also exert sufficient grazing pressure to prevent improvement of severely grazed sites (Norris 1950).

Kind of plant material consumed in relation to range condition has a bearing upon what effect a rodent species may have upon rangelands. The Merriam kangaroo rat stores large quantities of seed in the surface soil, much of which is never reclaimed. The spread and abundance of large-seeded perennial grasses is thus encouraged during favorable climatic periods (Reynolds 1950). However, on rangelands infested by mesquite, this same rodent is an important agency for the dissemination of this undesirable shrub (Reynolds 1954b).

The effect of rodents, particularly burrowing species, upon the soil cannot be ignored (Taylor 1935). Burrowing brings sublayers of soil to the surface and affects water infiltration and retention. The white-throated woodrat and the banner tail kangaroo rat are known to affect soil properties beneficially (Greene and Reynard 1932, Greene and Murphy 1932), whereas the activity of pocket gophers at high elevations in Utah sometimes leads to soil displacement and erosion (Ellison 1946).

Isolating the Rodent Effect

Exclosures can be used for either eliminating or measuring the effect of rodents. The main drawback is fence cost. Exclusion of a combination of climbing and burrowing rodents such as ground squirrels and gophers requires a 48-inch wire mesh fence equipped with a 12-inch horizontal top metal flange from the outer edge of which is hung a 10-inch metal strip. To discourage burrowing, fences may need to extend 30 inches underground and contain a 6-inch outer apron (Fitch and Bentley 1949).

Fences constructed to provide differential exclusion have been used effectively for separating the influence of rodents and domestic livestock on range vegetation. Taylor (1930) employed three plots for separating the different effects. One plot was constructed to exclude both rodents and cattle, another was protected from livestock only, and a third was open to all animals. Norris (1950) used a similar technique for studying the separate effects of rodents, rabbits, and cattle on semidesert rangelands. Each exclosure occupied 2½ acres and was constructed to exclude separately (1) cattle, (2) cattle and rabbits, and (3) cattle, rabbits, and small rodents.

Poisoning or trapping is sometimes used to eliminate rabbits and rodents. Success varies with area size and the cruising radius of the rodent. Elimination is not too effective on small areas or where rodents with a wide cruising radius are involved. The method has been used successfully around small reseeding trials and range plant reproduction studies (Paulsen 1950).

Measuring the Rodent Effect

The effect of rodents in some range studies can be estimated from a knowledge of food habits and populations. For example, by estimating the amount of forage required and the abundance of individual species, Culley (1939) approximated the potential significance of rodents for the Santa Rita Experimental Range.

Indirect methods can be used for estimating forage removal in different vegetation types. The average defecation rate of jackrabbits is 531 pellets per day (Arnold and Reynolds 1943). By counting pellet accumulations during given time periods, and applying the feeding requirements of rabbits (Vorhies and Taylor 1933), the amount of herbage removed by rabbits can be estimated.

Fitch and Bentley (1949) employed the enclosure technique for determining the effect of three rodents on annual grass range in California. Nearby constant populations of rodents were confined to enclosures and the amount of vegetation consumed was measured. With these data and with known populations of pocket gophers, ground squirrels, and kangaroo rats, the annual herbage consumption by these animals was estimated.

Census Methods

All methods of determining indirectly the effect of rodents in a range research undertaking require a census technique for ascertaining numbers.

Actual count: Counts of animals per unit area have been used successfully; particularly for diurnal species. Counts of prairie dogs can be made by selecting a high vantage point and watching a selected area for an entire day (Taylor 1930). Numbers of rabbits can be estimated by making counts along sampling strips or roadways (Vorhies and Taylor 1933). These latter workers also used an index system in which numbers of cows and rabbits were counted in a sample. With these data and knowledge of the number of cows on the range, jackrabbit numbers could be computed.

Rodent workings: Workings can be used satisfactorily in censusing some species. Nests of woodrats and mounds of bannertail kangaroo rats are conspicuous and easily counted. One adult is usually found in each den, so by examining dens for recent working and counting occupied ones, a census of adult animals can be obtained (Vorhies and Taylor 1922 and 1940). A count of jackrabbit pellets can also be converted to number of individuals per unit area (Arnold and Reynolds 1943). Mounds of pocket gophers, ground squirrels, and pocket mice can easily be counted, but conversion factors between number of animals and workings are necessary for an actual rather than a relative census.

Trapping: Trapping all rodents on a sample area is the only technique available for many nocturnal or wary species. Live trapping techniques are believed to give the most reliable results (Stickel 1946). Ordinarily, a grid of live traps is set on an area, and individual rodents are trapped, marked, and released. It is also possible to mark a portion of a population and to compute the total population from the proportion of the marked animals later captured, provided short intervals of time are involved.

Dead trapping is a time-saving and simple technique for censusing small rodents. However, because of the "drift" factor on small quadrats, correction terms must be applied to avoid exaggerated estimates of populations. Dice (1941) advocates applying an areal correction around the trapping unit equal to one-half the width of the home range. Hayne (1949) in a series of intensive studies has worked out correction techniques for both mark-and-release and removal trapping quadrats. In the first instance, total population is estimated by following the rate of increase of marked animals and, in the other case, rate of decrease of captured animals is related to the total population.

Insects

Probably the most damaging insects on rangeland are grasshoppers. However, numerous others consume leaves, roots, or seeds. Harvester ants not only eat green vegetative material but harvest large quantities of seed as well. Grasshoppers can be controlled effectively with newly developed insecticides, and large areas may be covered rapidly with aircraft. Nevertheless, control of grasshoppers on low value rangeland is still a comparatively expensive undertaking. As yet there is little quantitative information as to the damage done by grasshoppers either under normal conditions or under so-called outbreak conditions.

The problem of evaluating grasshoppers as biotic competitors with livestock cannot be approached from the standpoint of total numbers of grasshoppers alone. As many as 52 species of grasshoppers may occupy a 40-acre tract of range (Anderson and Wright 1952).

Food preferences among the different species of grasshoppers vary. Some are strictly grass feeders and may prefer certain species of grass; some are forb feeders and may also be quite selective; others are mixed feeders eating both grass and forbs, although they frequently exhibit a preference for forbs.

The first step in evaluating the effect of grasshoppers on rangeland is to obtain qualitative information on the feeding habits of the various species. Then, quantitative information as to how much forage will be damaged by a particular species complex can be sought.

Food Habits of Grasshoppers

Cage studies: Intensive studies of food preferences of caged grasshoppers have been made by Isely (1938, 1944, and 1946) and by Pfadt (1949). The technique consists of introducing various food plants into cages containing the particular grasshoppers under study. Observations are made as to which plants are preferred, which are refused, and related subjects. The effects of various diets on the ability of the insect to complete its li'e cycle can also be studied in this manner. However, there is no way of knowing whether grasshoppers in cages will behave the same as they would under natural conditions.

Observations under natural conditions: Anderson and Wright (1952) adopted the procedure of observing in the field the species of plants that were eaten by the various species of grasshoppers in the area. This technique presupposes considerable knowledge of the flora of the area and the ability to determine each species of grasshopper in the nymphal and adult stages, as well as considerable patience.

In order to reduce the effect of the observer, it was necessary to remain as motionless as possible. It was often necessary for the observer to wait as long as 30 minutes after assuming a prone or sitting observational position before the behavior of the grasshoppers in the immediate area returned to what could be considered normal.

Quantitative Studies of Damage

Cage studies: Morton (1936 and 1939) compared the dry weight of vegetation on a grasshopper-infested range with the dry weight of vegetation under cages from which grasshoppers were excluded. Using ocular measurements entirely, Hinkle (1938) compared the vegetation in cages from which grasshoppers were excluded. Pfadt (1949) determined the dry weight of grasses on which known populations of *Aulocara elliotti* had been placed in cages. With these methods the grasshoppers and vegetation behave under the cages as they would under natural conditions.

Sprayed and unsprayed areas: In the technique adopted by Anderson and Wright (1952), areas of winter range from which all livestock was excluded were selected for study. An area of 300 to 500 acres was sprayed by airplane with aldrin at a dosage of 1⅔ ounces per acre. This area served as a control against an adjoining area which was infested with grasshoppers. On both areas, plots of vegetation were clipped at ground level and the yield was sorted by species, air dried, and weighed.

The gain or loss in weight of vegetation on the control area was compared with that on the infested area. It was assumed that the infested area would have the same loss or weight gain as the control area if grasshoppers had not been present. Thus the actual amount of damage could be computed.

Grasshopper populations in the study area were measured by the use of bottomless cages with screen tops and sides. Each cage measured two feet long, two feet wide, and four feet high. Approximately two hours after sunset or at such time when little or no grasshopper activity was detected, the cages were randomly placed in the area to be sampled. The bottom edges of each cage were banked with soil, to prevent the movement of grasshoppers into or out of the cages. The next morning grasshoppers which had been caught in cages the previous evening were removed through a door in one side, and the number and instar of each species were recorded. The cages were then removed from the area. In this manner, the populations of grasshoppers were determined at intervals during the study.

Knowing the food preferences of the grasshoppers, the population of each species, and the amount of damage that occurs, the relative damage caused by each species can be assessed.

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Chapter 3
Methods of Studying Vegetation

INTRODUCTION

MEASUREMENT of the quantity and quality of vegetation is a major consideration in range research. For methods and techniques of measuring vegetation, the range research worker has drawn heavily from several other fields of specialization such as botany, agronomy, and animal husbandry. Specialized fields of ecology, plant physiology, and animal physiology have been major contributors.

Quantitative features of vegetation that can be measured or observed most readily are: (1) number of individuals, (2) cover, or area occupied, (3) height, (4) weight, and (5) frequency. Measurement of these characteristics makes it possible to assess vegetation changes due to time, place, or treatments applied, and to define plant communities and permit ecological comparisons. It also permits analysis and interpretation of (1) species composition, (2) stratification, (3) growth and development (phenology), (4) vitality or vigor, (5) life forms, and (6) forage production. Closely related and frequently simultaneously measured with the vegetation are several characteristics of the soil mantle such as texture, fertility, infiltration rate, reaction, litter, and stability.

Measurements of the quality of the vegetation most often of interest to the range research workers are those making possible evaluation of the quality of forage produced. Of interest may be (1) palatability of species to grazing animals, (2) nutrient content, and (3) digestibility.

MEASURING QUANTITY OF VEGETATION

Quantitative Measurements

Quantitative characteristics of the vegetation which can be observed or measured directly have received much attention recently in testing, comparing, and refining measurement methods devised in earlier years (Hanson

1950). There have also been advances toward standardization of methods, although complete agreement is not warranted by the present knowledge of range ecology and ecological methods.

Some characteristics of range vegetation lend themselves more readily to measurement techniques while others are more suited to ocular estimation. Brown (1954) gives four criteria as the essence of all methods for expression, assessment, or measurement of a plant species. These are: frequency, number, area covered, and weight.

Frequency

The concept of frequency was developed by the Danish ecologist C. Raunkiaer. The term refers to the degree of uniformity that a species shows in its distribution over an area. It is used when a list of species of one area is being compared with that of another. Frequency is determined by noting the presence or absence of each species in sample plots that are distributed within the study area. It may be expressed quantitatively in percentage as the "percentage frequency" or "frequency index," or in classes usually on a scale of 5 or 10 (Ecological Society of America 1952).

Measurements of frequency are of most value when they are used with other characteristics, especially numbers and cover.

The frequency-list method is rapid, particularly when number and cover are also estimated, since each species is noted in each sample area. It has yielded good indications of various treatments upon test plots, the effect of different kinds of soil, differences between vegetation types, effect of different systems of management, and in evaluating the importance of species in several communities and at different times within the same community.

Number

The number of individuals in a plant community is expressed as abundance or population density (Hanson 1950). Generally speaking, numbers of individuals connote (1) a rough estimate of plentifulness, (2) an approximation or simple count of the number of individuals, (3) a calculation of the number of individuals per unit area, or (4) a calculation of the ratio of the number of individuals of one species to the total number of individuals of all species (Brown 1954).

A classification system is frequently used for estimation of abundance, such as (1) very scarce or rare, (2) scarce or occasional, (3) infrequent, (4) frequent, and (5) abundant or very numerous. A more definite meaning may be given to these general classes by attaching numerical values to them.

The most common sample area used in studying numbers is one square meter in grasslands, and four square meters for shrubs. Smaller units may be used in dense vegetation as in meadows, annual grass, alpine-arctic, and subtropical vegetation. Number of trees per acre is used in forestry. Sample areas vary in size from ¼ milacre to 0.1 acre or more, depending on the purpose of the study.

In dense vegetation, measured areas of turf may also be taken to the laboratory, the plants separated according to species, and counted. The best method to use varies, depending on the nature of the vegetation, the objectives of the research, and the time and personnel available.

In solving many problems connected with range seeding, control of weeds, and effects of burning, the counting of plants, stems, or sprouts gives an adequate basis for making comparisons. The number of plants or stalks grazed compared to the number not grazed on sample areas has been used effectively to determine the degree of range use.

Area Covered

The area covered by vegetation is perhaps the most widely used measurement of the quantity of vegetation.

Terms used to denote area covered, especially density, have been used to denote many different specific measurements. When reporting results of experiments the terms used should be defined and the measurement method stated to avoid misinterpretation of the results.

Area covered should be viewed as an index to relative abundance of plant species for comparison with similar measurement taken at another time or place. Use of the term "density index," for example, instead of "density" is perhaps more specific and allows for further qualification as to its meaning. It is most useful for comparisons between the same species. Although widely used as a basis for expressing floristic composition of plant populations, such expressions must be used with care because of differences in growth form of plants.

Useful terms employed as expressions of area covered are (1) density, (2) basal area, (3) herbage area, (4) foliage density, and (5) cover.

Density: Throughout this chapter the term "density" is used in the discussion of methods for measuring vegetation. The use in each instance is in accordance with the use of the term for the specific method. Units of measurements of density obtained by the different methods are not comparable but may be highly correlated.

Density has been defined as the exact ratio between the number of individuals of the same species observed on a certain surface and the extent of the surface (Carpenter 1938). The Committee on Nomenclature of the Ecological Society of America (1952) defined density as "the relation between the number and/or volume of individuals of a species (or of *all* species) on an area, or more correctly, in a space; refers to the closeness of individuals to one another." This is the common, though not universal, use of the term in ecological literature.

However, the term density has been in general use in range management research since 1907 to express proportion of ground area covered by vegetation. Dayton (1931), following this concept, defined density as the relative degree to which vegetation covers the ground surface. The density of browse (i.e. twigs, shoots, and leaves cropped by livestock or game animals from shrubs, trees, and woody vines) is estimated from the ground surface covered by that part of the browse that is readily available to livestock.

The concept defined by Dayton is used in the point-observation-plot and reconnaissance methods widely employed in range surveys. The interagency "Instructions for range surveys" issued in 1937 (Inter-Agency Range Survey Committee 1937) includes the following instructions for estimating "density."

> In estimating density the spread of the vegetation above the ground must be carefully considered. The density of more or less upright weeds should be based upon the amount of ground that appears covered when the vegetation is viewed from directly above. In estimating the density of spreading weeds or browse or open clumps of grass this forage should be pressed together or raised at an angle so that all of the normal interstices between the leaves are completely filled without compressing or unduly crowding the vegetation. The forage is then so compacted that it will represent a 10/10 density. . . . The density of browse should be determined by the portion of the ground covered by that part of the browse that is accessible to stock. . . . Where a double story of available vegetation exists, such as browse over grass . . . both stories are included in the density estimates.

Basal area: Basal area in range and ecological literature refers to the area of ground surface covered by the root crown of the plant, or the surface area that is penetrated by the stems. It is often expressed as basal density which is the ratio of basal area of the vegetation to the total ground surface. Basal area is an especially important characteristic because it measures long-term effects of climatic and soil conditions and grazing. Effects due to season of year, current utilization, temporary overgrazing, or short-term droughts are less apparent in basal area. Basal area usually is a poor index to ability of plants to compete with or to dominate other plants.

Usually basal area is measured at one inch above the ground. Occasionally, as for short grasses, it may be necessary to measure closer than one inch. In plants that form bunches or mats with bare areas between the stems, it is often difficult to decide how much to include in the basal area and how much is bare ground and litter. It is desirable then to set an arbitrary size as the smallest area that will be counted as bare area; for example, bare areas less than two square centimeters in such bunchgrasses as Idaho fescue and bluebunch wheatgrass may be included as basal area. Another difficulty is found in single-stalked plants that occupy much less than 1 square centimeter.

Where this is a problem, usually a certain number of stems, from 3 to 10, depending upon their diameter, is arbitrarily counted as 1 square centimeter.

Basal area in some instances may be estimated. Ocular estimates are less precise than most measurement methods but for certain purposes they provide suitable data. Greater accuracy of estimation is obtained when small plots are used. For detailed research more quantitative methods are needed.

Foliage projection: The ground area covered by vertical projection of herbage is used as an expression of mass of vegetation shading the ground, herbage present to intercept precipitation, reduce wind velocity, and catch wind- or water-borne particles, and of other factors affecting environment. Dominance of species is probably expressed chiefly in this characteristic. Competition between species may often be analyzed to a large extent by foliage projection. So it is valuable in differentiating and comparing types of vegetation. It cannot, however, be applied to range that is being currently grazed or in comparisons of grazed and nongrazed vegetation.

Foliage projection is expressed as foliage area, herbage area, foliage density, and herbage density. These terms have been used with different meanings. The following is suggested for range research:

Foliage area refers to the area of ground that is covered by all of the aboveground parts of the plants and may be observed by looking vertically down upon the plants. *Herbage area* refers to the vertical projection of only those parts of the plants within reach of the grazing animal. *Foliage density* is used to indicate the relation of foliage area to total ground area expressed in per cent, and *herbage density* refers to the relation of herbage area to total ground area expressed in percent. The researcher should realize, however, that in the literature foliage density and herbage density have also been used to refer to the number of leaves, stems, and other aboveground parts per unit of area or space.

Crown density also is used as an expression of the relation of crown (canopy) area to the land area involved (Carpenter 1938, and Ecological Society of America 1952). It is used for trees and shrubs, and for this type of vegetation it is synonymous with foliage density as defined heretofore.

Tree overstory: The overstory vegetation on forest ranges is an important measurable feature that must also be recognized because it exerts a strong effect upon the herbaceous and shrub understory.

For stands of small trees (trees under 15 years of age or 3.6 inches diameter at 4.5 feet aboveground), the most commonly used measurement is number of trees on a unit area or the percentage of quadrats stocked. These are related but not equal expressions. Number of trees is useful for small areas or for stands that are uniformly stocked, but it tells nothing about the distribution of the trees. On the other hand, the percentage of milacre or 4-milacre quadrats stocked is a good measure of distribution. Either measure can be used to approximate the other (Wellner 1940).

For stands of larger trees, basal area, stand density index, and growing space are all used (Spurr 1952). Basal area is the cross sectional area of the tree stem, measured 4.5 feet aboveground. It is expressed as square feet per acre. But basal area per acre fails to indicate whether the stand contains a large number of small trees or a smaller number of large trees. Stand density indices are more informative, but more complex to compute. They break the basal area into two components: (1) The number of trees per unit area and (2) the diameter at 4.5 feet of the tree of average basal area. Several expressions of stand density index are discussed by Spurr (1952).

Growing space expresses the proportion of the horizontal space over a unit of area that is occupied by the sum of the crowns of the individual trees. Growing space can be approximated mathematically from measured tree diameters (Chisman and Schumacher 1940, Spurr 1952). An objective measurement of tree overstory is procured by measuring devices, such as the "moosehorn" (Garrison 1949).

Weight

Weight of herbage produced is one of the most important characteristics of range plants and it is probably the best single measure of growth (Hanson 1950). It is a most convenient term to express forage production and likewise can be used to indicate and measure ecological trend and range condition. Weight is the result of the metabolism of the plant and provides reflection of the environmental conditions that are responsible for that growth. Products of plant metabolism form the substances essential for the growth of the grazing animal. Weight of plants may refer to: (1) green weight (freshly cut plants), (2) air-dry weight (dried in the shade or in oven at about 60° C. and containing about 10-12 per cent water), and (3) oven-dry weight (dried at 100-105° C.).

The term "volume" is sometimes used as a synonym of weight in range literature. Actually in range work there is no volume measurement that is widely used and the use of the term to mean weight should be discouraged.

Weight is used to express amount of "herbage" and "forage." *Herbage* is defined (Ecological Society of America 1952) as "herbaceous vegetation considered as a collective unit." Carpenter (1938) defines herbage as "herbs taken collectively; grasses and forbs." It should be noted that these definitions do not include leaves and twigs of woody plants. In many reports of range research the leaves and other parts of woody plants have been included in estimates of "herbage." Perhaps this is for lack of a more inclusive term.

Forage is defined in range management (Soc. Amer. For. Committee on Forestry Terminology 1950) as "unharvested plant material of any kind available for animal consumption. It may either be used for grazing or cut for feeding. When cut it becomes feed." Forage includes not only the herbage but also the browse available for grazing. Forage is the product of herbage and available browse produced times permissible utilization (in per cent), so forage is always less than the total of herbage and browse. *Browse* (Soc. Amer. For. Committee on Forestry Terminology 1950) includes "twigs or shoots with or without attached leaves, of shrubs, trees, or woody vines available for forage for livestock and wild animals."

Determination of weight of herbage and browse is made difficult by the constant change in plants as they grow and mature and by the regrowth following grazing (figure 1). Growth characteristics and grazing may make it impossible to estimate herbage weight on ranges where animals graze during the growing season. To reconstruct to ungrazed conditions, Campbell and Cassady (1955) devised a descriptive utilization scale for approximating utilization percentages of bluestem grasses.

It is often necessary to use weight as an index for comparative purposes by determining the actual weight produced at a given stage of vegetation development in the same way at each time of observation. This weight index

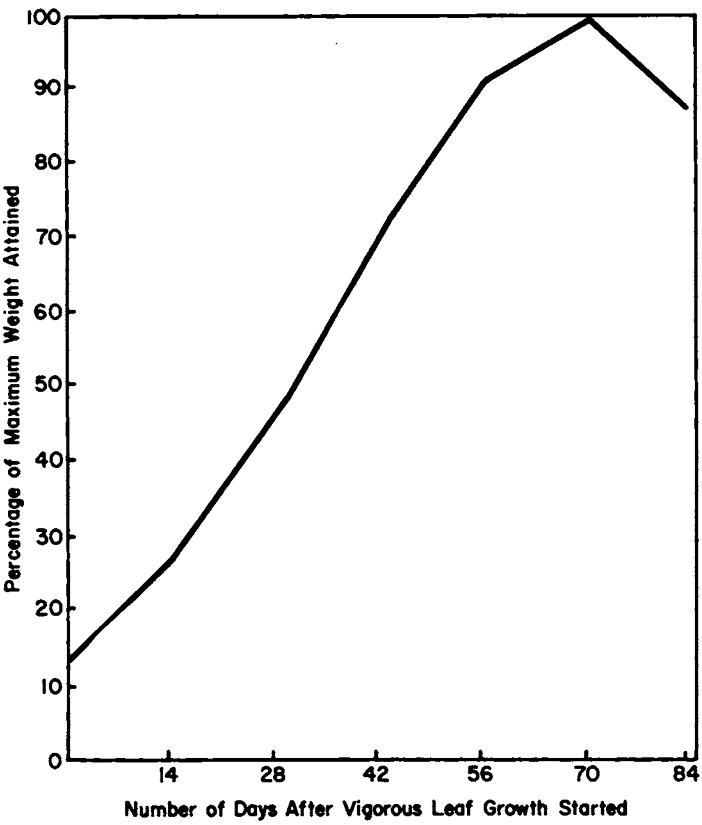

FIGURE 1. Air dry herbage weight production of Idaho fescue during the growing season *(Rocky Mountain Forest and Range Experiment Station 1955).*

may or may not approximate the total weight produced by a single species and is not likely to approximate it for a mixture. An approximate estimate of forage available for fall and winter grazing is possible by estimating the herbage after all growth is produced. Even so, leaching, weathering, and in some sections winter and early spring growth take place and affect the herbage available to the grazing animals.

Sampling Techniques

Good sampling procedures are essential for the study of range vegetation. It seldom is feasible or possible to examine every individual of a given plant population. Not only would this prove unreasonably costly but little would be gained from such laborious procedures. Much can be learned about the characteristics of a population through study of a relatively few representative individuals. If these are correctly drawn, certain generalizations or inferences of the population may be made by means of statistical techniques.

The importance of adopting a good sampling technique cannot be overemphasized. The technique employed will, in large part, depend upon the use that is to be made of the information. For example, if only broad indications are required, the technique will be different from that used where a detailed study of the vegetation is needed.

Techniques in sampling range or pasture vegetation are numerous and varied. Most fall into groups based on the kind of sample taken, such as techniques employing plots, plotless methods, techniques employing points, techniques employing lines, and reconnaissance methods. Each may vary in mechanical application, intensity, and information obtained. Furthermore, each has certain strong and weak points; one may be efficient for one set of conditions but not fit another set. Hence, the research worker must decide on the technique that will give the information desired about the plant population and then sample it with sufficient intensity to obtain meaningful results. Once the technique is selected and in use, it is important to continue the same method through the course of the study because different techniques may express the criteria being measured in different terms. If it becomes necessary to change techniques during a study, adequate correlations between the new and old techniques should be determined so that data can be reliably compared and interpreted.

Factors that should be kept in mind in the selection of a suitable sampling technique are as follows:

(1) *Degree of refinement desired:* The best technique is one that supplies the information required to the desired degree of reliability.

(2) *Elimination of bias:* Bias may contribute to the sampling error in any technique. Minimizing error due to bias requires good sampling techniques that are highly objective.

(3) *Cost:* Techniques should be considered in connection with time, manpower, and equipment available.

Numerous techniques have been devised, developed, and described for botanical analysis. Brown (1954) has described a great many and her publication is recommended for study by anyone contemplating range research. Only the techniques used most commonly in the range area of the United States are discussed in this chapter.

Techniques Employing Plots

Plots are areas of any prescribed size or shape that are used primarily to focus attention on small surface units for detailed examination. They furnish a unit on which measurable criteria of the vegetation, such as basal area, numbers, or weight, can be determined. The size, shape, arrangement, and number of plots are governed by the objectives of the study.

The list and chart quadrat: The quadrat is a square area of any selected size that is delineated for detailed study of the vegetation. Several innovations in the use of quadrats have evolved depending upon the requirements to be met. In its simplest form the quadrat is used in counting individual plants to determine their relative abundance and importance. Quadrats are often named according to their use. For example, the list quadrat is one in which the species are listed and numbers of each are counted within the quadrat area. On the basal-area quadrat the root crown area at the ground surface is either measured or estimated for each plant, while on the clip quadrat the dry weight of the vegetation is obtained by clipping.

The chart quadrat is one of the earliest plot techniques used in range research (Hill 1920). Basically, the method is one in which the ground position of each plant is indicated in its relative position on a quadrat record sheet (Weaver and Clements 1938). Initially, the technique involved subdividing the plot, which was often one meter square, into convenient smaller units by means of a grid system superimposed on the plot. The area and location of each plant unit are systematically sketched at a conveniently reduced scale on coordinate paper. Subsequent compilation of the quadrat data includes number of individuals of a species or basal area determinations of the plants represented either by means of a planimeter or actually counting of area units on the record sheet. Subsequent charting of permanently located quadrats reveals the behavior of individual plants over a period of time.

Mechanical devices such as the pantograph have been developed and used to simplify transposing from the ground to the quadrat sheet. Meter square quadrats are most commonly used. The pantograph consists of a low stand and pantograph arms (figure 2). Two diagonal corners (or all four in some cases) permanently mark the quadrat on the ground so that the same area is charted each time. The pantograph unit is set up along one

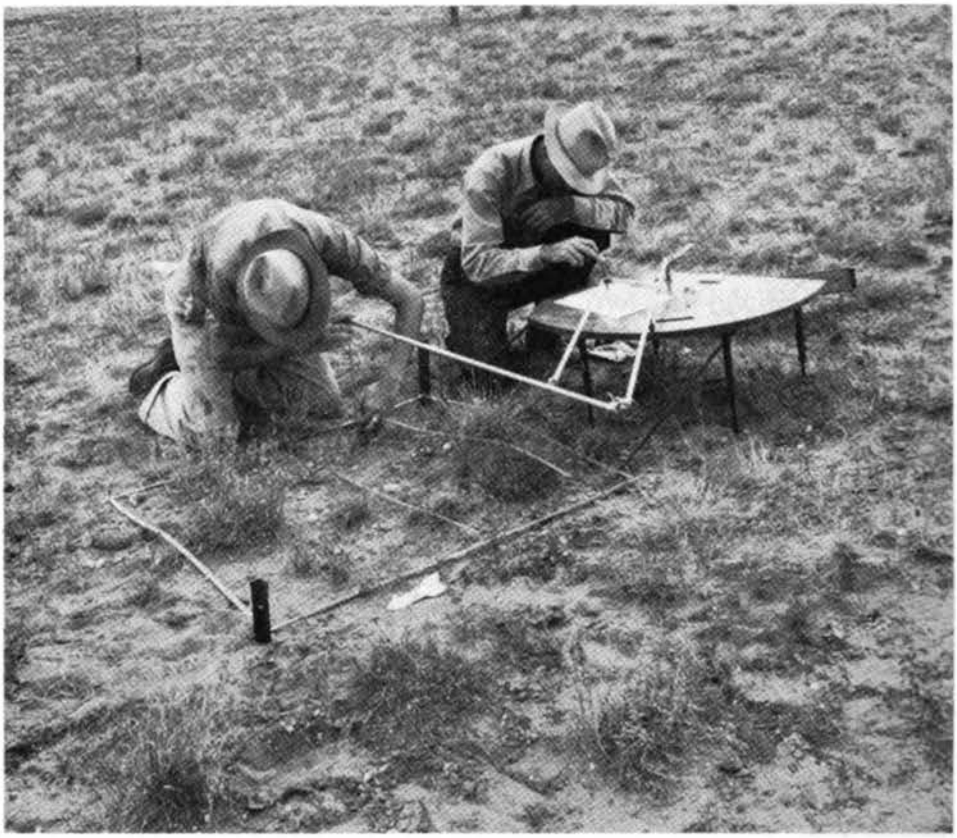

FIGURE 2. The pantograph used for charting quadrats. Two persons are required to chart the vegetation, one to identify and trace the vegetation and the other to handle the recording needle and make other records. *(U.S. Forest Service photo)*

designated side of the quadrat. The pantograph arms are attached to the charting table and adjusted so that the pencil on the pantograph coincides with corners on the quadrat sheet as the pointer is moved over the respective corners of the plot. The operator guides the pointer about the periphery of the individual plants while an assistant steadies the pantograph pencil on the quadrat sheet and records the name or symbol within the boundaries of the transcribed plant. Basal area or root crown spread for the plot can be computed from the chart for individual species or groups as desired.

Other modifications of the chart quadrat technique have included the use of cameras and tripod arrangements. In each case the charting methods are used with permanently marked plots. Temporary chart quadrats have been used to show comparative differences in density and composition between pastures treated differently. However, the time of charting usually is so great that other methods are preferable.

Accuracy in charting depends on the ability and care of the operators and to some extent on the mechanical perfection of the charting device (Ellison 1942). Although it can provide a reasonably accurate record of vegetation, use of the chart quadrat is time consuming and of little value for sampling range pastures or large areas where great numbers of plots are required. However, it is useful for intensive studies of plant communities, such as changes in time on the same area. It is more accurate when used for charting basal area than for charting herbage area, the outline of which can easily be distorted or is subject to more personal judgment. It is most useful for studying bunchgrasses.

With the chart quadrat method, especially where repeated measurements are made, it is essential that care be taken not to trample the plot or surrounding area, thus affecting the site characteristics.

Charting brush: A coordinate method similar to the chart quadrat is used to chart or map the crown canopy of browse vegetation (Pickford and Stewart 1935). Two steel tapes graduated in feet and tenths of feet are stretched tightly along the sides of the plot at a convenient height above the shrubs to be mapped. A light metal crossbar, also graduated and of T-beam construction, is slotted on both ends to receive the tapes. As the crossbar is moved along the tapes the examiner records on coordinate paper the points of intersection of the edges of the crown. The heights of the shrubs may also be measured.

A plot 4 feet by 25 feet has proved satisfactory for mapping sagebrush and similar shrubs. Longer plots may be used if additional stakes are used to support the tapes. The method is fairly rapid; one man can map six plots per day in dense sagebrush.

Another technique for charting brush is the *traverse board* method (Nelson 1930). Using a traverse board or plane table, the board is set over a permanent stake and the point on the map sheet located by a plumbing arm. A steel tape attached to the ground stake is used to obtain distances to the various shrubs and an alidade, or similar sighting instrument, is used to plot direction on the map. By locating several points on the perimeter of the crown canopy, the outline may be drawn on the sheet. Crown canopy areas may be computed by planimetering the map sheet. The method is suitable for measuring tall shrubs but is slow and costly.

Photographic plots: Photographic plots provide a visual record of change or lack of change in the vegetation cover. They are useful for illustrative purposes but in themselves do not provide a quantitative measure of the vegetation. When used in conjunction with quantitative methods they become valuable records (Parker 1951).

The U.S. Forest Service has used the so-called "photo plot transect" method. In this method photographs are taken at 3- to 5-year intervals from established camera points and plant and soil conditions are recorded for comparative purposes. Ten or more plots 3 feet by 3 feet in size are permanently marked at mechanical intervals of 100, 200, or 400 feet along a transect line, and photographed. A sketch map is made of each plot identifying and locating plants appearing in the plot photograph. Detailed notes on plant cover and soil are also recorded for each plot. Supplementary photographs are usually taken to show location of the transects. The method is primarily useful to study long-time changes in range condition.

When repeat photographs are desired, permanent camera points should be established and camera settings, time of day, date, and other essentials should be made part of the record. The boundaries of the photographic plot should be delineated on the ground to show clearly in the photograph.

Most photographs are taken from an oblique angle to the ground surface. Photographs taken vertically have been attempted as a means of obtaining better estimates of density but cumbersome and costly equipment is necessary.

Point observation plot (square-foot density): The point-observation-plot method (Stewart and Hutchings 1936) is an estimate method whereby accuracy of estimates on each plot is sacrificed for large numbers of rapidly established plots on the area being sampled. Density of each species within each plot is estimated ocularly in square feet. Where 100-square-foot plots are used this gives the density of each species on the area in percent. The range area is studied using a number of plots and the precision with which an area is sampled depends upon the number of plots, the variability of the vegetation, and the reliability of the observation on the individual plots. Plots may be either temporary or permanently delineated for repeated observations.

Circular plots are most widely used with this method. Square or rectangular plots have proved successful in some studies. The size of the plot depends upon the vegetation. When the method first came into use plots 100 square feet in area were most commonly used; 200-square-foot plots were used to sample scattered desert type vegetation. More recently plots 25 square feet in area have been found best adapted to more dense vegetation. The plot size should be large enough to sample the major species, yet small enough to be viewed readily from above and to require only a short time for observation and recording.

When using circular plots the circumference of the circle can be easily outlined by a marker, one end of which is attached to the plot center by a light chain. Density of the vegetation inside the plot is estimated by species to the nearest ¼ square foot of ground cover. It is necessary that the estimators have a mental concept of how much of the particular species is required for one square foot of vegetation. In training for this concept, the plants are picked and placed in the one square foot frame in such a way that they completely occupy the frame without distortion. Daily checking of his concept is required by each estimator.

Field application and office compilation and analysis of the data from the point observation plot method are rapid. Training of observers is not unduly difficult and with experience a technical man can work 20 to 50 plots per day (Stewart and Hutchings 1936).

The method has value in many types of studies. It is rapid to use and data obtained can be tested statistically. It is most useful for comparing vegetation on different areas where the same individual or group of individuals make estimates on all study areas. It has less value for studies comparing vegetation changes with time or where different personnel will take data at different times or places. Because the data obtained with the method are subjective, there have been conflicting opinions as to their quality. Not only are there differences in density estimates between individuals but the same individual may estimate differently at different times.

Weight-estimate method: The weight-estimate method was described by Pechanec and Pickford (1937) as a technique for obtaining herbage yield. Within plots yield and floristic composition of the vegetation are recorded in units of weight of the current growth. The size of the plot varies with the vegetation to be sampled. Intensive training is required before sampling an area. Training instructions are given by Pechanec and Pickford (1937):

> First, estimate the weight of either one or several plants of a single species, attempting from the first to define a 10-, 20-, 50-, or 100-gram unit. Count the herbage in terms of such units. Then clip and weigh herbage to determine the error of the estimate. After each estimate the individual should attempt to alter the size of his unit to conform with the last weight check made for that particular area. Train on one species at a time. While working on the second or third species, it is well to refer back frequently to the species formerly studied. Before completion of the training period, after units for all species have been defined . . . it is advisable to check a few times on sample plots of the same size as those selected for study of the area. . . .
>
> During the inventory of an area, each day all individuals should make estimates of herbage on the same temporary plots. From 10 to 20 per cent as many plots should be estimated in this manner as are estimated by each individual per day. These plots are then clipped and a permanent record made of each individual's estimates and of actual green weights. From these data can be calculated a regression by species for determining actual weights from estimated weight for any individual at any date or on any area. In the case of appreciable discrepancies between estimates and actual weights, these regressions can be used to make adjustments for such differences.

The method provides weight estimates that are reliable and rapid, indicative of yield, and subject to mechanical check. Data obtained are comparable regardless of location, type of vegetation, or species. With the double sampling procedure, the weight-estimate and clipping methods have been combined to take advantage of the rapidity of the weight-estimate method and the accuracy of the slower clipping method. Production on all plots is estimated. Then a portion of the plots taken at random is clipped and the herbage weights used to adjust the estimates by regression techniques. This procedure adjusts for consistent errors of estimates.

The weight-estimate method is sufficiently rapid that an adequate number of plots can be used to sample large range areas. Also it can be used on permanent plots, because the vegetation on the plots remains undisturbed.

Plot sizes most commonly used with the weight-estimate method are 192, 96, 24, and 9.6 square feet, the size depending upon the character of vegetation. The 192-square-foot plot is adapted to sparse desert vegetation. Plots of these sizes are used because herbage production estimated in grams per plot can be easily converted to pounds per acre by multiplying the grams by the factors 0.5, 1, 4, and 10 for the different sized plots, respectively.

Clipping methods: Many investigators prefer to obtain estimates by clipping the herbage on the plots (figure 3). Clipping has the advantage of obtaining a reliable measure of the herbage produced on the plot at the time of clipping. This is the only method of getting such information on a single plot. It is best adapted to uniform vegetation such as seeded range and small research areas where great accuracy is demanded. The principal weaknesses are that (1) the method is slow in use so that it is usually uneconomical to

FIGURE 3. Clipping blue grama *(Bouteloua gracilis)* to determine herbage production. Upright strips have been welded to blades of grass shears to assist in collecting the herbage. The chain with the steel pin at both ends is a kind commonly used to circumscribe boundaries of circular plots.

use sufficient numbers of plots to obtain a reliable sample of the vegetation on a large range area, and (2) clipping the vegetation may in itself affect the vegetation clipped. As a result it is necessary to use an estimate method by which an adequate sample can be obtained even though a larger personnel error of estimate on individual plots must be tolerated.

Grasses, grasslike plants, and forbs usually are clipped as close to the ground line as possible. This, however, varies with growth habit of the species. Sod formers, such as Kentucky bluegrass and buffalograss, may be cut ½ inch above the ground. Large bunchgrasses such as Arizona fescue are not often cut below three inches. Such close clipping of the plants is detrimental to plant vigor, and plots, once clipped, should not be used again unless the clipping itself is the treatment. Effects of clipping overshadow effects of grazing treatments. Where clipping methods are used to determine production, only temporary plots should be used.

Clipping of shrubs is so slow it is impractical as a method of estimating production. Even so, it may be necessary to use this method for measuring forage used by wildlife.

It is especially important to determine the most efficient size, shape, and number of plots to use with clipping methods because of the high cost involved.

At the time of clipping the plants may be separated into species, or groups of lesser species such as miscellaneous grasses, forbs, and invaders. In complex, dense stands clippings from sample areas may be taken into the laboratory for separation and weighing. Grass shears or knives are commonly used for clipping. However, if herbage weight without differentiation by species is desired, mowers with catching devices may be used to advantage. Plucking the plants by hand is often used in place of clipping because it closely simulates grazing.

Cage methods: The cage method is used in conjunction with either the weight-estimate method or the clipping method previously described. Several variations of the method are used but essentially the technique uses small plots which are covered with cages to prevent grazing of the vegetation on areas where the herbage is to be measured at some later date. Cages should be somewhat larger than the area to be clipped to eliminate border effect.

The cage method permits a measurement of herbage production on an area while the surrounding vegetation is currently being grazed. Moreover, by moving the cages during the growing season or putting out new cages, regrowth of the vegetation is measurable. The greatest disadvantage to use of cages is the cost of the large number required for a reliable sample. Also cages remove the treatment from the plots the year the weight determinations are made.

Capacitance meter for estimating herbage weight: Fletcher and Robinson (1956) proposed the use of a capacitance meter for estimating forage weight

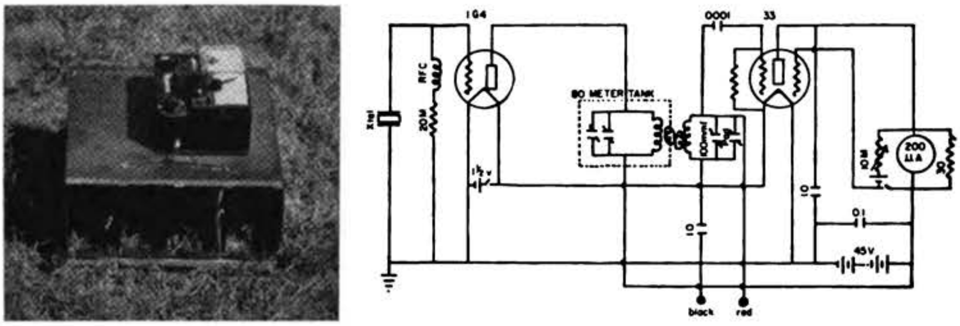

FIGURE 4. *A*. Capacitance meter used for estimating herbage weight as made by Rauchfuss (no date). *(Photograph courtesy of Robert E. Bement)* *B*. Circuit for capacitance meter. *(From Fletcher and Robinson 1956)*

(figure 4). The capacitance method is based upon the herbage having a high dielectric constant, and air, which has a low dielectric constant. By determining the dielectric constant of the plot the amount of herbage may be determined. Details of the equipment and its construction are contained in Fletcher and Robinson (1956).

Use of equipment of this kind is still in the experimental stage. It has the advantages of being rapid and leaves the plot vegetation undisturbed even though repeated measurements are taken. It has the disadvantages that only total weight can be determined on the plot so determinations are restricted to studies where only the total for all species combined is of interest or where stands of only a single species are to be measured as on some seeded ranges. Results also are affected by soil moisture and herbage moisture content.

Plotless Methods

The plotless methods of vegetation analysis have been used in ecological studies but only to a limited extent in the range field. Briefly, in these methods individual plants are selected and measured based on their proximity to randomly located points or plants. Several variations of the methods can be used (Cottam and Curtis 1956, Greig-Smith 1957). The four most common are:

1. Closest individual method. This measures the distance from the point to the nearest plant. The mean distance (d) is equal to half the square root of the mean area (M) occupied by a plant or $d = \frac{\sqrt{M}}{2}$.

2. Nearest neighbor method. This measures the distance from a randomly located plant at each point to its nearest neighbor. The mean distance equals the square root of the mean area divided by 1.67 or $d = \frac{\sqrt{M}}{1.67}$.

3. Random pairs method. From the sampling point a line is taken to

the nearest plant and a 90° exclusion angle is set out on either side of it. The distance from the individual and the nearest individual lying outside the exclusion angle is measured. The mean distance is equal to the square root of the mean area divided by 0.8 or $d = \frac{\sqrt{M}}{0.8}$.

4. Point-centered quarter method. The distance from the point to the nearest individual in each quadrant is measured. The mean distance is equal to the square root of the mean area or $d = \sqrt{M}$.

Plotless methods give the mean area per plant and, therefore, the number of individuals per unit of area. By supplementing this measurement with measurements of basal area, herbage weight, and other plant attributes the usefulness of the methods can be increased. The Bitterlich method of "variable-radius" sampling (Grosenbaugh 1952) was developed to determine basal area of trees in a forest. Cooper (1957) has suggested a somewhat similar method for measuring shrub density and Hyder and Sneva (1960) for tufted grasses.

Plotless methods have been used primarily for studying forest trees. They should be adaptable to any vegetation where an individual plant can be readily recognized. Their usefulness on grasses, forbs, and shrubs should be tested, however, before they are adopted generally.

Reconnaissance Method

The reconnaissance method (Pickford 1940) of estimating density and composition is subject to considerable personal bias, and designed for estimating vegetation on large areas.

In field use the examiner estimates on the vegetation type or plot: (1) the total density to the nearest 5 or 10 per cent and (2) the per cent that each class of vegetation (grasses, grasslike plants, forbs, and browse) is of the total vegetation. The percentage composition values are then assigned to the species in each vegetation class in proportion to the estimator's opinion of their abundance. The density of each species is the product of the total density of the vegetation and the percent composition of the species in the vegetation.

The principal weakness of the method is that it is based on the examiner's concept of density which varies among examiners and sometimes with the same examiner (Reid and Pickford 1944). It is well adapted to general surveys of large areas and takes a minimum of time.

Point Analysis Techniques

Point analysis techniques are primarily useful for obtaining expressions of basal or foliage area and botanical composition. Two most commonly used techniques are discussed here.

FIGURE 5. Apparatus used in the point method. Points can be held in vertical position as shown or at an angle of 45 degrees. *(Utah State University photo)*

Point method: One apparatus used in the point method consists of a small frame containing 10 sliding pins spaced at equal intervals varying from a few inches to a foot (Arny and Schmid 1942, Levy and Madden 1933) (figure 5). The pins may be placed in the frame either in a vertical position or at a 45 degree angle. In use, each pin is pushed down until it comes in contact with vegetation or the ground. Hits may be recorded by the plant first touched or by all plants encountered. Sometimes a hit is recorded only if the pin contacts the base (root crown) of the plant.

The system for recording hits depends upon the type of vegetation sampled and the purpose of the sample. For example, if only the first plant hit is recorded, taller vegetation will be recorded more often than the lower forms. Conversely, when only hits near the ground are counted, shorter plants are more numerous. Broadleaf plants are more frequently hit than linear leaf plants so there may be no relation between plant numbers and number of hits. Goodall (1952) found the point method often overestimates percentage cover, especially if blunt pins are used. Therefore as fine a pin as possible should be used.

A single observation may consist of one set of points or several sets within a small predetermined sized plot. The nature of the cover, species represented, and sparsity of individuals will have a bearing on the number of samples needed for the point method.

Composition and density of the plant cover can be obtained from the number of hits and expressed in percentage.

The technique is best adapted to moderate or dense cover consisting of short plants. It is not adapted to sparse desert vegetation. Brown (1954) reports that many investigators favor the method and predict its acceptance for large-scale surveys as well as smaller, more detailed field studies.

There is generally a saving in time and labor over other methods in the analysis of basal area, and when hits on plant basal area are recorded the method is accurate and free of bias. However, when hits on foliage are used, wind movement may bias the number of hits and introduce inaccuracy.

A practical variation of the method of point analysis is to drop a point vertically every foot along a 100-foot tape, recording the vegetation in the same manner as when using the frame.

Step point method: The step point method or pace transect merely consists of recording the species encountered under certain points selected by pacing across an area of vegetation (Costello and Schwan 1946). The examiner makes a "point"—a white mark or notch—about ⅛ inch wide on the tip of one shoe sole. He then selects a course, preferably a straight line, which will take him through an average or representative part of a selected plant community. A transect often consists of 100 paces. Usually the basal portion of a plant must be hit to be counted. Density, plant composition, percentage bare soils, and percentage of area covered with litter are determined from the number of hits.

The technique is most suitable for measuring major characteristics of the vegetation of an area. Large areas can easily be sampled particularly if the cover is reasonably uniform. Often the technique is useful to determine features of the plant composition and density rapidly as a preliminary step toward more refined and detailed appraisal.

Techniques Employing Lines

Lines are one form of transects. They may serve as independent sampling units or as a course for distributing other sampling units such as plots or points. Lines are well suited for determining zonation or gradient effects when placed in the direction of the change. They are useful for extensive type surveys as well as for detailed studies.

Line interception method: As developed by Canfield (1941 and 1942) and modified by others (Anderson 1942, Parker and Savage 1944, and Roe 1947), the line interception method consists of recording the horizontal linear measurements of plants along a line. Plant intercepts along the line are measured and the total of the intercepts is accepted as the percentage of ground surface occupied by the plants. Then density of the cover, individual species, or groups of species are usually expressed as a percentage of the whole line.

The line may be of any length. Long lines (100 or more feet) are commonly used in sparse vegetation and short lines (50 feet) in dense cover. In field use a small diameter, kink-proof wire is tightly stretched between two stakes as close to the ground as possible. Grasses and forbs are measured at the ground level but shrubs are measured on the crown canopy spread intercepting the line (figure 6).

Often the line transect is given a dimension in width (Parker and Savage 1944, Anderson 1942). When used in sparse vegetation or in shrubs, it may be a foot or more wide. Parker and Savage (1944) used 10 centimeters in the sagebrush-grass type in Oklahoma. In grass vegetation, however, the width is much less, such as one centimeter. Measurements are made in the same manner as on the line transect; each plant within the belt is measured by its linear intercept of the belt. This should not be confused with the *belt transect* (Weaver and Clements 1938), which is a strip of vegetation of uniform width and of considerable length on which the plants usually are charted in place or counted as with quadrats.

The line interception method has proved valuable in measurement of

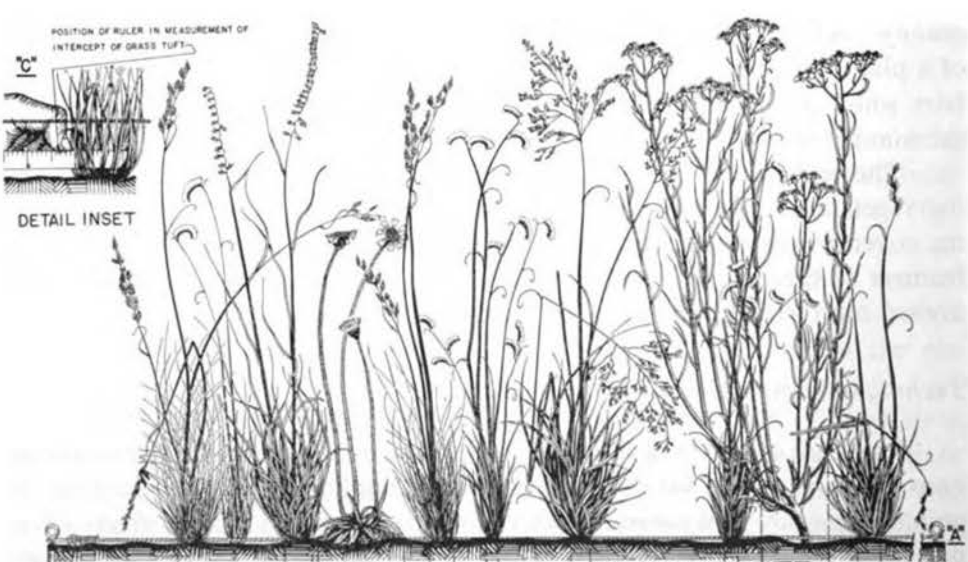

FIGURE 6. A segment of a line transect showing the manner in which the vegetation is measured. *A*. As the transect appears to the observer in the field. *B*. A diagrammatic projection of the intercepted portion of tufts on the line of measurement. *C*. Detail of measuring plant at ground level. *(From Canfield 1942)*

the semiarid vegetation of the Southwest, and has been used for shrub types and other grass types of vegetation. It is best suited where the plant limits are rather easily defined. Under such conditions the method is fast and accurate and reasonably free of bias. However, clear-cut definitions of what constitutes a plant crown, the size of interstices within a plant that will be considered as bare ground, and how to record single stemmed species would materially increase the accuracy of the line interception method.

The loop method: The loop method is an example of a line transect being used as a directional guide for the location of plots (Parker 1951). A ¾-inch diameter loop or ring (plot) is used as a compromise between larger sized plots and the point. Basically it is similar to the method employed by Huffaker and Holloway (1949) to follow changes in grassland vegetation following control of *Hypericum perforatum*.

In this method a 100-foot tape is used as the guideline for location of the loops. If the transect is to be permanent, angle iron stakes are placed at the 0.0-, 50.5-, and 99.5-foot marks as reference points for exact relocation of the tape. Readings are made at one-foot intervals along the tape. A 50-foot tape with readings at 6-inch intervals or a one-chain tape with readings at one-link intervals also may be employed. The loop is attached to a shank about 16 inches long and may be variously equipped to facilitate plumbing the loop below the tape. If any portion of the root crown (or stem for forbs and crown canopy for shrubs) is within the loop, a hit is recorded for the particular species (figure 7). When more than one species is encountered in the loop, each is listed. When no root crown or stem base is within the loop the hit is recorded as dominated by litter, bare ground, or rock. Overstory vegetation is recorded separately as such for each one-foot interval. Transect data provide an index to plant density, composition, and ground cover.

The method is reasonably simple and rapid to use, with limited bias. Although developed for grasslands of moderate density, it can be used on browse range or meadows with some modification.

Measuring Quality of the Vegetation

Forage quality may be studied by determining values and other characteristics of the vegetation either from the vegetation directly or as expressed in animal products. Qualities of vegetation commonly tested are palatability, total digestible nutrients, and individual nutrients such as protein or phosphorus. Since animals require certain quantities of food for maintenance, growth, and reproduction, animal responses that are manifested in milk, wool, meat, hides, or offspring are useful criteria for measuring forage quality. Measurements of forage quality may be obtained from field grazing trials, laboratory analyses, or a combination of both. Combined field and laboratory

FIGURE 7. Method of using the ¾-inch diameter loop. One man makes the observations and records the data as to species, litter, bare ground, erosion pavement, and rock. Photo on right is closeup of wire loop showing an observation on a perennial grass.

methods involve digestion, balance, and grazing trials, which on large range areas are not often practicable. A somewhat modified technique also has been followed wherein range forage is grazed in small enclosures where the animals can be closely observed.

Grazing trials are a practical means of indirectly evaluating forage quality but obviously provide little quantitative knowledge of nutritional composition. Hence, laboratory tests are commonly used to measure the nutritional level of the range forage. Much has been published on the chemical composition and digestibility of various range forages which vary according to species, site, season, and other factors (Watkins 1955). Knowledge of adequacies or shortages that exist enables a range manager to supplement during critical periods to sustain animal production.

Animal Gains

Animal gains as a measurement of quality of vegetation are the net results of specific combinations of a large number of variables. Among these is quantity of vegetation available to the animals. Sufficient forage should be available at all times so that the total intake does not directly influence animal gains. The objective should be to provide a rate of stocking which will be near the level for sustained production. Because this level can seldom be determined exactly, it is advisable to use a stocking rate a little lighter than calculated to be proper for the experimental range. This will assure that gains are not directly influenced by the quantity of forage available.

Weights of animals should be determined at intervals that will reflect any change in nutrient content of forage. Before and after weights may be adequate for short grazing period trials, such as spring grazing trials on seeded grasses. During period of slow changes in moisture content of plants, weight determined at 28-day intervals may be sufficient. When moisture content of the vegetation is changing rapidly, weights determined at 14-day intervals may be more desirable, particularly if an experiment is designed to use weights as a criterion for removing animals from a pasture or as a measure of the need for supplemental feeding. Except under unusually intensive studies, weights at seven-day intervals are not desirable because (1) excessive handling of the animals may produce undesirable side effects and (2) changes in amount of fill in the digestive tract are likely to be greater than the changes in body weight.

Two qualities of vegetation are most commonly tested and related to animal gains: total digestible nutrients and individual nutrients. Total digestible nutrients can also be used as a quantitative measure of the forage produced.

Total digestible nutrients (TDN) may be determined as follows:

(1) Using published standards (Guilbert *et al.* 1945, Pearson *et al.* 1949, Morrison 1947), determine TDN maintenance requirements for the kind and age class of animals to be used.

(2) Determine TDN requirements for each pound of animal gain and loss (based on caloric values for gain or loss).

(3) Pounds of TDN provided by pasture = maintenance TDN ± (pounds gain or loss × TDN required for gain or loss).

This determination of total digestible nutrients is based upon certain assumptions, particularly the total digestible nutrients required for maintenance and for gain or loss of body weights. There is also the assumption that no single nutrient is so deficient as to prevent otherwise normal body growth and the utilization of range.

It is often desired to determine whether a single nutrient (phosphorus, protein) is so deficient in forage from a range as to affect animal health. Tests of deficiencies are often conducted on a weight gain basis. Such tests do not give quantitative measurements of nutrient deficiency, but only indicate general levels of nutrient supplementation necessary. In this sort of an experiment the supplement is given to a number of animals and not provided to check animals. Sheep can be separated into groups for differential supplemental feeding each day, then turned out together to graze. The complex of environmental variables, including amount and quality of range feed, are thus effective on all animals, and weight differences can be assumed to be due to the nutrients fed in the supplements.

Cattle cannot be handled easily on an individual feeding basis and are usually fed as groups on several units of range. In this sort of an experiment, the differences among pastures in range forage speciation, topography, and other factors must be considered. If the pastures are comparable in species and topography, then design and analyses need consider only animal and treatment variables. Such similarity of pastures is seldom found, however, and experimentation must proceed with this in mind. There are two methods of determining the effect of different ranges. Animals can be grazed on the several range units without supplemental feed and the capacity of each range to put gains on the animals evaluated. The subsequent feeding of supplements and the analysis of data must then assume no change in the range environment with time. Such an assumption is difficult to justify except during trials entirely within a period when forage plants are dormant.

The second method is to use a rotation of control and fed groups so that the variability in gains among pastures can be assigned to differences in the nutritive qualities of the range units.

Chemical Composition

Nutritive Value of Range Forage

Chemical analysis of range forage plants serves as a comparative measure of differences between species and changes with season. Also, it is an index to mineral and vitamin content when evaluating deficiencies or excesses in the diet. However, it should not be considered a direct determination of nutritive value of range plants.

Most constituents of plant material are of some importance to nutritive value. The usefulness of determining them depends upon how broad or how precise an appraisal of nutritive content is to be made. Chemical analyses are useful for measuring differences between plant species, effects of stage of growth, and effect of site quality on the chemical constituents.

No one chemical constituent or any combination of chemical constituents will properly evaluate the nutritive content of range forage (Cook and Harris 1950, Lancaster 1943, Patton and Giesecker 1942, Phillips and Laughlin 1949). A chemical analysis of plant material for a particular constituent merely indicates that the plant is comparatively high or low in that particular constituent. There are no two chemical constituents that are directly associated in all plant material. For instance, browse plants are comparatively high in lignin whereas grasses are comparatively low, yet from the standpoint of nutritional value grasses are better in some respects and shrubs are better in others. Mature grasses generally are higher in crude fiber content than shrubs, yet they may have greater total digestible nutrients.

Chemical content of plant species may differ because of inherent ability to withdraw certain nutrients from the soil and concentrate them in the tissues. They may also vary in susceptibility to leaching, or may produce different proportions of leaves, stems, and flower stalks or stage of maturity at a given date.

Chemical composition of the same species often varies with stage of maturity, soil conditions, or general climatic conditions. Collection technique and analytical procedure also affect results.

Collecting Forage Samples

Range vegetation is highly variable and care must be taken in collecting plant material for chemical analyses. Gross samples of plant material may be representative of a particular species or of a range area and not indicate nutritive value because only portions of the plants are taken by grazing animals. Such data may be of value when comparing species but cannot be used to evaluate the nutritive content of the forage.

In every case the portion of the plant collected should be identified. In addition, it is important to collect samples from several sites where the plant is commonly found. Likewise plant material should be identified as to stage of growth so that the data will be representative of a particular season.

Analyses of herbage may be made of samples composited from several areas or, if the areas represent replications, samples may be analyzed separately to obtain an experimental error for measuring treatment differences.

A small sample for chemical analyses can be obtained from the composite sample by mixing the material thoroughly and taking a grab sample from each quarter or sixth of a pile. If the material shatters then the entire composite should be ground and run through a Riffles sampler until the proper sized aliquot is obtained. Sometimes it is wise to run large samples of mature or dry materials through a hammermill and then through a sampler or divider until an aliquot is obtained sufficiently small to be handled by a Wiley mill for grinding.

When collecting plant material it may be wise to wash and dry the material to eliminate dust which will increase the ash content.

Frequently it is desirable to collect material representative of what the animals are eating. The grazing animal harvests range forage in an assortment of species and portions of plants. The selectivity of the animal may be influenced by kind of animal, intensity of grazing, plant species present, stage of growth, and general climatic conditions.

There are several methods of collecting samples representing the material being consumed by the grazing animal or arriving at the nutrients ingested. These methods include hand plucking to simulate grazing, cage clipping, strip harvesting, collecting plant units before and after grazing, and by the esophageal fistula.

In the hand plucking method, plant samples representing ingested forage are obtained by observing individual grazing animals for several hours daily, and hand plucking material comparable to the forage actually being consumed. Many small random plucks should be taken over the area. For accuracy it requires from four to six man-hours daily and gentle animals that can be approached closely.

With the cage method the chemical content of the diet may be determined by difference between a grazed sample and an ungrazed sample. Usually a number of portable cages are located randomly over the range to prevent grazing on small plots. Ungrazed herbage samples are collected from these plots and compared to samples from adjacent grazed range. Then the cages are moved to protect a sample for the next sampling period. The intervals between sampling periods should be short, especially on rapidly growing forage. Otherwise plants in cages will be in more advanced growth stages than the plants being grazed (Amer. Soc. Agron. 1952). This method has a distinct disadvantage on heterogeneous range since it is impracticable to sample enough plots to obtain representative samples of the general area. In addition, the abundant species are oversampled and the minor species are greatly undersampled if composition by species is desired.

A similar method involves the use of mowed strips. In several areas a strip is harvested by mowing before grazing and an adjacent strip is harvested after grazing. Samples from each strip may be separated into individual species or analyzed as a composite sample. The difference in weight and chemical content between the before-grazing strip and the after-grazing strip represents the diet. Again the interval between samples should be brief or the vegetation not growing or weathering appreciably (Amer. Soc. Agron. 1952). This method is better adapted to homogeneous vegetation than to usual range conditions.

A before-and-after method suitable to heterogeneous range was used by Cook *et al.* (1948). This method of collecting material to determine the botanical and nutritional content of the diet consists of collecting a number of distinct plant units of each dominant species before grazing and another comparable group of units after grazing. These two samples are weighed and analyzed chemically. Chemical composition of the diet can be approximated by determining the volume that each species contributed to the entire range (usually an estimate), multiplying this by utilization (based on "before" and "after" weights), and multiplying by chemical content.

It has often been stated that a representative sample could be obtained only by letting the animal forage it. This has been accomplished by an esophageal fistula (Torell 1954, Cook *et al.* 1958).

Chemical determinations

Some of the common chemical determinations for plant material are: total digestible nutrients, crude protein (nitrogen × 6.25), ether extract, ash, lignin, cellulose, other carbohydrates, crude fiber, nitrogen-free-extract, calcium, phosphorus, and carotene (precursor of vitamin A). For a more detailed discussion of chemical analyses of plant material see Sullivan and Garber (1947).

In addition to the above analysis it frequently is desirable to determine gross energy values with the bomb calorimeter. It has been found in domestic feeds that a close relation exists between digestible energy and total digestible nutrients. Thus, by using gross energy determinations of feeds and feces, energy values for feeds can be appraised more simply and more economically.

Gross energy determinations are necessary to calculate metabolizable energy. To determine metabolizable energy, losses of gross energy through the feces, urine, and gases are subtracted from the gross energy consumed in the feed.

Total digestible energy or total digestible nutrients can be used as an index to energy of grasses, but in some cases it is inaccurate for shrubs or forbs because of the presence of ether extract material, other than fatty acids, that is passed off in the urine of the animal, and thus is not available for body use. Metabolizable energy is the most suitable index to energy-furnishing qualities for range forages (Cook *et al.* 1952).

Conventional methods of evaluating energy of feeds by total digestible nutrients and digestible energy are not adequate for many range plants, especially browse plants where the content of essential oils is high (Cook *et al.* 1952).

Proximate analysis of feeds includes ether extract, crude protein (N × 6.25), ash, crude fiber, and nitrogen-free-extract. The latter is determined by difference. It has been suggested that crude fiber and nitrogen-free-extract determinations be replaced by determinations of lignin, cellulose, and other carbohydrates. Digestibility of crude fiber and nitrogen-free-extract may be nearly equal for many forages whereas lignin is indigestible and other carbohydrates and usually cellulose are highly digestible (Norman 1939). Crude fiber and nitrogen-free-extract determinations are of value to compare relative content of these constituents in range plants with domestic feeds since most feed analyses, until recently, included these determinations. Analyses of lignin, cellulose, and other carbohydrates are more meaningful from the standpoint of interpreting the nutrient value of range forage. A weakness is the assumption that the ether extract fraction consists largely of fatty acids. This is not the case with many species of forbs and browse which are high in various oils and resins. These are extracted by ether but do not furnish energy that is available to the animal.

Recommended analytical procedures can be found in the Association of Official Agricultural Chemists' guide, published periodically to keep analytical procedure as nearly standard as possible. A satisfactory procedure to determine important constituents in range forage is as follows: nitrogen by the Gunning method as outlined by the Association of Official Agricultural Chemists (1945) except that ammonia should be collected in boric acid as outlined by Scales and Harrison (1920), lignin by the method suggested by Ellis *et al.* (1946), cellulose by the method of Matrone *et al.* (1946), phosphorus by the method of Koenig *et al.* (1942), and carotene by the method of the Association of Official Agricultural Chemists (1950) with suggestions for preparing the sample from Jones *et al.* (1953).

The inorganic elements in plant material such as calcium, phosphorus, iodine, cobalt, copper, iron, selenium, and molybdenum can be measured directly by chemical analysis. Analysis of vegetation for its content of the various vitamins is not well developed.

Digestibility

The value of a forage to the grazing animal depends on the digestibility of the ingested nutrients. The digestion coefficients are the average percentage of each nutrient digested (Morrison 1947). These coefficients are a direct means of determining available nutrients. They may vary slightly according to age, species, condition, sex of animal, nutrient intake (nutrient level of the ration), and activity of the animal. Therefore even when the diet and digestibility are accurately determined the evaluation of the nutrient is only approximate for all animals.

Some digestion trials have been made on range plants by standard procedure using digestion crates. Such studies involving controlled feeding of clipped or hand plucked forage have been described by Forbes and Grindley (1923) and Maynard (1947). These have distinct disadvantages because the animal is not allowed to select normally among species and plant parts and because the animal is not naturally active.

Field digestion trials have been used to measure nutritive value of native range plants (figure 8). With this method it is necessary to use as an indicator a plant constituent that appears in the forage and is indigestible so that it can be recovered in the feces. Cook *et al.* (1951), studying sheep grazing on winter range plants, found that lignin gave satisfactory results. Smith *et al.* (1956) found indication that deer digested some of the lignin. Reid *et al.* (1950) suggested that plant chromogens (plant pigments absorbing light at a wave length of 406 $m\mu$) could be used as an indicator substance. However, Cook *et al.* (1951) found that the chromogen method was not satisfactory for some range species. Fecal nitrogen concentration has also been used as an indicator. Vallentine (1956) and Harris *et al.* (1959) review the use of

FIGURE 8. Sheep being grazed in field digestion trials of native range plants. Photo on right shows harness for holding catchment sacks in place. *(Courtesy C. Wayne Cook)*

indicator methods in digestion trials in range research and these sources are recommended to the researcher desiring to employ such methods.

In the indicator method, animals select the forage in a normal manner and from the ratios between lignin and other constituents in the feed and feces, digestion coefficients can be determined. Since the entire amount of the indigestible indicator is recoverable in the feces, the percentage of each nutrient that is digested is determinable by the following formula:

$$100 - \left(100 \times \frac{\text{\% indicator in forage}}{\text{\% indicator in feces}} \times \frac{\text{\% nutrient in feces}}{\text{\% nutrient in forage}}\right) = \begin{array}{l}\text{per cent}\\ \text{digestibility}\end{array}$$

The entire fecal output can be collected in specially designed fecal bags, or representative samples can be collected from intermittent defecations. In the latter method, small samples are taken from several defecations from several animals or from a single animal during each day of the collection period. Urine samples likewise can be collected from male animals in specially devised bags. If the total quantity of both feces and urine is collected, nutrient balance trials can be conducted and metabolizable energy values determined (Cook *et al.* 1952).

Digestibility trials can be carried on by grazing pure stands of a single species or by grazing mixtures of many species. It is important to determine accurately the chemical intake of the grazing animal.

Mineral Balance

Mature animals not in gestation or lactation should be in equilibrium for mineral intake and loss. With growing animals and pregnant animals there should be an excess of intake over output that provides for growth or fetal development. Trials with lactating animals must account for the loss through the milk in addition to the losses in feces and urine.

Mineral balance trials are made on a similar basis to digestion trials except that the urine and any product such as milk are collected and analyzed in addition to fecal material.

In range nutrition it is sometimes desirable to know whether animals are in positive or negative balance for any one of several minerals, particularly phosphorus. Mineral content in both the solid and liquid excreta is subtracted from the content in the food to determine whether the body is gaining or losing any of these elements.

Trials under field conditions with male animals can be run by using the technique developed by Cook *et al.* (1952). For female animals, data from males of comparable age can be used. However, this is not applicable for females in gestation or lactation.

Requirements for various mineral elements can best be determined under controlled metabolism trials where levels of feeding can be administered accurately. If requirements for growth, gestation, and lactation are to be based upon quantity of maximum retention several levels of feeding are required.

Mineral requirements determined by feeding trials have been found to vary and, therefore, represent a range rather than a specific quantity. This results from the failure of the various experiments to agree upon maximum retention and level of feeding and failure to obtain maximum animal response and welfare at the level where maximum retention was obtained.

Palatability

Palatability is that quality in a forage plant that makes it preferred when a choice of various plants is available. It is defined by the Committee on Forestry Terminology (Soc. Amer. For. 1950) and Dayton (1931) as the relative relish with which forage plants are consumed. Palatability of any species is subject to a considerable variation due to the influence of a large number of environmental, animal, and plant factors. Knowledge of palatability is an important tool in formulating management practices, establishing grazing or stocking rates, planning reseeding and pasture mixture studies, and studies involving managing and stocking ranges for proper forage utilization.

Usage of the term palatability has changed several times during the last 40 years as discussed by Brown (1954), Sampson (1952), Stoddart and Smith (1955), the U.S. Forest Service (1937), and the Committee on Forestry Terminology of the Society of American Foresters (1950). Palatability has sometimes been expressed in percentage of the plant that will be grazed under good management. However, this use of the term is easily confused with the proper use factor. The proper use factor denotes the proportion of a plant's current herbage within easy reach of livestock that can be grazed, year by year, without permanent damage to the plant, the important associated plants, or the soil.

Palatability of the dominant forage plants is a major factor in forage utilization (discussed in Chapter 5). The difference between utilization and palatability must be stressed. Utilization is the proportion of herbage consumed under actual conditions and is one of several factors to be considered in establishing palatability ratings.

Factors that Influence Palatability

The palatability of a plant will vary with different animals, seasons, growth stages, soils, vegetation types, location, and similar factors. Therefore, it is impractical to assign to a plant exact palatability ratings that will cover all conditions. Tribe (1952) discusses such factors according to their origin —animal or nonanimal.

Some of the animal factors that may influence palatability are:

(1) Grazing preferences of different kinds of animals. Cattle and horses tend to prefer grasses, sheep generally prefer forbs, and goats and deer prefer more browse.

(2) Age, degree of maturity, stage of pregnancy, and general physical condition of an animal.

(3) Hunger of animals. Hungry animals or those in poor nutritional condition may eat plants that are often considered unpalatable under normal conditions.

Some nonanimal factors that may influence palatability are:

(1) Season and growth stage of the plant. Palatability depends to a great extent on succulence and relative amounts of sugar, protein, and minerals. These are directly related to growth stage and season.

(2) The palatability and relative abundance of associated plants.

(3) Differences in locations, sites, and climates. Soil fertility, moisture, and drainage are particularly important.

Tribe (1952) pointed out that palatability is not an infallible indicator of nutritive value. Grazing animals do not always select the things that are most nourishing and healthful. Also, palatability and digestibility are not necessarily related. Some plants classed as unpalatable may be digested as efficiently as highly palatable plants.

Methods of Measuring Palatability

Palatability ratings are a useful tool in management of the range. However, researchers have not spent much time perfecting methods of measuring palatability alone. Most palatability ratings are based on observations and qualitative notes of animal preference for individual plants under a variety of conditions. Also, palatability is often determined in connection with studies of production, utilization, and grazing capacity.

Methods using utilization: Palatability often is determined from an analysis of relative utilization of a species in relation to utilization of associated species under a variety of sites and conditions. Methods of determining utilization are discussed in Chapter 5. Actual and relative utilization of species will seldom be the same on any two areas but often the use of species is proportional. Conclusions as to palatability from such data can be made by classifying utilization of each species on each area by adjective ratings such as "high," "medium," and "low," or ranking them by number, in order of preference. Palatability can then be estimated from inspection of data from several areas (Hurd and Pond 1958). A less subjective method is to array the species according to percentage utilization estimates, assigning 100 to the most important species that receives the highest utilization and is common to all areas. Other species are assigned larger or smaller numbers according to the use they received in relation to the species assigned 100. The numbers thus assigned on each area studied can be averaged for each species and used as a basis for assigning palatability.

Feeding minutes method: Many workers have used the feeding minutes method to study the feeding habits of livestock and game on the range and to determine the relative palatability of forage species. The basic premise of this method, and probably a false one, is that the relative time spent grazing a selected species is an indication of relative palatibility of that species.

When using the feeding minutes method, different areas with different topography, plant composition, and type of livestock require different techniques of observation. Care must be taken not to disturb the grazing animals unduly. A pair of binoculars is usually needed and accurate identification of the plants grazed is necessary. After a sufficient number of observations, palatability ratings may be determined on the basis of the time spent grazing each species. However, it should be recognized that, as with all methods, abundance may be of greater importance than palatability in determining the time spent grazing selected species.

Feeding minutes alone will not give an accurate indication of the total amount of forage consumed by species. Animals may consume a large amount of a readily available plant in the same time required to consume a relatively small amount of a small, low-growing plant. In any case, a combination of the observation of feeding minutes and the collection of quantitative data should give a much more reliable indication of palatability than the observation of feeding minutes alone.

Peterson *et al.* (1958) found that comparisons of clipping before and after grazing to determine palatability of 20 selections of tall fescue gave unreliable estimates of consumption, primarily because of the sampling errors involved. More reliable results were obtained by recording the number of sheep grazing on each plot, at 5-minute intervals during the hours 7 a.m. to 10 a.m. for a 2-day period. Relative palatability was then expressed as the total number of times the plot was grazed during the period of observations.

The largest difference in palatability among the 20 selections was during the period of lush spring growth. Discussion of the feeding minutes method may be found in the works of Archibald *et al.* (1943), Cory (1927), Hubbard (1952), Jones (1952) and Staten (1949).

Cafeteria or free-choice methods: The cafeteria or free-choice method gives the animals a chance to select their forage from a number of species all of which are made available to them in approximately equal amounts and equally accessible. Palatability is then determined by estimating or measuring the relative amount of each species utilized under regulated use.

One method is to place before penned animals known amounts of clipped herbage or twigs of a number of selected species. This method is well adapted to study of palatability of plants to big game animals.

A second method is to use paddocks containing a variety of growing plants. This latter method is well suited for study of the palatability of planted species that have similar growth habits and seasons. Selected species are planted in replicated and randomized plots (rows, squares, rectangles) that are comparable in area. Grazing animals are permitted to use the area in regulated numbers during the selected grazing period. The method is well suited to determine the palatability of species under consideration for use in a range seeding program. The fact that the different species are planted in a definite arrangement facilitates visual observation and collection of quantitative data. Burton (1947), Rogler (1944), Schmautz (1954), and others have used this method.

Any outside factors tending to influence grazing concentration on the study area must be avoided so that grazing is relatively uniform over the entire area.

Measuring Plant Vigor

Plant vigor is synonymous with plant health. It denotes the relative appearance, vitality, rate of growth, and herbage production of the plant. A vigorous plant has reserve vitality, is free from defects and disease, and for maximum vigor it requires a favorable ecological environment.

Plant vigor is a relative abstract term and, therefore, difficult to describe, measure, or interpret precisely. It is a composite expression of the influence of all environmental growth factors. Changes or modifications of any growth factor, such as soil fertility, soil moisture, rainfall, or the biotic influences of insects, rodents, and livestock grazing, affect the vigor of the plant.

On many ranges plant vigor is closely associated with grazing intensity. Whenever ranges are overgrazed, deterioration is often first reflected in plant vigor, followed by changes in plant density, composition, and soil stability. Plant vigor, herbage yields, species density, plant composition, soil stability, and litter have all been used to classify range conditions and serve as criteria for evaluating range improvement or deterioration (Ellison *et al.* 1951, Evanko and Peterson 1955, Hutchings and Stewart 1953, Parker 1954, Pechanec and Stewart 1949, and Talbot 1937). Increase in plant vigor is also one of the first expressions of range improvement.

Plant vigor is manifested, or indicated, in several ways:

Physical characteristics

(1) Size and appearance of plants—manifested as dead centers, decadent appearance, dead branches and broken sod for poor vigor and the opposite of these characteristics for good vigor
(2) Height and number of stems
(3) Number and size of fruiting bodies or seed heads
(4) Size and color of foliage
(5) Date of renewal of spring growth and rate of foliage development
(6) Herbage production

Physiological and root characteristics

(1) Manufacture and storage of plant food reserves
(2) Root development and growth
(3) Amount and characteristics of chlorophyll
(4) Winter and drought hardiness

Prompt renewal of growth in the spring when growing conditions are favorable indicates adequate food reserves in roots of grasses and forbs and in the stems of shrubs. Satisfactory growth in height, abundant twigs and stems, numerous flower stalks, and adequate seed crops all indicate good vigor. Most of these characteristics result in high herbage yield and optimum root development.

Measurements or observations on any of these criteria provide information on plant vigor. However, most investigators measure and evaluate several. All possible clues to plant vigor must be considered before a final evaluation is made. The greater the number of valid factors considered and measured, the greater the confidence in the results and interpretations obtained.

Size, character, and condition of plants are the most visible and easily recognized indicators of plant vigor. Many studies (Albertson *et al.* 1953, Aldous 1930, Biswell and Weaver 1933, Bukey and Weaver 1939, Canfield 1939, Nelson 1934, Talbot 1937, Weaver 1950) have demonstrated that frequent close clipping or grazing reduces plant size, breaks up sods and crowns of grasses, injures twigs and foliage of shrubs, and leaves the plants in decadent condition. Severe clipping or grazing of some shrubs for a period of one or two years sometimes stimulates twig growth, but continued close cropping, year after year, markedly reduces plant size and vigor (Garrison 1953).

Height of leaves (Albertson *et al.* 1953, Evanko and Peterson 1955, Holscher 1945, Hutchings and Stewart 1953, Nedrow 1937, Nelson 1934, Biswell and Weaver 1933), length of twigs (Johnson 1945, Julander 1937, Young and Payne 1948), number of flower stalks (Weaver and Hougen 1939), and amounts of seed produced (Hutchings and Stewart 1953, Julander 1937, Sampson 1914) are the most commonly used and most easily measured criteria for determining and evaluating plant vigor. These attributes are probably the most sensitive to grazing treatments and they can be measured quantitatively.

If plant vigor is appraised by plant height, all measurements should be on a comparative basis and a new set of guides established each year to eliminate differences attributable to weather. Parker (1954) recommends that yearly guides to stem length or leaf height be established. Parker (1953) suggests dividing grasses into 5 equal groups on the basis of height: excellent (tallest plants), good, fair, poor, and very poor (shortest plants). He also suggests the possibility of using arbitrary height groups to classify vigor as follows: Plants in excellent vigor are those that have leaf or flower stalk lengths 95 per cent or more of the average maximum lengths of randomly selected plants considered to be in optimum vigor. Plants in lesser vigor classes would have leaf or flower stalk lengths of the following percentages of the average maximum leaf or flower stalk under optimum vigor: 94-85 per cent for good, 84-75 per cent for fair, 74-65 per cent for good, and 64 per cent or less for very poor.

Caution should be used in selecting plants for measurements in establishing height criteria. Only mature plants growing in representative sites should be used. Seedlings, young plants, and tall, isolated, robust "wolf" plants should not be included.

Bostick (1947), in the Southwest, established criteria for evaluating plant vigor. For grasses, the criteria are based on plant height, leaf length, and herbage yield per acre. For shrubs, leaf size, twig length, twig mortality, and production of fruit and flowers were used in appraising plant vigor. Julander (1937) and Garrison (1953) used twig length and herbage yield in measuring plant vigor in shrubs. They found that pruning stimulated twig growth so that twig length was not always a sensitive measure of plant vigor in shrubs. Weight of herbage produced was more sensitive in most shrubs.

All the factors that affect plant vigor are integrated in herbage production. Therefore, herbage yield is undoubtedly a more accurate measure of plant vigor than any single vegetal character.

If accurate measurements and valid comparisons are to be made of plant vigor by herbage yield, certain restrictions are needed. All comparisons should be made under controlled treatments where plant populations are comparable as to age and size. Whenever possible, individual plants of equal age should be selected for comparisons. Yearly fluctuations—precipitation and other weather factors—also influence herbage yield; therefore, comparisons must be made each year. If vigor comparisons are to be made between years, it is imperative that yield data be obtained at approximately the same date each year or when the plants reach a given stage of development.

Root development and production are related to plant vigor. While root production is difficult to study and therefore is not readily usable in the field for making comparisons, when available it adds to the information and interpretation of plant vigor. Weaver (1930, 1950) and Weaver and Darland (1947) have outlined methods of evaluating plant vigor by root mass and production. Weaver and Darland (1947) transplanted sections of sod of various grass species, under different grazing treatments, to the greenhouse for planting and observation. After 4 to 6 weeks tops were clipped and the soil removed from the roots. Leaves and root production were closely associated with vigor of plants and grazing intensity. Weaver (1950) compared roots of various forage species under three grazing treatments. Trenches were dug and soil washed from the roots. Amount of roots, length of roots, size of roots, production of leaves, and number of stems were all associated with plant vigor.

Production and storage of plant-food reserves, like herbage yield, are essentially a summation of plant vigor. Aldous (1930), Bukey and Weaver (1939), Julander (1945), McCarty (1935), McCarty and Price (1942), and Stoddart (1946) have all recorded and measured the plant-food reserves and found the amount of storage to be associated with plant vigor.

Determination of plant-food manufacture and storage requires detailed chemical analysis in the laboratory, and involves a study and understanding of the physiochemical process in the plant. McCarty and Price (1942) used carbohydrate reserves at the end of the growing season as a measure of treatment on vigor. They found that herbage yields and carbohydrate reserves were closely associated. The carbohydrates analyzed were sucrose, reducing sugars, starch, and hemicellulose.

Confining observations and studies of plant vigor to a few selected species fails to evaluate fully range condition or trend because invading or undesirable species are ignored. A comparative appraisal of plant vigor for desirable and undesirable forage species would provide a much more complete and effective evaluation than vigor of key species alone.

Braun-Blanquet (1932) recognized the ability of a plant to carry out its life cycle regularly and efficiently in a plant community as an indicator of vigor. The following scale was set forth as a measure of plant vitality within a community:

(1) Well developed, regularly completing the life cycle
(2) Strong and increasing but usually not completing the life cycle
(3) Feeble but spreading, never completing the life cycle
(4) Occasionally germinating but not increasing

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Chapter 4
Studies of Root Habits and Development

Introduction

An UNDERSTANDING of the principles of range management depends on a basic knowledge of plants. This includes knowledge about their hidden parts—the roots—a factor which has not been fully appreciated until quite recently. Few ecologists have studied the root systems of plants growing in nature. A beginner who wishes to embark on root investigations will soon learn why this has been so. But it should be remembered that whenever methods are cumbersome and tedious, the potentials for innovation are great.

In 1957, Troughton published a book on "The Underground Organs of Herbage Grasses." This includes 25 chapters divided into three parts; description of underground organs; factors influencing growth; the effect of the plant upon the soil. This book is recommended for study by those investigators interested in roots.

Value of Knowledge of Root Reactions

Roots have one or more of the following roles: (1) absorption of nutrients and water; (2) anchorage and support; (3) propagation; and (4) storage of food reserves. They also play a prominent part in the growth and welfare of other plants through (5) soil development.

Studies of responses to drought, fertility, competition, and other environmental conditions can be aided by, and are often entirely dependent on, a thorough knowledge of root habits: depth of penetration, extent of branching and distribution through soil profile, rate of growth, ratio of root to shoot, and other such characteristics which determine the absorptive ability of the plant.

Investigations concerning the role of the root systems in anchorage of the plant can be of great importance to range management. Examples to be cited are the value of depth and tensile strength of the roots to resist frost heaving of seedlings, washing or blowing out by erosive agents, and pulling up by grazing animals.

In the strict sense, roots of grasses and other plants encountered on rangelands rarely act as organs of propagation. On the other hand, rhizomes, which are rootlike in appearance but actually are underground stems, are important means of propagation among perennial plants. While studies of rhizomes can be categorically denied a hearing in this chapter on roots, it should be emphasized that they occupy major efforts in weed-control techniques (e.g., eradication of bindweed), plant breeding programs (e.g., development of creeping alfalfa), and revegetation research.

The role of roots as a storage place for food reserves is the basis of many of our present-day range management concepts and practices. The principles of range readiness, range condition and trend, rotation grazing, and selective spraying are associated with the distribution of food materials in the plant from season to season. The subject of vigor is important from both ecological and production phases of range management research. A whole section of this chapter is devoted to the technique of studying root reserves, their analyses, and interpretations that can be made from them.

The fifth area of root study is concerned with the effects of roots on the habitat itself. This is the study of range influences, and includes the effect of plants on soil formation, soil fertility, and erosion control.

Root Reserve Analyses

Storage of food reserves is an important function of perennial plants. An understanding of this storage function, and its response to environmental factors and management practices, is indispensable to enlightened management of pasture or rangeland. Not only is such information needed to maintain high yields of desirable forage, but also to control undesirable plants. Although our knowledge of this subject is still rather fragmentary, particularly in the range field, enough has been learned to establish general principles and characteristics concerning root reserves and to stimulate further research.

The significance of food reserves in the management of perennial forage plants was early emphasized by Graber *et al.* (1927) and Graber (1931). Aldous (1930) was among the first to stress the importance of food reserve levels in relation to the time of applying measures to control undesirable pasture plants. Sampson and McCarty (1930), McCarty (1932, 1935, 1938), and McCarty and Price (1942) have made intensive studies of food reserves of certain western range grasses in relation to stages of growth and management practices. Aldous (1930), Bukey and Weaver (1939), McIlvanie (1942), and Benedict and Brown (1944) have also studied food reserves of certain native grasses. Various other American workers have investigated food reserves of pasture and hay species (Moran *et al.* 1953, Phillips *et al.* 1943, Smith 1950, Smith and Graber 1948, Tesar and Ahlgren 1950) and recent work at the U.S. Regional Pasture Laboratory, State College, Pennsylvania (Sprague and Sullivan 1950, Sullivan and Sprague 1943, 1949, 1953) has been pertinent in clarifying the role of specific reserve components, as well as their responses under carefully controlled conditions. Reserves of several native and introduced grasses in South Africa have been studied by Weinmann (1947, 1948a, 1952) and by Weinmann and Reinhold (1946).

Reserve Substances

Reserve food substances may be defined as organic materials elaborated and stored at certain times to be utilized later by the plant for energy and production of new tissues. From this generally accepted viewpoint, food reserves of vegetative organs are composed primarily of certain groups of carbohydrates.

Minerals and nitrogen are essential *nutrients* but not sources of energy, nor reserve food in the true sense. Protein may be included among the food reserves, but evidence indicates that carbohydrates far overshadow protein as a reserve substance in vegetative plant organs. As often applied to range and pasture management problems, studies of reserves usually can be limited to the carbohydrates.

There are various classifications of carbohydrates, and terminology differs somewhat between the physiologists and the chemists. The subject is treated briefly here. For more adequate information on reserve compounds and their characteristics, the investigator should refer to textbooks on plant physiology (Bonner and Galston 1952, Loomis and Shull 1937, Meyer and Anderson 1952, Miller 1938) and biochemistry (Bonner 1950, Pigman and Goepp 1948). Reviews of literature concerning carbohydrates which function as reserves may be found in several articles such as those by Eaton and Ergle (1948), Sullivan and Sprague (1943), and Weinmann (1948, 1952).

Carbohydrate compounds which have been found to be important as reserves—the so-called "available" carbohydrates—in the higher green plants are sugars, starch, and dextrins (glucosans), and inulin and fructosans. The more complex polysaccharides, such as hemicelluloses and pentosans, are apparently structural materials which probably cannot be utilized by the plant as reserves.

Three sugars are important as carbohydrate reserves; two monosaccharides ("simple" sugars): (1) glucose (dextrose or grape sugar) and (2) fructose (levulose or fruit sugar), and the disaccharide, (3) sucrose (saccarose or cane sugar). Glucose and fructose have a reducing action in alkaline solutions on certain metalic compounds (e.g. cupric hydroxide to cuprous oxide) and are commonly reported as "reducing sugars." The mixture of these two sugars, which results from the hydrolysis of sucrose, has also been termed "invert sugar." Sucrose, a "nonreducing" sugar, is not only a major storage substance, but also the principal form of carbohydrate translocation within the plant. Other sugars occur in various types of chemical combination in plants but are not considered important reserve substances.

Starch is the most abundant reserve carbohydrate of the plant world and is found under favorable conditions in most plant organs. Hydrolysis of starch yields glucose as the end product.

Dextrins, which are composed of short chains of glucose molecules, are transition products in the hydrolysis of starch and do not often accumulate to any extent in the plant. However, considerable amounts have been reported in early work (Graber 1931), perhaps because of the laboratory techniques employed, and some recent workers consider dextrins to be significant as reserve substances in those grasses that store large amounts of starch (Weinmann 1947, 1948, 1952, Weinmann and Reinhold 1946).

Fructosans and inulin are known to be important reserve substances in certain plants, but have been studied less intensively than other reserve carbohydrates. Inulin, a specific polysaccharide (polyfructoside) in which fructose is the repeating unit, might be considered comparable to starch, in which glucose is the repeating unit. Fructosans include a group of short-chain polysaccharides of fructose, having in common the property of cold water solubility (inulin is soluble in hot water). In a sense, fructosans are intermediate between the disaccharides on the one hand and the polysaccharides on the other. Inulin replaces starch as the reserve carbohydrate of some plants; some others store both inulin and starch. Although inulin does not occur in the more common forage species, it is particularly prominent in the composite family, and occurs also in a number of other families of dicotyledonous plants and the families *Liliaceae* and *Amaryllidaceae* of the monocotyledons. It has been found in relatively large amounts in *Helianthus, Parthenium, Solidago, Cichorium, Dahlia, Inula, Lappa, Iris,* and numerous others.

Fructosans occur widely in the grasses (Bonner 1950, Sullivan and Sprague 1943) and are important reserve substances in some species of grass, but not in other common forage plants such as legumes. Weinmann (1948, 1952) points out that grasses native to cool temperate climates tend to store fructosans but not starch, while grasses of warm regions tend to store starch but not fructosans. Only recently has the significance of fructosans been recognized, and, as pointed out by Sullivan and Sprague (1943), fructosans were probably reported as dextrins and starch in much of the early work on grasses. Also, a large proportion of the fructosans present may have been lost through using methods of hydrolysis suitable for the breakdown of dextrins and starch but resulting in the partial destruction of fructose (Weinmann 1952).

Procedures for Chemical Analysis

In the chemical determinations of reserve substances, the standard methods recognized by the Association of Official Agricultural Chemists (1950) are usually recommended and used. Also recommended is "Modern Methods of Plant Analysis" by Paech and Tracey (1955-56).

The main problem in plant chemistry is in separating the wanted constituent from interfering substances. Once that is accomplished, the standard chemical procedures give satisfactory results. Experienced biochemists recognize that analytical procedures must be "tailored" to fit the specific type of plant material being studied, as well as the equipment available. Consequently, innumerable variations in procedures are reported in the literature.

Based on extensive experience at the U.S. Regional Pasture Research Laboratory, State College, Pennsylvania, Sullivan (1951) has prepared a succinct guide to the analysis of carbohydrates in forage plants. An investigator will find this guide helpful in selecting methods suitable for his circumstances.

In selecting appropriate methods, the types of carbohydrate reserves involved must first be ascertained, and methods chosen which will give reliable results for all reserve substances present. The same procedures may not apply to all grasses because some store fructosans and others starch. Therefore, preliminary trials will be necessary to work out details of analysis for little-known species.

The purpose and nature of the study will also influence the relative efficiency of analytical methods. In case the investigator is primarily interested in the total available carbohydrates, rather than the individual compounds, a recent method (Sullivan 1951, Weinmann 1947) for directly determining this total has been used successfully with grasses and legumes (Lindahl *et al.* 1949, Smith 1950, Tesar and Ahlgren 1950).

Places of Storage

Consideration of food reserves should not be restricted to underground organs alone. Storage occurs, temporarily at least, in all portions of the plant (Bonner and Galston 1952). Most pertinent to research related to forage plants or range management are those portions which remain unutilized or live over the winter: the roots, rhizomes, stolons, and crowns or stem bases (stubble) of herbaceous species, and also the aerial parts of shrubs. In grasses, and perhaps other herbaceous plants, reserve carbohydrates tend to accumulate in the basal portions of the aerial parts even during vegetative growth stages. Intensive studies on perennial ryegrass and orchardgrass have shown that greatest concentrations of soluble carbohydrates occur in the lower parts of the leaf blades and sheaths (Sullivan and Sprague 1943). It is appropriate, therefore, that investigations of reserves of forage species are usually limited to basal aerial portions and underground parts.

Higher concentrations (percentages) or reserve substances usually are found in rhizomes, stolons, or the basal portions of aerial parts than in the roots. However, the total amount is often greatest in the roots because of their volume.

For these and other reasons, procedures should be adopted which not only will insure consistency in portions of the plant samples, but also provide a measure of the amounts of the different plant parts involved.

Hints on Field Procedures

Field procedures to be followed in studies of reserves will necessarily be dictated by the nature of the problem or the plants under consideration and the specific information desired. However, a few guides gleaned from the literature or from experience may be helpful to those contemplating such studies for the first time.

Advanced thorough consideration of the kind and amount of data required to meet the specific objectives of the study, together with detailed plans for collecting, analyzing, and interpreting the data, will do much toward insuring positive results and also toward saving time, effort, and money. Procedures appropriate and necessary for studying the basic physiological aspects of reserve substances may be unnecessarily refined in studies of an applied nature, such as investigating reserve levels in relation to season or management practices. Sampling requirements will also vary widely. Whereas frequent sampling is necessary to establish seasonal trends and critical levels of reserves, one sampling at an appropriate period may be adequate in evaluating different management practices. The use of uniform potted plants is often more efficient than working with field-grown material.

Preliminary tests not only should check field and laboratory techniques but also provide an idea of the amount of variability to be expected and the possibilities for reducing it. Care in segregating different plant parts and living and dead material, and in removing foreign matter will give greater consistency in results.

To permit adequate interpretation, study design must provide an estimate of experimental error. As a result of compositing field samples before chemical analysis and lack of replication, investigators often have not been able to distinguish between biological variation and real trends or treatment effects. Consequently, interpretations have sometimes been difficult, weak, and erroneous.

To stop enzymatic action and chemical changes, the plant samples should be killed immediately after harvesting and preserved until analysis can be completed. Handling sampled material in moderately low temperatures to reduce the rate of chemical reaction is desirable, but speed is ordinarily more important. Rapid drying in circulating air or in a vacuum oven is usually the simplest procedure if suitable equipment is available. Since moderate temperatures will permit enzymatic changes, and high temperatures in air will promote oxidation and caramelization, intermediate temperatures of 60 to 80° C are safest (Sullivan 1951). Raising the internal temperature of the tissue to 80° C or higher within seconds after starting the killing process is desirable—and imperative for accurate evaluation of the various carbohydrate fractions (Loomis and Shull 1937).

Such quick killing can readily be achieved by autoclaving for 5 minutes at 5 pounds pressure, or by a blast of air at 100-120° C for a few minutes, followed by drying at 50-70° C. For alcohol preservation, a standard procedure is to immerse the fresh tissue in sufficient boiling 95 per cent alcohol (roughly 4 cc per gram of tissue) to obtain a final concentration of 70-80 per cent after dilution by the water in the sample. A small amount of calcium carbonate may be added to neutralize plant acidity if it is important to prevent any change from one form of carbohydrate to another by acid hydrolysis.

Mason jars with glass or enameled-metal lids (not zinc) are convenient containers for alcohol-preserved samples. Dried material can be stored for a reasonable time in paper bags before grinding. For finely ground material, airtight containers are necessary to prevent excessive absorption of hygroscopic moisture, chemical changes, or spoilage from fungus growth in humid climates.

Samples should be as free as possible of soil and dead or extraneous plant material. Fresh material can be washed in water and roots scrubbed thoroughly with a brush, then blotted or sponged dry with soft cloths before being weighed or put into alcohol. Surface moisture is usually a less serious error in the green weight than is soil material in the dry weight. Aftermath plant material will, of course, markedly alter the percentages of chemical content in the sample and confuse the interpretation of results. Such material should always be removed and, if pertinent, weighed separately.

Different storage organs, such as roots and rhizomes, should be sampled separately. Also, a measure of the total amount of the various plant parts (roots, rhizomes, herbage) is necessary for a full evaluation of total food storage in certain types of studies.

Appropriate sample size will depend upon the uniformity of the plant materials, the chemical determinations to be made, and the methods employed. Ordinarily, 25- to 30-gram samples of airdry material will provide enough material for chemical analyses.

Complete records of plan development should be kept and include rate and stage of growth, pertinent climatic factors such as temperature and moisture conditions, time and procedures of sampling, and other measure-able or observable conditions that might affect the physiology of the plants or the composition of the samples. Such records are helpful and often essential for adequate interpretation of results.

Application and Interpretation of Data on Food Reserves

Data on food reserves have been used most widely in the past to support and explain effects of various management practices, such as herbage yield at various seasons and intensities of grazing. More recently, they have also been used as a primary basis for developing and evaluating management requirements of range and cultivated forage plants. For the latter purpose, studies of reserves offer a direct fundamental approach which can be quicker, more efficient, and often less expensive than the usual empirical methods. For example, reserve levels and trends, which can often be established in a single year, provide perhaps the best indication of the most and least appropriate times for grazing or harvesting. Also, effects of management practices involving defoliation can often be detected much earlier through food reserves than through herbage yields or other secondary responses. Reserve levels should offer an objective, quantitative measure of plant vigor.

Because carbohydrate reserves readily change from one form to another in the plant, the total amount is more pertinent and meaningful than the amount of the separate components for interpreting studies of an applied nature. Commonly all fractions, including starch, are reported as equivalents of the sugars, glucose (dextrose) or sucrose. If so, the fractions are directly additive—the total representing equivalents of sugar. The relationship for converting between sugar and starch equivalents is: starch $\div$ 0.9 $=$ glucose.

Total carbohydrate reserves represent the net difference between the gain through photosynthesis and the loss through respiration and growth. Consequently all factors which influence any of these processes should be considered when interpreting fluctuations in carbohydrate levels. The rate of photosynthesis is predominantly governed by the effective leaf area. The general relation between photosynthetic area and the accumulation or depletion of reserves is well known, but quantitative relations have yet to be established. It is definite, however, that the leaf area necessary to balance the drain of growth and respiration will vary with environmental factors influencing these latter processes. It will also vary among species.

Respiration apparently utilizes the bulk of the products of photosynthesis. For perennial ryegrass plants that were clipped and placed in darkness, weight loss from the stubble and roots was five times the weight of new growth produced (Sullivan and Sprague 1943). Even in light, weight loss from stubble and roots was 74 per cent greater than the weight of new growth 40 days after clipping (Sullivan and Sprague 1949). Such results indicate that the major amount of carbohydrate reserves disappearing after defoliation enters into the process of respiration (Sullivan and Sprague 1953).

Although rapid respiration necessarily accompanies rapid growth, respiration also is a continuing process and the rate appears to be even more closely correlated with temperature than with growth rate. At high temperatures, utilization of reserves by respiration is rapid (Sullivan and Sprague 1949). Consequently, abundant reserves increase a plant's tolerance to high temperatures (Julander 1945). However, there is great variation among species regarding optimum and critical temperature in relation to food shortage and survival.

The relation of growth to food reserves and the cyclic fluctuations initiated by spring growth or regrowth following defoliation are well known. Utilization of reserves is increased by conditions that stimulate rapid growth: favorable moisture, warm temperature, high soil nitrogen, and, in some instances, defoliation. Conversely, conditions which restrict growth tend to limit the rate of depletion and favor food storage. For example, limited moisture has been found to increase the concentration of reserves in grasses (Julander 1945), alfalfa (Granfield 1943), cotton (Eaton and Ergle 1948) and other plants. On the other hand, severe moisture stress depletes carbohydrate reserves in such plants as beans and tomatoes (Woodhams and Kozlowski 1954).

Many investigators have found that abundant nitrogen and moisture hasten exhaustion of food reserves under repeated harvesting, but under protection the same conditions tend to increase the total reserves by increasing the total amount of storage tissue. The foregoing will suffice to suggest interrelations of environmental factors that may explain or account for seemingly confusing data. Measurements or records of such environmental variables can be valuable for interpretation of experimental results.

It is important to recognize that the total weight of storage organs fluctuates as reserves are withdrawn or stored, and this necessarily changes the percentages of components other than reserves. Growth of underground organs is also markedly influenced by the level of food reserves and, conversely, the total amount of reserves is necessarily related to the total amount of underground organs. Therefore, evaluation of reserves on the basis of percentage composition alone is less informative than on the basis of absolute amount or weight.

Several investigators working with pasture species have found relatively small differences among experimental treatments at the end of the season on the basis of percentage of reserves, but pronounced differences in absolute amounts of reserves as a result of differences in total growth (Graber *et al.* 1927, Smith and Graber 1948, Sprague and Sullivan 1950, Tesar and Ahlgren 1950, Weinmann 1952).

Until more information is accumulated on critical, adequate, or optimum levels of reserves, results must necessarily be interpreted on a comparative basis. After winter dormancy or following defoliation, reserve levels characteristically exhibit a U-shaped curve when plotted against time as the abscissa.

However, maximum and minimum levels as well as rates of change vary with species, with initial levels of reserves, and with environmental factors mentioned previously.

At maximum levels of storage, reserves may comprise over 40 per cent of the roots or other storage organs in some forage plants, although maximums of 10-25 per cent are more common. Critical minimum levels have not been well defined. Several investigators have reported that seasonal new growth of native forage species reduced reserves to minimum concentrations amounting to 20-30 per cent of the maximum (McCarty 1938, McCarty and Price 1942, McIlvanie 1942). The degree of depletion of reserves by new growth of pasture plants has been shown to be related to the initial concentration at the time of cutting (Moran *et al.* 1953, Sprague and Sullivan 1950). No depletion was detectable in Ladino clover defoliated at an already low level of carbohydrate reserves (approximately 6 per cent of the stolons and roots). Available reserves of perennial ryegrass when placed in darkness have been reduced to 0.6 per cent in the stubble and 0.2 per cent in the roots (Sullivan and Sprague 1943).

The determination of adequate levels of reserves is perhaps of greatest importance in practical management. It is recognized that any degree of herbage utilization will reduce food storage to some extent in most species, but the levels to which reserves can be allowed to fall during various seasons or periods of growth without seriously damaging vigor and yield have not been well established.

Methods of Studying Roots

Root Excavations and Descriptions of Root Systems

The following nine methods involve the description of natural root systems *in situ* or their removal from the soil intact. Some variations of these methods can be found, the modification depending upon the type of plant or community, soil type, topography, and resources at hand. Where a large number of roots are to be studied in a given area it may be practical to employ mechanized ditch-digging equipment to open the trenches before using the more meticulous ice pick and hand trowel.

Trench Tracing Method

This method has great variations in its application, depending upon type of plant roots (tap or fibrous), age of plants (mature or seedlings), and type of soil (Weaver 1926, Albertson 1937).

Before digging the trench, a careful survey of plants should be made to find a typical site in respect to topography and soil type. Also proper spacing of plants is desired. When the site is selected, stakes are set and a string stretched to mark one edge of the trench. This trench should be at least 30 inches wide and as long and deep as required.

It is desirable, but not always possible, to have all the plants located on one side of the trench. Soil can then be thrown to the opposite side to avoid damage to the plants to be studied.

When the trench is dug, a flat spade is used to provide a vertical trench wall where root studies are to be made. With the trench completed, ice picks and sharp trowels and spades are used to remove the soil from roots, beginning at the top and working in a perpendicular rather than a horizontal direction. As the roots are exposed, they are drawn to scale on paper with type of growth, diameter, and direction indicated (figure 1).

Root Photography in situ.

Spraying roots with paint from pressurized cans has been effective in the photography of grass, brush, and tree roots *in situ* (Haas and Rogler 1953, Schultz and Biswell 1955). The first step is to make an excavation on one side of the plant. A portion of the root system is then isolated from the surrounding soil with an ice pick. Enough roots should remain imbedded in the soil to hold the plant top in its normal, upright position. The roots are then

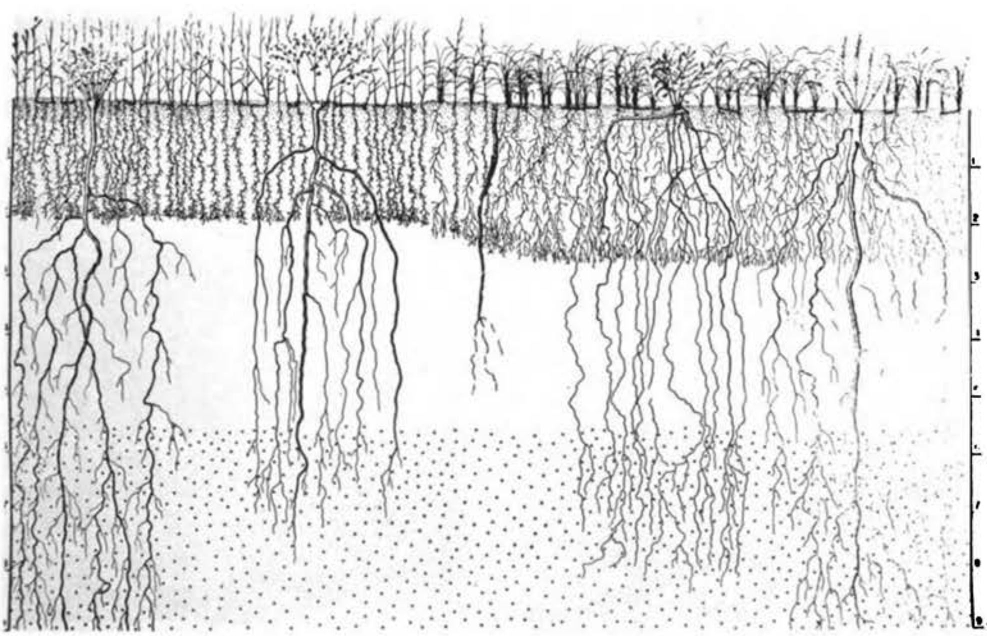

FIGURE 1. Bisect of prairie plants showing root habits of forbs and grasses. *(Courtesy J. E. Weaver)*

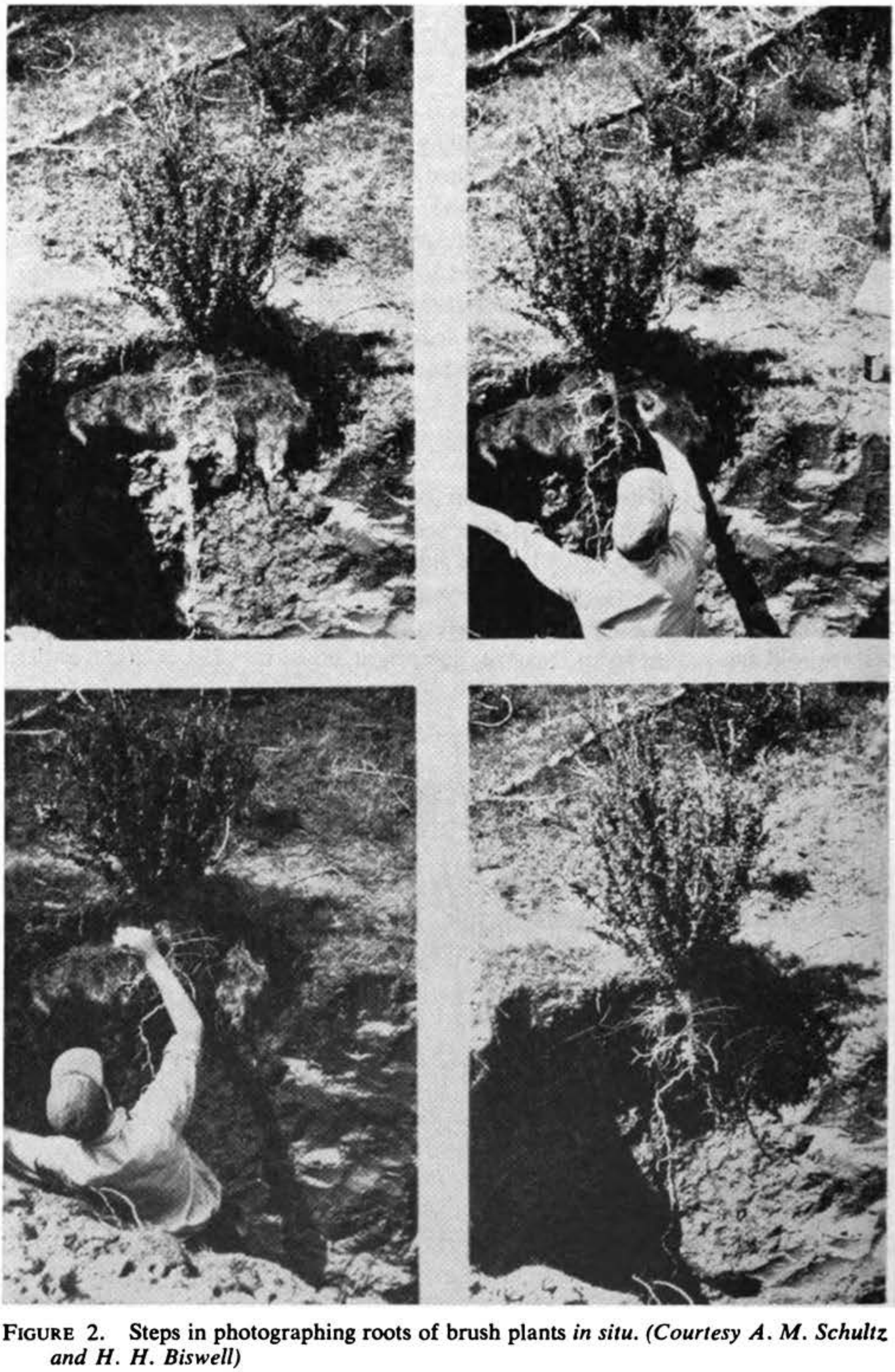

FIGURE 2. Steps in photographing roots of brush plants *in situ*. *(Courtesy A. M. Schultz and H. H. Biswell)*

sprayed with paint. Both aluminum paint and yellow enamel are satisfactory for black and white photography. Other colors can be used effectively for kodachrome. The paint which has adhered to the soil behind the exposed roots is removed by chipping off a thin layer of soil with an ice pick. Thus a dark background is restored giving the needed contrast for photographs.

Trench Washing Method

This method is similar to the trench tracing method except that water under pressure is employed to aid in softening and removing the soil (Stoechler and Kluender 1938, Tharp and Muller 1940, Upchurch and Lovvorn 1951).

The ice pick may be effectively used to supplement action of water in exposing roots. Using water will make it possible to separate soil from the finer roots while the roots remain in a fairly natural position until drawn on scaled paper. The two methods described above are qualitative rather than quantitative. In fact, it is usually impossible to make drawings of roots in exactly the same number per unit area (square foot, for example) as actually found in the soil. Drawings, however, should show such factors as relative abundance, diameter, and type and extent of growth.

Hydraulic Method

For the hydraulic method, excavation sites must be located along road cuts or faces of deep gullies, accessible to tank trucks equipped with power pumps. The pumps are fitted with two types of nozzles—a high-pressure single stream type and a fine spray type. The bulk of the soil or parent material around the plant being studied is removed with the high-pressure nozzle. The fine spray is then used to wash the soil away from the smaller roots (Hellmers *et al.* 1955). Caution must be used with high-pressure nozzles or the delicate root systems will be torn apart.

Soil Prism Washing Method

In this method a trench is dug entirely around a prism of soil one foot thick and as long and deep as is required to include full root depth of plants studied (Weaver 1926). Wire netting is then stretched securely over the sides and ends of the prism. Next, sharpened wires or thin rods are driven through the prism of soil in parallel rows along the meshes of netting.

The loose surface soil is then removed, with the plant crowns left exposed. One technique is to replace the surface soil with plaster of Paris. This holds the plants in position during the washing process. Soil around the roots is washed away by water from a force pump or allowed to soak away in a canal or small streambed with gentle agitation by finger tips. Washing should proceed from top of the plants downward. In washing, extreme care should be given to preserve as many small roots as possible.

The cross-wires help to hold roots in natural position. This method, however, is not designed to remove all roots of any plant but only those in the prism studied.

Soil-Block Washing Method

This method is sometimes used when the entire root system of a plant is being studied (Pavlychenko 1937). Plants grown in the greenhouse or under field conditions are satisfactorily studied in this manner. If gradual progress in root development is to be followed, soil blocks of various sizes should be used. For the five-day stage, soil blocks 14 × 14 × 14 inches are usually sufficiently large. For 20- 30-day plants, blocks 24 × 24 × 32 inches are satisfactory. When root systems of mature plants are studied the blocks should be considerably larger, often 40 × 40 × 70 inches for three-year plants. Extent of roots will depend upon species, age, and type of soil in which the plants are growing.

When the block is marked out, a trench is dug around it to the desired depth, then the block is encased by a wooden frame of sufficient strength to support the weight of soil. The block is hoisted from the pit and hauled to a tank of water. After soaking for several hours, time depending upon size of block and soil type, a spray of water is applied slowly and carefully to wash the soil from the roots.

When all soil is removed from the roots, place the entire plant in a tank of water large enough for the roots and tops to be spread in natural position for analysis. The tank should be painted black on the inside and a scale with one-inch and five-inch divisions marked along one edge of the bottom. Flood lights may be used to increase illumination. This arrangement makes it possible to float the plant in water for the most efficient analysis.

Modifications of this method are in common use. Half square meters of sod four inches deep may be employed effectively in determining amount of plant material (roots and rhizomes) in the upper four inches of various kinds of prairie sod (Shively and Weaver 1939).

Steel Cylinder Method

Galvanized iron cylinders have many uses and modifications in application. They may be used for studies pertaining to soil-root relations in undisturbed sod, filled with greenhouse soil, seeded to various plants and later used for studies on root development in relation to such factors as clipping rate, vigor due to past use, type of soil, and amount of soil water (Weaver 1938). Metal cylinders (phytometers) for this work would vary considerably in size depending upon the results which the scientific investigator desired.

For example, galvanized cans 6 × 20 inches could be used to study root growth on sods of prairie grasses as it relates to degree of utilization during past years. Similar cylinders may be used to determine root growth of various species of seedlings. Studies may be made by rolling sheets of galvanized iron into cylinders held tightly in position by iron bands. The cylinders are often placed in tin containers, such as one-gallon cans. When the growing period is completed, the cylinder is lifted from the can, the bands removed, and the galvanized sheet unrolled to permit washing of soil from roots. Roots then may be floated in water while drawings and calculations are made, after which they may be removed from the tops for drying and weighing.

Soil Core Method

Cores of grassland sod are made by driving cylinders 4 × 6 inches into the soil and then digging around them sufficiently for their removal. When removed the cores furnish such information as number of roots that penetrate beyond six inches in the circle and volume of roots in the cylinder. These cores can be taken quite rapidly, allowing many samples to be made over a relatively short period of time. This method has been effectively used in determining certain phases of root growth in relation to drought and intensity of grazing (Weaver and Albertson 1943). Soil cores, four inches or less in diameter, can be taken by forcing a boring tube several feet into the soil. Cores thus obtained can be used to determine behavior of roots in relation to such soil factors as texture, compactness, or intensity of clipping of vegetation (Ruby and Young 1953).

The core method is used extensively at the Grassland Research Institute in England with fertility experiments (Williams and Baker 1957). In these experiments no attempt is made to separate roots from other macro-organic matter—rhizomes and stem bases. The initial disposal of clay, silt, and fine sand has been mechanized with a root washing machine. This consists of a 60-mesh sieve in a rotating funnel and under a spray of water. After washing in this manner, the sample is dried, weighed, and ignited. The plant ash is dissolved by sulfuric acid, leaving the residual mineral ash which is subtracted from the sample dry weight.

One important advantage of the core method is that the small holes left in the sod have little effect on grass growth in small experimental plots, a large part of which would be disturbed with excavations.

Monolith Method

The monolith was designed to provide for more detailed study of plant roots than may be accomplished in some of the other methods. For example, detailed information may be obtained on such factors as relation of main root growth to growth of branches, and root growth of one species of plant in respect to growth of other plants with which the species is associated. There are many other advantages to the monolith method. For instance, roots freed from soil can easily be mounted and placed on exhibit or they may be cut at various depths and root weight determined.

In this method a trench is dug three feet wide alongside the plants included in the study. The wall of the trench is made smooth and plumb. Then a shallow wooden box 12 inches wide, 3 inches deep, and the desired length with one end open, is placed against the side of the trench (open end of box at the top) and is tapped vigorously with a sledge hammer. With the impression of the box made in the side of the trench, the monolith is marked out and three inches of soil cut away. The box is then fitted tightly over the protruding block. After the box is carefully braced, the soil behind the box and on the side of the trench is cut away until the box can be lifted from the trench (figure 3). Soil on the open side of the box is now trimmed to exactly 3 inches deep. The monolith of soil can be transported to the laboratory.

Here repeated soaking and washing with a spray will eventually remove the soil from the roots. The roots are transferred to a painted board where they are prepared for mounting. Blotters can be used to remove excess water and then the mounting board covered with black felt is placed, face downward, over the roots. The painted board and the mounting board, held tightly together, are now inverted and the painted board removed leaving the roots spread properly over the top of the black felt (figure 4). The roots are now ready to photograph. They may be mounted to preserve, or cut as desired to obtain weights of roots at various levels (Weaver and Darland 1949).

Where the relation between root behavior and soil structure is to be demonstrated, permanent soil monoliths may be prepared by using vinyl resin and cellulose acetate to impregnate the profile and to keep the monolith stuck to a supporting board (Smith *et al.* 1952).

Rate of Growth and Longevity of Roots

In studying the growth of individual roots, a number of methods may be used. These involve the marking of individual roots and later observing their growth.

Field-Excavation Method

This method exposes representative new main roots for observation. The roots remain in their natural state, and the rest of the root system is not disturbed. With a minimum of exposure, small apical sections of the roots

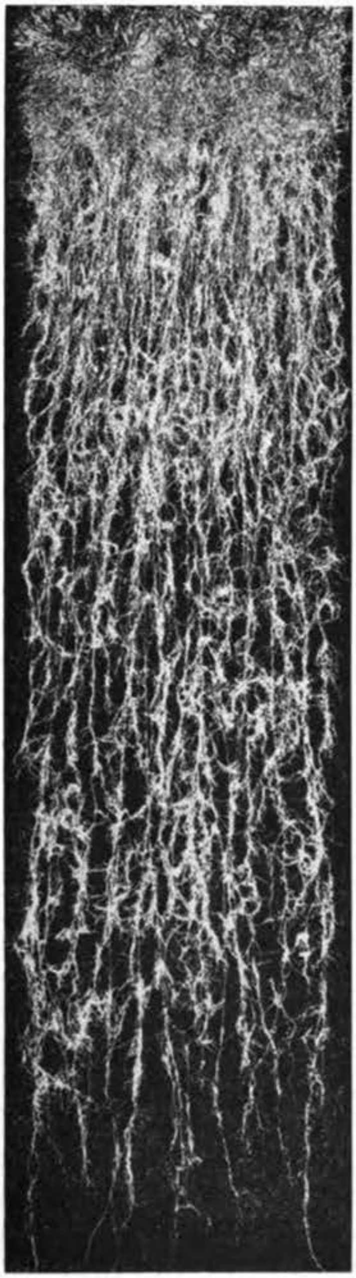

FIGURE 3. (Left) Monolith of soil showing roots partially washed out. *(Courtesy J. E. Weaver)*

FIGURE 4. (Right) Root system washed from a soil monolith and arranged in natural position on black felt for photographing. *(Courtesy J. E. Weaver)*

are blackened with moist carbon black and wrapped immediately in wet sphagnum. This is covered with wet burlap and then soil to ground level. Subsequent examinations to determine growth are made by lifting the burlap and gently removing the sphagnum (Crider 1955).

Root Blacking Method

In constrast to the field-excavation method, the root blacking method exposes all growing roots of the plant for observation. It consists of growing the plants in clay pots and eventually removing the soil core from the pots and painting the roots. At each subsequent examination the white apical root growth can be seen and measured. Alternate painting with carbon black and examining the roots at definite intervals is an effective way to study root growth. If the soil is liberally mixed with sphagnum, exposure and repotting are facilitated (Crider 1955).

Glass-Box Method

Plants are grown in narrow, deep wooden containers, the fronts of which are fitted with windows of heavy plate glass. A convenient size for the boxes is 2.5 inches wide, 24 inches long, and 24 inches deep. Small holes in the bottom of the boxes and about an inch of pebbles provide drainage. The boxes are filled to an inch from the top with screened, uniformly mixed, fine sandy loam soil. The grasses or forbs are seeded (or seedlings may be transplanted) into the boxes. During growth, the windows should be covered with tar paper or wooden panels. When kept tilted forward at an angle of 30 degrees, most of the root will grow along the glass surface. Day by day record of root elongation is made directly on the glass by marking apexes with a red grease pencil (figure 5) (Crider 1955).

Banding Method

The life span of individual roots can be determined by banding while some of the roots are young (Weaver and Zink 1945, 1946). This method is effective for plants grown in containers where the roots can later be washed out easily. However, under field conditions the technique is not satisfactory since natural conditions are disturbed when the roots are first banded.

Grasses are prepared for banding by washing away the sand or loam from the roots with a spray of water. Bands 8-10 mm long and 2-3 mm wide are cut from material obtained from new, unpainted toothpaste or ointment tubes. The thickness of this material is only about 0.12 mm, so it is pliable, yet durable. Banding is done on damp or rainy days, and over a wet floor.

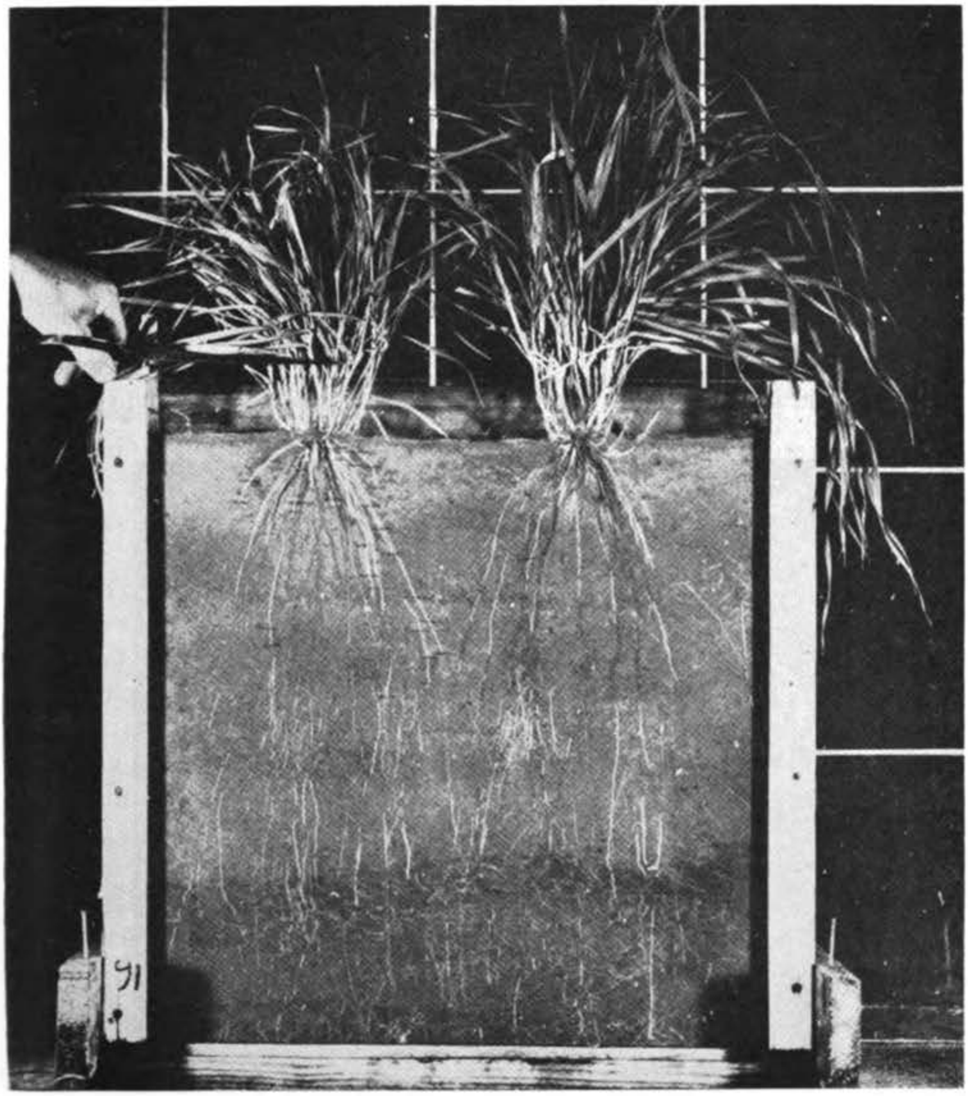

FIGURE 5. Roots showing through glass window, marked for measuring growth increment. *(Courtesy F. J. Crider)*

Roots must be moistened frequently by spraying with a bulb-type hand sprayer. Grasses are not injured by exposure to this treatment.

The tin is formed into an open band by rolling it into a cylinder around the small end of a pipette, then fitting it over the root. With thumb and forefinger, it is then gently, but tightly, rolled until it fits closely around the root (figure 6). The band can partly unroll itself when the root grows in diameter.

When the banding procedure is finished, the roots are again covered with soil and immediately watered.

For examination after an interval of growth, the entire banded (upper) portion of the root system is removed. Each banded root is examined to determine whether it is still alive. Living roots generally are yellowish white or a brownish color. Their tensile strength is good and they are not brittle. The same test is not valid for each species—this must be learned by experience. Sometimes the root will have decayed so that the band lies free in the soil mass. The proportion of living to dead roots should be noted. If desired, part of the system may be exposed for examination at one time and the remainder saved for another date. Replicated plants can be used to achieve the same purpose.

Banding is unsatisfactory for species with fine roots, such as Kentucky bluegrass and lovegrass, or where the number of roots is great and the roots

FIGURE 6. Roots banded with small strips of tin cut from tooth paste tubes. *(Courtesy J. E. Weaver)*

are compact, exemplified by smooth brome and crested wheatgrass. With others, such as switch grass and big bluestem, the technique is relatively easy. It would be well for a beginner to practice with these species.

Tracer Method

This is an "indirect" method which depends on the uptake of certain chemical elements or compounds from the soil and the subsequent detection of those materials in the plant tissue. Dyes, rare elements, or isotopes of common elements can be used.

Some of the rarer elements not normally found in soils are lithium and rubidium. Lithium, for example, is easily absorbed and accumulated by plants, much like sodium and potassium. It is not toxic to plant tissues so concentration used is of little consequence. However, even dilute amounts can be detected by a spectroscope. No other element gives a line at 6709 angstroms. The method has been used to measure lateral growth of corn roots (Sayre and Morris 1940) but as far as is known, not for range grasses or depth of rooting studies. Lithium chloride, the salt most convenient to use, is immobile in the soil so it can easily be adapted for depth studies.

Radioactive tracers are ideal for such root studies. They are readily detectable in all organs of the plant, can be located where probability of entering plant is high, and they remain near the point of placement in the soil throughout the period of study. One of the more commonly used is an isotope of phosphorus, P^{32}. The technique will be described using P^{32} as the example.

The isotope is applied to the soil in a statistically designed pattern of horizontal and vertical distribution. The concentration should not be so high as to change the level of soil phosphorus by the P^{32} carrier. Ordinarily a solution of 10 to 50 microcuries per millilitre is sufficient. Where the soil phosphorus level is already high detectability of P^{32} will be reduced so the concentrations should be higher, or perhaps another isotope used.

The specific activity of the plant (as determined by Geiger counter or survey meter is a measure of the P^{32} uptake from a given locus in the soil. The specific activity of P in the soil changes as some of the P^{32} is withdrawn and also with time. Normally, 80-90 per cent of isotopic exchange occurs during the first 24 hours after placement. After a period of 5-10 days there is no longer any appreciable change, other than that due to withdrawal. In order to see at what dates roots have appeared in given zones, information on the change in specific activity of a system in which part of the P^{32} is withdrawn with a subsequent redistribution of the remaining P^{32} should be obtained.

At a given depth there is not much variation in specific activity but in different soil horizons the variation will be great since vertical distribution of soil phosphorus varies. The more soil phosphorus, the less specific activity.

This is equalized by the greater absorption from the loci having the higher amounts of phosphorus. Thus, the activity of the plant is the product of the specific activity of the test locus and the total amount of P withdrawn from that locus. The contributions made by the P^{32} of the different zones of placement can then be interpreted as representing proportionate amounts of root growth in those zones at a given time. An illustration of the technique is given by Hall *et al.* (1953) for corn, cotton, peanuts, and tobacco and by Burton *et al.* (1954) for a group of eight important southern range and pasture grasses.

Soil-Moisture Measurement Method

Root penetration can be determined by measuring soil moisture at intervals through the soil profile (Veihmeyer and Hendrickson 1948). It is assumed that decrease in soil moisture below field capacity is largely due to absorption by roots and ultimate transpiration. This is true except in the top few inches where evaporation may take place. By inference, any horizon or lateral zone where a measurable change (decrease) in soil water occurs indicates extension of plant roots to that zone. This method was developed and used in California where there is little or no rain from May to October.

Soil moisture measurements can be made in several ways. The oldest method takes the difference between fresh soil samples and their oven-dry weights; the moisture is expressed as a percentage of the dry weight. This method consists of sampling horizons with a soil tube or auger, or from an open trench.

Continuous methods involve the use of electrical-conductance blocks (Bouyoucos and Mick 1940) and fiber-glass units (Colman 1947). The readings on the resistance meters must be calibrated with actual moisture percentages determined by the older method. Where soils are of similar texture and organic matter content, it is probable that no recalibration is necessary between soil types. Various methods of soil-moisture measurement are thoroughly discussed by Lull and Reinhart (1955).

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Chapter 5

Methods of Measuring Forage Utilization

Introduction

FORAGE utilization is defined as the degree to which animals have removed the current growth of herbage and is expressed in percentage of growth within reach of the grazing animals (Soc. Amer. Foresters 1950). This concept may be applied to a single plant, group of plants, or to the range forage as a whole. Cook and Stoddart (1953) suggested that since utilization refers to the percentage of current growth removed, a better term might be percentage utilization. In this chapter utilization and percentage utilization are used interchangeably.

Correct utilization of forage is one of the most important items in the whole field of range management. A forage cover can be maintained in vigorous healthy condition only so long as it is utilized to such extent that it will regrow and reproduce. Consequently, range technicians have given much attention to utilization and its measurement.

Numerous methods have been developed. Some are more rapid or may be more detailed and accurate than others. Also, for certain objectives and conditions some methods are more suitable than others. The method adopted by a given research worker will be that which best fits the purpose of his study, the man-power available, and the kind of vegetation. More than likely he will find that none of the methods in this chapter are wholly satisfactory and will proceed to develop a method suitable for his own research. The literature on methods of measuring utilization has been reviewed by Pechanec and Pickford (1937a), Dasmann (1948), and Heady (1949).

In addition to working on techniques to measure utilization accurately, the technician has directed much attention toward learning what constitutes proper utilization—i.e., developing utilization standards for each of the important forage plants and types and for grazing conditions. In developing these standards the investigator has first studied the life histories and requirements of individual plants. Later he has studied the effects and interactions of different intensities, frequencies, and grazing seasons on the health and vigor of the plants, changes in the plant community, soil compaction, runoff and erosion, animal gains, range condition and trend, and other factors related to grazing. Many of the studies have involved clipping the plants while actual grazing by animals has been used in others. Because of the great variability in plants and the many conditions under which they grow, it has been difficult to develop exact standards. This has led to some question about the practical aspects of utilization measurements.

Another phase of research has been directed toward developing more satisfactory methods to check percentage utilization for such management practices as setting and adjusting stocking rates and in following trend in range condition. While administrators and ranchers are interested in accurate methods, they also want them to be easy and rapid (Campbell 1937).

METHODS

Ocular Estimate-by-plot

This is an estimate of the percentage of herbage removed in terms of weight. These estimates are made on plots small enough that the entire plot is clearly visible from one point. A worker first spends at least one day checking his estimates against actual weights. Plots are clipped to simulate grazing. Then an estimate of the percentage weight removal is made and the remaining stubble clipped. Both clippings are weighed, and the actual percentage weight removal is computed.

In field practice, an investigator tests the accuracy of his estimates each day by clipping and weighing the herbage on at least 10 plots.

Usually circular plots with an area of 25 to 100 square feet are located at random. In studying utilization of key species on a homogeneous key area, 30 plots generally give sufficiently precise results (Reid and Pickford 1941). This method is suitable for grasses, forbs, and shrubs.

The advantages of this method are listed by Pechanec and Pickford (1937) as "(1) observations are confined to a small area, which makes possible more accurate decision, (2) errors in personal judgment on individual plots frequently tend to be compensating, (3) data thus collected can be subjected to statistical analysis, and (4) data collected from these randomized samples are valuable in studying the distribution of grazing on range areas." Clark (1945) recommended this method as sufficiently rapid and accurate for general field use.

The chief disadvantage is that estimates are used rather than objective measures. These estimates are subject to personal error among individuals and for the same individual at different times. Much emphasis should be placed on training and checking. In addition, the error of estimation should be determined by statistical methods based upon a known number of clipped plots compared to estimates other than those used for checking or adjusting. Error of estimation should be determined after all plots have been estimated and then clipped, since adjustments for error after each plot are not permissible in calculating the actual error of estimation.

Ocular Estimate-by-average of Plants

This is based on estimates of weight removed from individual plants, instead of the entire forage as in the previous method. These estimates are then weighted and averaged by species to obtain plot ratings. Although slightly less rapid than the ocular estimate-by-plot there is less personal error since each observation is confined to a single plant. Its high correlation with actual weight removed adapts it to accurate range studies.

Actual Weight or Difference

Plots protected by cages or other suitable exclosure are clipped to compare with similar plots on adjacent grazed areas. The difference in weight is the percentage of forage consumed.

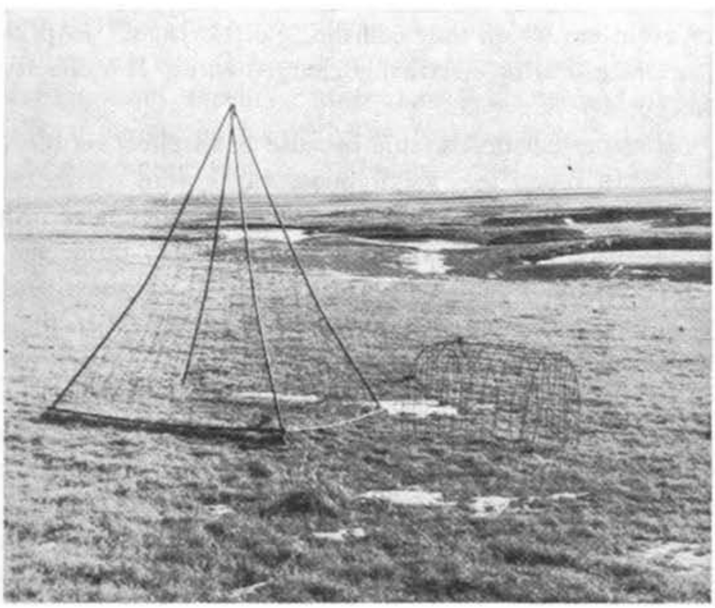

FIGURE 1. Two types of portable exclosures. Tepee-shaped exclosure (left), made of steel rod and woven wire; is not easily disturbed by livestock and protects an area one meter square. Quonset-shaped exclosure (right), made entirely of woven wire, protects one or two square-foot quadrats. *(Courtesy G. W. Tomanek)*

Two similar quadrats are selected on the basis of composition, growth, and utilization. These are within 20 feet of each other but never closer than 10. One of these may be placed randomly and the second is selected to pair with it (Klingman *et al.* 1943). After the two quadrats are placed a coin is tossed to indicate which unit to cage. At the end of each sampling period new areas are selected as nearly as possible like those to be harvested. This method measures both utilization and yield.

This method with slight variations has been widely used on ranges and in pastures, (Darland and Weaver 1945, Weaver and Bruner 1948, Riegel *et al.* 1950, Fuelleman and Burlison 1939, Hodgson *et al.* 1942, Boyd 1949, Nevens 1945, Linehan 1952, Davies *et al.* 1950, Bentley and Talbot 1951). Instead of exclosing areas, Everson (1951) randomly clipped grazed and ungrazed spots in a pasture. He found this unsatisfactory from the standpoint of time and labor because large numbers of clipped spots were needed for acceptable accuracy.

Size of quadrats may vary from one square foot to several meters. The smaller plots often are more desirable, since they make it easier to employ sufficient samples for statistical treatment. On the other hand, large sample areas have less border effect from the cages.

Various types of portable exclosures have been used (Brown 1954, Fenley 1951). Some are quonset-shaped, some rectangular, and others shaped like a tepee (figure 1). Prendergast and Brady (1955) developed a new type of exclosure which they call the "electric cage." In principle, it is a rectangular frame bearing electrically charged wires. It is effective for both cattle and sheep.

A cage is somewhat undesirable because of its effect on the vegetation. Cowlishaw (1951) found that yields under cages were significantly greater than from unprotected areas. He attributed these differences principally to the reduction of wind velocity and increase of humidity inside the cages. In work on the California annual type, Heady (1957) obtained similar results during the early part of the growing season. However, when the plants had matured differences in growth in and out of cages had disappeared. Daubenmire (1940) has pointed out that since the object of exclosure studies is the control of a single factor of plant environment, the utmost attention should be directed to the problem of minimizing the effect of the barrier upon wind movement, insolation, and precipitation. He recommends that the exclosure be the largest size and lowest and most open structure possible for the purpose of the study.

A common objection is that differences in growth on the protected and grazed areas may distort utilization. The greater the period of time between caging and clipping the larger this becomes.

Weight Before and After Grazing

Difference in plant unit weight before and after grazing forms the basis for this system. It is best adapted to forage grazed for short periods where regrowth is not a factor. For example, it can be used where a band of sheep passes over an area and the forage is grazed within a few hours or a few days (Cassady 1941).

The method consists of collecting a given number of specific plant "units" before grazing and a similar number after grazing. The plant "unit" which is collected is an easily definable and recognizable portion of the individual plant. It varies with the species but may be a single stem or an entire plant. It must be large enough so as never to be entirely consumed since after-grazing units must be collected to determine what percent has been removed by the grazing animal. Therefore, utilization is based upon percent of the unit selected which in some cases may include more plant material than is actually represented in the current year's growth.

Reduction in Height

This is based on the premise that percentage of grass utilization is equal to the reduction in average leaf or stem height as a result of grazing (Pechanec and Pickford 1937). Following grazing, the difference in average heights of the plants on grazed and ungrazed areas is considered the removed portion and is used to calculate percentage utilization. Pechanec and Pickford (1937) pointed out that the mechanics of the method are imperfect since it involves the erroneous assumption that the volume of grasses varies directly with their height.

Stubble-Height-Class

This is based on the concept that intensity of grazing is reflected by a combination of grazed stubble heights and amount of ungrazed grass left on the ground at the end of the grazing season. Transects 50 feet long are adequate on ranges supporting a grass cover of 5 per cent or more, whereas ranges having less than 5 per cent of the area occupied by perennial grasses require a transect 100 feet long (Canfield 1944). Plants are recorded in stubble-height classes. The following stubble-height classes were found adequate for southern Arizona mixed grama grass ranges. However, the class intervals given here may or may not be the most suitable for areas supporting other species. When tall, coarse-stemmed grasses are the principal forage plants, it may be necessary to have more or larger class intervals.

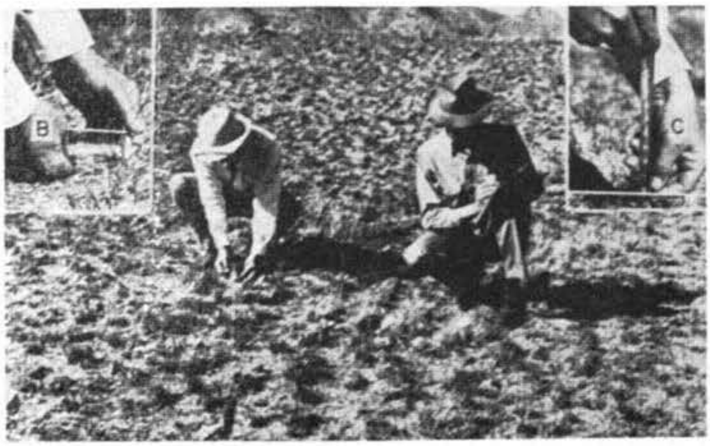

FIGURE 2. Laying out and measuring a sampling unit in obtaining utilization by the stubble-height-class method. *(Courtesy of R. H. Canfield)*

Class No.	*Stubble height in inches*
1	0-½
2	½-1
3	1-2
4	2-4
5	4-6
6	6-8
7	8-10
8	10 and over
9	Ungrazed plants

The height of each tuft is measured from ground level (figure 2). Its lateral extent is measured at ground level along the transect. In cases where the tufts are grazed to two or more stubble heights, the ground measurement is split between the height classes according to the portion of the tuft in each class. The data for each species are compiled by stubble-height classes with the percentage of plants in each class. These can be converted to percentage utilization for each species. Also, the data can be summarized to show mean percentage utilization for all species combined to cover the range as a whole.

Height-Weight Ratio

Since percentage of weight removed is a commonly used standard of forage utilization, a possible approach is the conversion of some other measurement to weight through regression relationships (Lommasson and Jensen 1938). The weight distribution in relation to height in blue grama is illustrated in figure 3. The first task is working out the relationship or developing the standard. To do this the leaves and culms of grass plants are held in place

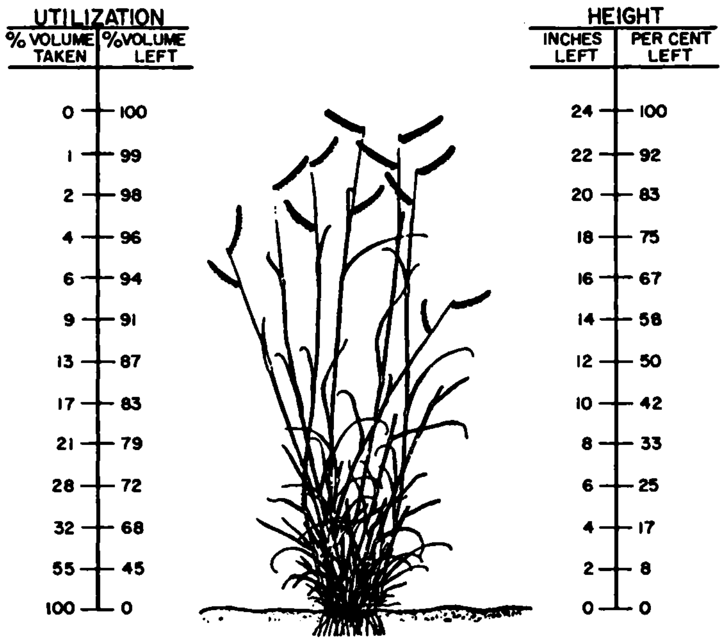

FIGURE 3. Volume or weight distribution in relation to height in blue grama *(Bouteloua gracilis)*. *(Courtesy E. D. Crafts)*

by first wrapping a string spirally around the plant from the base upward and then removing the herbage slightly above ground level. The entire plant is cut into one-inch segments which are dried and weighed. Percentage of the total weight is calculated for each one-inch interval of height. Lommasson and Jensen found that each species has a more or less definite form, as illustrated by Campbell (1942) in figure 4. A detailed description of the method of

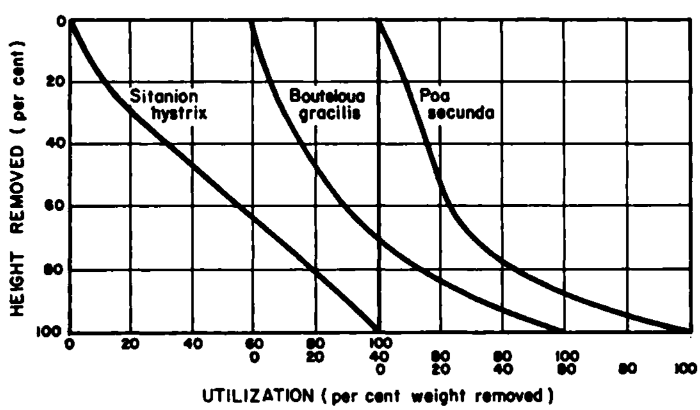

FIGURE 4. Three types of height-weight curves of range grasses, all with seed stalks. *(Courtesy R. S. Campbell)*

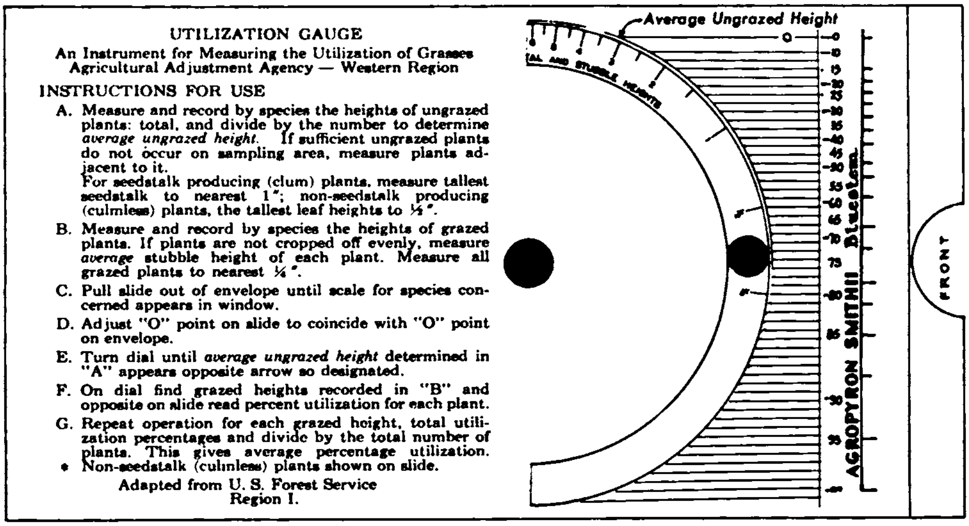

FIGURE 5. Utilization gauge giving height-weight relationship for 22 species of range grasses. *(Courtesy T. Lommasson)*

constructing conversion tables and the field application is given by Lommasson and Jensen (1942, 1943) and by Campbell (1942, 1943).

Samples are taken either systematically or at random, of both grazed and ungrazed heights to determine percentage reduction of height. This in turn is converted to weight reduction.

The following devices have been used to make this conversion: (1) charts (Crafts 1938), (2) circular logarithmic gauges (Lommasson and Jensen 1943, figure 5), (3) tables (Collins and Hurtt 1943), (4) cards with scales printed on them so percentage utilization may be read directly when the card is placed along side the plant (Valentine 1946, figure 6), and (5) a slide rule developed from regression equations of stubble-height on total height (McArthur 1951).

To calculate a single utilization figure for the entire range, the utilization of each species must be weighted by the percent it contributes to the floral composition.

Sample size depends on the variation within the population being sampled (see Chapter 8). In measuring utilization, each worker should determine and use a sample size that meets specifications satisfactory for his studies. This may vary from several hundred to a thousand or more.

The height-weight method is based on the premise that growth form of grasses is sufficiently constant between years, seasons, and sites to allow the use of average height-weight tables with reasonable accuracy. Caird (1945) found variations in growth form of plants of the same species growing on different sites (figure 7). Clark (1945) estimated errors as great as 10-25

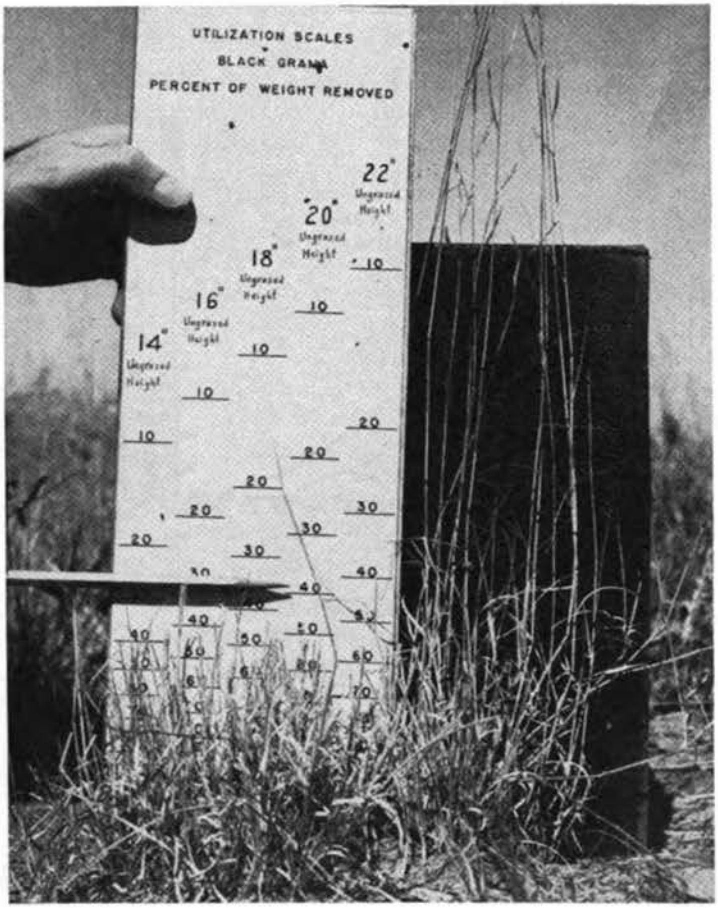

FIGURE 6. Scale used to measure utilization of black grama *(Bouteloua eriopoda)*. This particular plant, occurring in a stand in which the average height of ungrazed plants is 20 inches, is shown by the 20-inch scale to have had about 40 per cent of its weight removed. *(Courtesy K. A. Valentine)*

per cent may occur because of differences in growth from one year to the next on the same site. Heady (1950) found variations from year to year, but differences among sites were greater than those among years. However, he pointed out that much of the variation can be eliminated with the use of separate tables for different height classes since the growth form, at least of bunchgrasses, seemed to be more closely related to total height than to any other factor measured. McArthur (1951) drew similar conclusions.

Reid and Pickford (1941) compared the height-weight ratio method with the ocular-estimate-by-plot. Both methods gave substantially the same result when stubble height was uniform, but when this was uneven the estimates were low. About the same number of plots were required in both

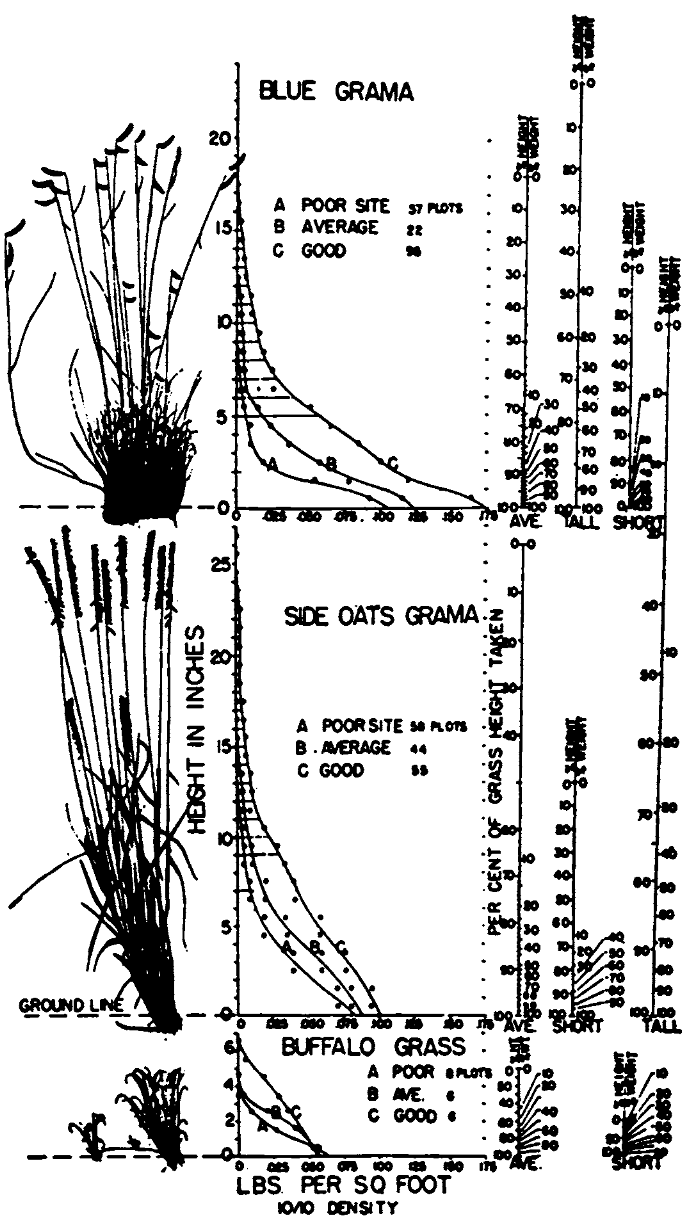

FIGURE 7. The graphs illustrate the effects of environment on the height-weight relationship in blue grama, sideoats grama *(Bouteloua curtipendula)*, and buffalo grass *(Buchloë dactyloides)*. *(Courtesy R. W. Caird)*

methods but the increased speed in the ocular-estimate-by-plot methods led them to recommend it. On the other hand, Lommasson and Jensen (1943) and McArthur (1951) obtained more consistent results when the height-weight ratio method was used.

In summary, the height-weight procedure seems to be an accurate and reliable method for determining utilization of perennial grasses. However, the construction of height-weight tables is a tedious undertaking and must be done with considerable attention to variations in growth form resulting from differences in site, weather, and genetic causes. Experience indicates that the tables need to be made for specific conditions and used in restricted areas. Once they have been made the determination of utilization becomes a relatively accurate procedure except where grazing is primarily on leaves and the stems are left ungrazed. So far the method has been applied only to perennial grasses.

Stem Count

Stoddart (1935) developed the stem-count method in which he showed that percentage utilization was a direct function of the total number of stems grazed. The work was done with western wheatgrass *(Agropyron smithii).* It required a count of grazed and ungrazed stems from a randomized plot or transect procedure. Little error results from personal or procedural causes. If proper grazing is attained when 80 percent of the stems have been grazed it is a simple calculation to determine whether use has been under, proper, or over. This method was tested with thickspike wheatgrass *(Agropyron dasystachyum)* at Dubois, Idaho, and was not sufficiently accurate for this species (Pechanec 1936). The percentage utilization was based on the volume of forage removed. The difference was due largely to the fact that all the stems grazed were not completely grazed. The error was greater with light grazing than with heavy grazing.

Short-cut

This is based on the relation among three factors: the amount of a grass stand grazed to a stubble height of two inches or less, the amount grazed above a two-inch stubble height, and the ungrazed complement (Canfield 1942, 1944a).

The relative amounts, in terms of tuft area, of partially grazed and ungrazed grass that are most likely to be present when various percentages of the total grass stand have been grazed to a stubble height of two inches or less are shown in figure 8. These data were obtained from 713 transects distributed over the Santa Rita Experimental Range. Each transect was 100 feet long. The chart was constructed using the two-inch stubble-height class as the base of each column. The 3 categories in each column total 100 percent and represent the total grass stand.

In using the chart, one estimates in terms of basal tuft area the average percent of stubble grazed to two inches or less without regard for species or

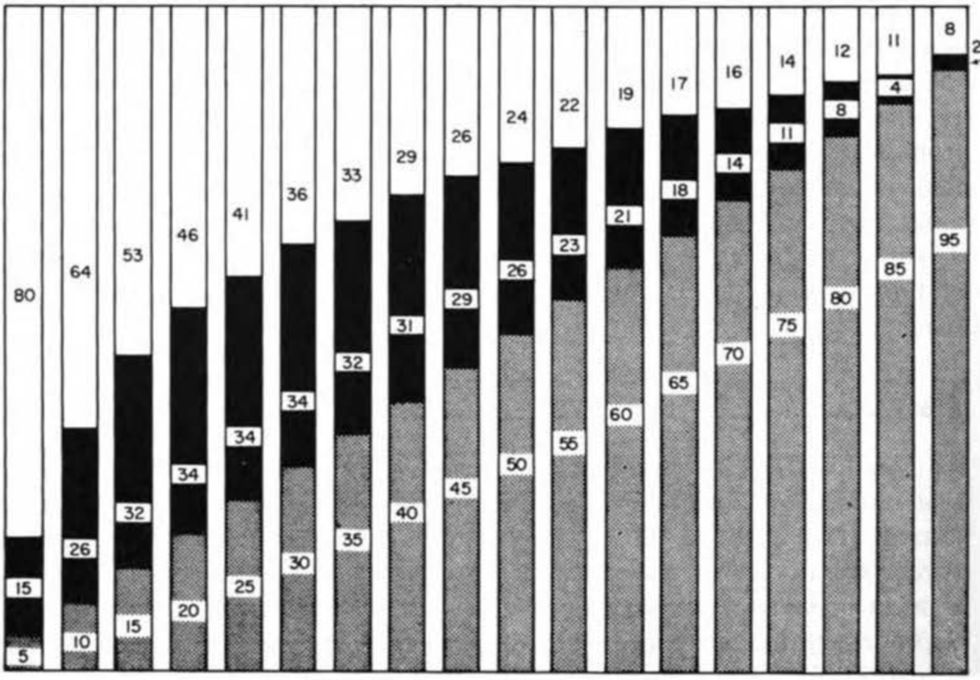

FIGURE 8. Relation between percent of total grass stand grazed to two inches or less, amount grazed above two inches, and ungrazed remainder. *(Courtesy R. H. Canfield)*

density. This estimate is then referred to the bar nearest that obtained. The observer then looks at the upper two segments of that bar to learn the expected percentages of partly grazed plants and the expected percentage of ungrazed plants.

A point of interest about the chart is the constancy with which the percentage of partially grazed grass is maintained until about 50 per cent of the cover has been grazed to a height of 2 inches or less. This may be the point where full grazing is attained and over-use begins.

Per Cent of Plants Ungrazed or Grazed

This is based on the relation between the per cent of plants ungrazed (Roach 1950) or grazed (Hurd and Kissinger 1953) and the per cent of total weight removed (figures 9 and 10). Basic data needed in preparing the graphs consist of the per cent of plants ungrazed or grazed and the associated percentage utilization by weight on areas grazed to various intensities.

Roach used straight line transects of 100 double paces. At each double pace the grass plant nearest the toe was classified as either grazed or ungrazed. At the same time data necessary to determine the percentage

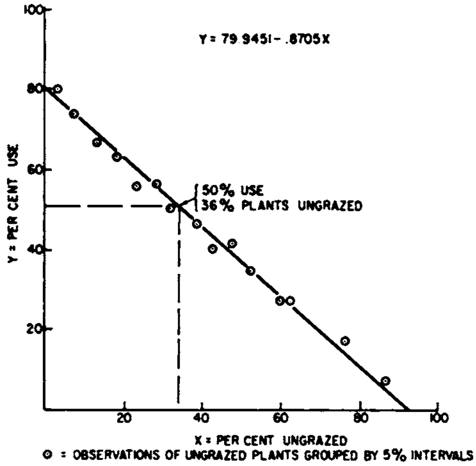

FIGURE 9. Utilization as determined by the percent of ungrazed plants of all important grasses on the Santa Rita Experimental Range. *(Courtesy M. E. Roach)*

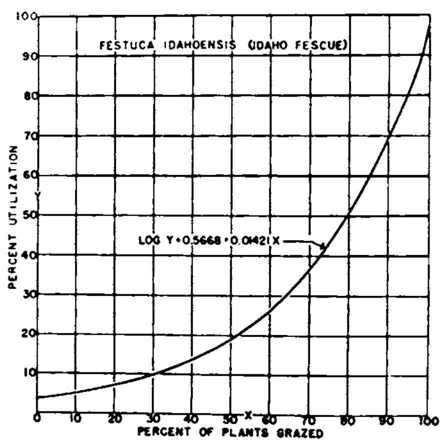

FIGURE 10. The relation between per cent of plants grazed and utilization of Idaho fescue *(Festuca idahoensis)* on cattle ranges. *(Courtesy R. M. Hurd and N. A. Kissinger, Jr.)*

utilization by the height-weight method were recorded. The data for per cent ungrazed plants and percentage utilization for each transect line were then plotted and a regression line computed, as shown in figure 9. In preparing this graph, 125 transect lines were used. The regression equation computed from these data was $Y = 79.9451 - 0.8705X$ where X is the per cent of plants ungrazed, and Y is the percentage utilization calculated from measured stubble heights. The correlation coefficient, 0.92, indicates a constant relation.

Data obtained by Hurd and Kissinger for the graph in figure 10 came from 42 500-foot transects where the ungrazed plants were counted and the percentage utilization was determined by the ocular-estimate-by-plot method. Utilization measurements on the plots ranged from 1 to 80 per cent. The curve was derived from the equation Log $Y = 0.5668 + 0.01421X$ wherein the logarithms of Y (per cent utilization) and the natural numbers of X (per cent of plants grazed) were used. The correlation coefficient was highly significant, having a value of 0.916.

Twig Tagging

The twig measurement method has been used to determine percentage utilization of browse species on winter ranges (Aldous 1944, Dasmann 1951). With this method one to several twigs on each bush or tree to be sampled are marked. Twig lengths between the markers and branch tips are then measured.

A first measurement is taken after the plant has made its full growth, to determine the length of twigs available for browsing. A second measurement is taken just before the start of the next growing season, to determine the length of twigs left. Utilization is the percentage of twig length eaten. This method is similar to the "before and after method" except it is based on twig length rather than weight.

Twigs to be marked should be distributed at different height levels within reach of the animals in order to reduce the effect of differential browsing. Fresh twig clusters should be tagged each season rather than to remeasure the same cluster year after year.

Estimate of Twig Utilization

The technique used in estimating twig utilization varies with browse species. With shrubs like sagebrush *(Artemisia* spp.), manzanita *(Arctostaphylos* spp.) and snowbrush *(Ceanothus velutinus),* on which seasonal growth is not easily measured, the following procedure is used: (1) the shrub is examined to reveal the extent of cropping, (2) the shrub is mentally reconstructed as it would have appeared had it not been cropped, (3) an estimate is made of the percentage twig length utilized. A comparison of browsed with unbrowsed shrubs facilitates estimation. Where heavy use prevails, it is sometimes necessary to protect representative shrubs from browsing in order to have them available for comparison at the time the check is made. This method is similar to the ocular estimate-by-average of plants method except it is based on twig length rather than weight.

With shrubs like bitterbrush *(Purshia tridentata)* yearly twig growth is easily defined. A variation of the visual estimate method described by Hormay (1943) works well with this class of browse plants. This involves an estimation of average uncropped leader length, average cropped leader length, and percentage of the leaders which have been cropped.

It is good practice to measure with a ruler or tape the uncropped leaders on perhaps a half dozen twig clusters on each shrub. This will aid in ocular estimation of twig lengths. The shrub is then scanned to determine whether the measurements are representative of the seasonal growth on the entire plant. The final average is recorded for future reference.

Average length of cropped leaders may be determined in a similar fashion. Estimation of percentage of the twigs that has been cropped may be facilitated by an actual count of cropped and uncropped leaders on several twig clusters picked at random.

The final estimate for a shrub on which uncropped leaders average 5 inches in length and cropped leaders average 2 inches, and on which 30 per cent of the leaders have been cropped would be 60 per cent $\times$ 30 per cent, or 18 per cent average utilization.

On deer winter ranges, where checks are made in the fall to determine the percentage of the forage crop consumed by livestock before deer arrive, the average uncropped leader length for each shrub is recorded for reference when the second survey to determine full utilization is made. This record helps immensely on ranges where most shrubs are heavily cropped by the end of the browsing season.

Photographic

Here different per cents of utilization which serve as standards in rating utilization on similar ranges are portrayed photographically.

Great care is taken in selecting the spots to be photographed. Usually these will be experimental pastures where detailed studies of utilization, range condition, and trend have been made. In such pastures, spots are selected, percentage utilization determined by other means such as the actual weight method using cages, and pictures taken. Usually about six pictures will suffice to show gradation in utilization from 0 to 100 per cent. These photographs are taken so the forage 25 to 35 feet from the camera is in focus. This provides a sweeping view of the type and at the same time shows utilization detail. Enlargements are made to bring out detail. These are mounted for convenient use in the field.

The photographs can be related to a scale such as the one shown in table 1 to permit interpolating between the degrees of utilization pictured in the standard photographs.

This method is best adapted to open grass types where most of the herbage is not obscured by shrubs or trees. Once accurate photographs are obtained, the method is easy and rapid, and has proved satisfactory for extensive research. In California, it is used in pastures where research might not be

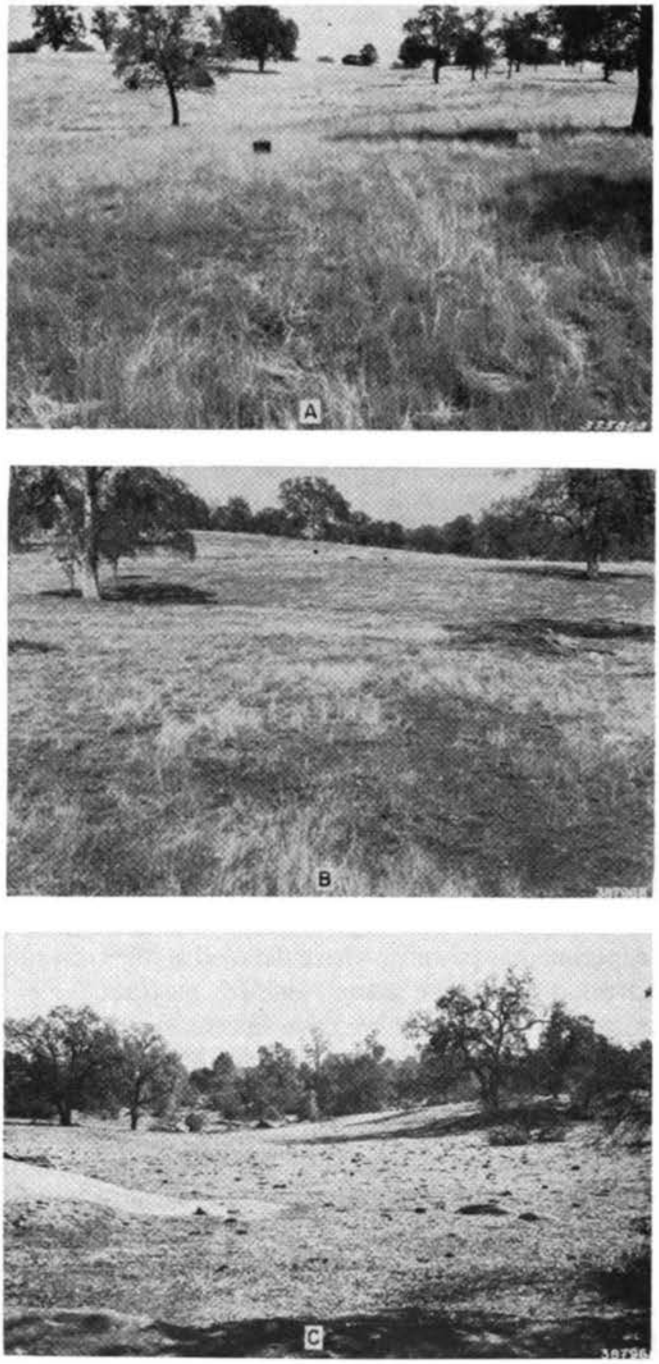

FIGURE 11. Standard photographs used in rating percentage utilization on annual type ranges in California by the photographic method. Refer to table 1 for key to percentage utilization. *A*, light utilization; *B*, moderate utilization; *C*, close utilization. *(Courtesy U.S. Forest Service)*

possible if more time consuming methods were required. The method has been tested by different technicians for accuracy. It is found that, with little or no training, technicians can usually estimate within five per cent of each other.

TABLE 1. Percentage utilization rating scale by the photographic method. Photographs 1, 4, and 6 are shown in Figure 11. (Adapted from Hormay and Fausett 1942)

		Percentage utilization	*Photograph number*
NONE		0	
		5	
	Very light	10	1
		15	
		20	
		25	
LIGHT	Light	30	2
		35	
		40	
	Moderately light	45	3
		50	
MODERATE		55	
	Moderate	60	4
		65	
		70	
		75	
CLOSE	Close	80	5
		85	
		90	
	Very close	95	6
		100	

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Chapter 6

Livestock Selection and Management in Range Research

SINCE the problems involved in the selection and management of experimental animals are complex, no single set of recommendations can be applied to all conditions. The basic principles set forth in this chapter will be of value in developing management techniques adapted to varied environmental conditions and in determining the types of animals best suited to different research problems.

TYPE OF EXPERIMENTAL ANIMAL

Species

In general, the kind and class of animal to which the results of an experiment are to apply should be used for the experiment. When the primary objective of the research is to measure the yield of forage produced by different treatments in terms of total digestible nutrients (TDN), any one or several kinds of livestock may be used, provided suitable TDN conversion factors are available. In certain types of studies, other species will give the same information at a much lower cost. Small animals often can be used in pilot studies to predict large animal responses to differential treatments, and in other studies to provide basic information about the charactertistics of the herbage. Small animals are advantageous because of their rapid reproductive cycle, large number of offspring, and economical production.

Common or dual use of experimental range areas by two or more species of livestock either at the same or different times may be desirable in some studies. This practice results in a more uniform utilization and greater over-all grazing capacity, providing the combined numbers of each kind of animal are commensurate with herbage production.

Breed

Although the Hereford breed of beef cattle has been predominant for many years in the range area, a number of new breeds derived from crosses of British with French and Brahman breeds are assuming greater significance. Shifts from the British breeds to new types in the Deep South indicate a lack of adaptation to large sections of the country. As little work has been done in the development of new breeds of cattle adapted to the range area, these problems still lie ahead and constitute one important facet of future range research.

The Rambouillet, Columbia, Targhee, and Corriedale are the common breeds of range sheep. The Targhee, Panama, and Columbia were developed in the western range area from crosses of the Lincoln and Rambouillet breeds.

In most range research studies, a single major breed or a relatively small number of breeds should be used. Unless the experimental design takes into account differences among breeds, they will be confounded with treatment effects.

Class

The class of animals within the species, i.e., steers, heifers, or cows, used in a particular grazing experiment will be determined largely by the project objectives. For example, the primary objective might be to determine the effects of different pasture management programs on the yield of pastures *for fattening steers*. In certain types of studies, any one or several classes may be used.

The relative advantages of using breeding females or steers in experimental grazing trials should be carefully weighed. In studies which are conducted for only one growing season or which are adequately replicated in different years, steers are preferred since disturbances due to estrus, pregnancy, and lactation are eliminated. As a result, the analysis and interpretation of results are less difficult. Cumulative pasture or treatment effects are lost with annual replacement of steers.

Incorporation of a research project in the normal operations of a breeding herd results in a multiplicity of problems. For example, in herds operated on a cow-and-calf or ewe-and-lamb basis, replacement of breeding stock is more difficult. Reproductive losses tend to upset replacement procedures and the analysis of results. Some females do not conceive. Progeny losses sometimes occur before weaning. If reproductive losses are great, true treatment differences may not be measurable. The addition of bulls or rams at breeding will cause a temporary change in number of animal units per pasture.

In long-term studies where cumulative effects are important, breeding animals must be used. In this event, proper sampling techniques and procedures for evaluating data gathered on animals of various age classes must be devised. Results expressed in terms of cow-and-calf or ewe-and-lamb production are most meaningful to local ranchers.

General Health and Condition

Since health can have a profound effect on performance, precautions should be taken to ensure that sound and disease-free stock is placed on the experimental range unit. Any disturbance in the physical condition of an animal before or during the test period will be confounded with its response to treatment.

The condition of an animal at the time of entry on test will have a bearing on its response to treatment, especially on short-term gains. In the case of shrunken yet thrifty animals, spectacular gains can be obtained over a short term. Such results often have been misconstrued. Only animals of similar condition should be placed on the various treatments. If this is impossible, animals of like condition should be randomized among treatments. In experiments extending over several years, animals should be in the same condition at times of entry in subsequent seasons.

Genetic Variability

Uniformity in appearance, either in color or body conformation, does not denote uniformity of inherent capabilities. Wide differences exist within the established breeds for most characteristics of a strictly utilitarian or economic nature. Even if great care were exercised in the selection of experimental animals, a sizable amount of uncontrolled genetic variability would remain.

In range investigations concerned with the assessment of treatments such as grazing intensity, seasonal use, and vegetation composition, genetic variability must be reduced as much as possible. Prime consideration should be given to obtaining experimental animals from herds or flocks in which a consistent breeding policy has been maintained throughout the years. Uniform pretest environment will be had by this procedure in addition to some degree of genetic homogeneity due to the sustained selection.

If animals from different breeders are combined in a single grazing experiment, an equal number from each owner should be assigned to each experimental treatment. Otherwise, more than a proportionate share from an individual breeder whose stock has superior germ plasm, or who provides better or worse than average care on his ranch, might appear in a single pasture. Again the effects of differences between herds would be confounded with treatments.

In some instances, genetic-environmental interactions may be important, i.e., results obtained on the same treatments will differ appreciably between unrelated lines of approximately equal inherent productivity. When genetic-environmental interactions are known to exist, they should be taken into account in the experimental design.

Individual animal variation constitutes an important problem in interpreting and evaluating animal response in range research. Inherent differences among individual animals include such factors as time devoted to grazing, selectivity of forage, distance traveled in a day, ability to convert carotene to vitamin A, and basic differences in gaining ability and efficiency of feed utilization. If the animals are properly randomized, these factors plus many others are included in the "within-lot" variation used to test the significance of treatment differences.

If the analysis of variance is used to estimate parameters in the population from which the sample came, certain assumptions about the population and the method of sampling must be made if the statistical results are to be valid. Actually, the role of genetic variability is determined by the experimental design and consequent mathematical model. If inferences are to be made concerning the population from which the sample animals came, the genetic differences among animals must be considered as random variables. If, on the other hand, inferences are to be made concerning the particular animals used in the experiment, the genetic differences should be considered as fixed effects.

Since continuous trials in which a particular treatment or paddock is used for a number of years are characteristic of much range research, animals of considerably different genetic constitution may be included in the various years. As a consequence, the procedure used to allot animals is of more concern than the inherent qualities of the sample in a particular year. Typical factors known to have an important effect on productivity include breed, sex, age, season of birth, twinning, condition, and weight. Animals in the various classifications should be allotted equally between treatments. Since none of the traits used to allot animals is known to predict subsequent performance, animals cannot be accurately allotted on the basis of their inherent performing ability. Usually, genetic variability will be randomly distributed among treatments.

Identical twins offer an excellent method of obtaining animal behavior patterns for various treatments. They are particularly valuable for studies with many observations per animal.

Number of Animals Required for Optimum Accuracy

The sensitivity or precision of a grazing experiment is dependent upon (1) the experimental error components, (2) the number of animals per replication, and (3) the number of replications per treatment. Decreasing the experimental error by increasing the number of animals per replication or by increasing the number of replications will increase the precision of the experiment.

Animal variation appears to be the major source of experimental error in nutritive-value studies. However, in yield studies where results are expressed as gain, animal days, or total digestible nutrients per acre, pasture variation appears to be the larger source of experimental error. Lucas (1950) has said that the optimum number of animals per pasture in the humid region is about seven for nutritive-value studies and about two for yield studies. Different kinds and classes of livestock probably will require different numbers of animals per pasture for a given accuracy. Large numbers may be required in range studies to insure natural behavior. Precise recommendations for optimum numbers of animals to be used cannot be made since information is lacking on the relative sizes of the experimental errors for specific conditions.

Yield studies at the Southern Great Plains Field Station[1] indicate a minimum of 2 animals per pasture and 3 pastures per treatment over a period of 8 years gives satisfactory precision to detect a 15-pound difference in gain per head between treatments.

The optimum number of animals per pasture varies with the type of study, pasture size, animal size, and the length of grazing season. Ten animals per pasture are usually considered the minimum for statistical analysis. If variation in the number of animals required to obtain a given degree of herbage utilization during the grazing season is anticipated, the pasture should be large enough to allow for at least 10 animals even under the lightest expected intensity of grazing.

The costs involved and the information desired often will control the number of replications used in a grazing experiment. The expected probabilities of detecting true differences of various sizes between treatments with different numbers of replications are shown in table 1. A coefficient of variation of between 7 and 17 per cent was used. Two replications will detect differences of 40 per cent from 60 to 90 per cent of the time. Four replications are required to have the same probability of detecting differences of 30 per cent, and eight for detecting differences of 20 per cent. More than 12 replications are required to have the same probability of detecting differences of 10 per cent or less.

[1] Private communication from E. H. McIlvain 1958.

TABLE 1. Estimates of the probability of detecting true differences when testing at the 5 per cent level with a coefficient of variation of 7 to 17 per cent (Lucas, 1950)

Number of replications	*Differences*			
	10%	*20%*	*30%*	*40%*
2	.1– .3	.2– .7	.4–>.9	.6–>.9
3	.1– .4	.3– .9	.5–>.9	.8–>.9
4	.1– .5	.4–>.9	.6–>.9	.9–>.9
8	.2– .8	.6–>.9	>.9	>.9
12	.3–>.9	.8–>.9	>.9	>.9

The number of replications required for detecting various differences at a fixed probability level of 80 per cent is given in Table 2. No entries are given when more than 44 replications are required. In order to detect a difference of 15 per cent 80 per cent of the time, the number of pastures needed, assuming a coefficient of variation of 12 per cent, is rather prohibitive. As a general statement, about 5 replications will do only a fair job of detecting differences of 20 per cent or larger. Practical considerations often limit the number of replications to two or at most four.

TABLE 2. Estimates of the number of replications required to yield an 80 per cent chance of detecting specified differences at the 5 per cent level (Cochran and Cox, 1950)

	Coefficient of variation					
Difference	*4%*	*8%*	*12%*	*16%*	*20%*	*24%*
5	11	41	—	—	—	—
10	4	11	24	41	—	—
15	3	6	11	19	29	44
20	2	4	7	11	17	23
30	2	3	4	6	8	11
40	2	2	3	4	5	7

METHODS OF SELECTION AND ALLOTMENT TO OBTAIN UNIFORMITY BETWEEN GROUPS

Unless factors such as breed, age, condition, type of breeding, and previous treatment are taken into account in the experimental design, animals differing as little as possible with respect to these factors should be selected.

If animals of considerably different inherent productivity must be used, restricted randomization should be used in assigning individuals to the different treatments, i.e., animals with similar predicted performances are placed in separate outcome groups. Each outcome group should contain at least one animal per treatment. Equal numbers from each outcome group are assigned at random to each treatment. Differences between the outcome groups are later removed from the experimental error by the analysis of variance.

The increase in efficiency obtained by first placing animals in outcome groups, rather than by assigning them at random to the treatments, depends on (1) the size of the anticipated differences between the outcome groups, (2) the number of treatment groups, and (3) the number of animals on each treatment.

In general, the use of outcome groups becomes more efficient as the differences between them increase; however, the possibility of an interaction between outcome groups and treatments is likely to increase. Thus, the advantage gained by having more diverse outcome groups may be offset. In some cases, previous information indicates that an interaction between outcome groups and treatments may be expected. For example, animals which vary considerably in age and weight probably will respond differently to treatments which materially affect growth. When an interaction of this type is expected, the design should be changed to one where the interaction can be measured and interpreted.

As the number of treatments increases, the value of placing animals in outcome groups before assignment to the treatment groups decreases. This results because of less similarity in predicted outcome among animals in the same outcome group as the number of animals in that group increases.

The number of animals on each treatment has an indirect effect on the value of placing animals in outcome groups before assigning them to the treatments. With a completely randomized design, the number of degrees of freedom for estimating error is $n(k\text{-}1)$, where n is the number of treatments and k is the number of animals on each treatment. When outcome groups are used, the number of degrees of freedom for estimating the experimental error is $n(k\text{-}1)\text{-}(m\text{-}1)$ which equals $(n\text{-}1)(k\text{-}1)$ when m, the number of outcome groups, is equal to k. Therefore, as k increases, holding n constant, the less important will be the loss of $(m\text{-}1)$ degrees of freedom from error.

If the differences expected between animals on the same treatment are associated linearly with such factors as initial weight or age, it may be more efficient to assign the animals at random to the treatments, and remove the variation due to these factors by covariance. A smaller number of degrees of freedom is removed from the error by this method, and its efficiency is not affected by the number of treatments. This depends, however, on how closely the relations approach perfect linearity.

Orderly Replacement of Breeding Stock in Long-Time Trials

The problem of replacement must be considered in grazing studies which will extend for periods longer than the productive life of the class of livestock involved. Obviously, death or disability may occur at any time during the experiment. If cumulative effects of grazing are important, the cows should be retained as long as useful and then replaced at one time. Otherwise, normal replacement due to age can be handled by ordinary management procedures. For example, in the case of cattle, 20 per cent of the total number involved may be culled yearly and replaced by heifers. Since age of cow affects weight of both cow and calf, equal numbers of replacement heifers should be allotted to each treatment.

The manner of selection of the replacement females is somewhat controversial. Many investigators question the use of random selection as a method of replacement in large animal studies because of the limited numbers involved. Since considerable genetic variability exists for the growth responses normally measured in grazing studies, results may be biased by sampling errors when replacement is made by random selection in a small population.

An alternate method of selection is based on the mean response by treatment. Under this system, replacement females are selected from those animals in a given treatment nearest to the mean of the traits studied. As an illustration, if replacements are selected at weaning, females of average birth and weaning weights within a treatment would be chosen. If the selection of replacement heifers need not be made until they are 18 months of age, post-weaning growth or weight at 18 months may be used as additional criteria. Any available measure of inherent productivity should be fully used.

Maintaining differential treatment until replacement females enter the experiment may be difficult, but should be carried out if at all possible. Alternate replacements should be kept until the original animals have been replaced.

Replacement of dams by their daughters is one method of maintaining uniform genetic differences between pastures. Small numbers and disproportionate sex ratios often make this method impracticable. Any errors in original allotment will be continued.

Further replacement throughout the course of an experiment may be necessary due to disability, death, or low fertility. Losses of this nature are commonly higher in sheep and goats than in cattle, but are more easily replaced due to the higher reproductive rate. Replacements for each age group maintained under conditions similar to those of the experiment is the most effective answer to this problem. Local conditions determine the number of replacements to be kept.

When replacement animals cannot be maintained under similar conditions, losses should be replaced by animals of similar age and weight. Substitute animals should be removed by the rotation system at the first available opportunity.

Decisions involving the removal of experimental animals should be made with extreme care. Reproductive failures and various disabilities should be assessed to determine whether the causes are random or result from the treatment. Useful data may be lost by hasty decisions.

VARYING NUMBERS OR GRAZING PERIOD TO COMPENSATE FOR VARIATION IN FORAGE PRODUCTION

Variation in herbage from year to year must be translated into equivalent stocking units. This variation, if not compensated for by a proportionate adjustment in stocking, will result in utilization departing from the prescribed intensity sought.

Two general methods of solution are available. One consists of making a direct evaluation of herbage before stocking, and adjusting grazing numbers accordingly. The other consists of determining utilization concurrently with grazing, and regulating stocking to attain the desired use on the basis of the stocking and utilization already attained. This may be done by maintaining a fixed number and removing them when desired utilization is attained, or by adjusting numbers as grazing progresses to arrive at correct utilization at a fixed date. The fixed period generally is preferable as a variable season of grazing is not involved, although the animal response data is complicated since not all within a group can be treated alike.

Herbage production to the prescribed usage is obtained by sampling as a basis for estimating the yield of the entire pasture. Stocking based on this value and a reasonable forage allowance, reflecting forage destroyed by trampling, used by wildlife, and left on unavoidably lightly used outlying areas, should result in use of the pasture approximating the prescribed value. Owing to limitations of accuracy in sampling and changes in the forage crop after sampling, it is not advisable to depend solely on forage crop appraisal to achieve a prescribed degree of utilization. Utilization checks and appropriate stocking adjustments should be made periodically to insure attainment of desired use.

Two types of error peculiar to light utilization are considered here because of their influence on stocking capacity prediction. The first results from inaccuracy in determining light degrees of use and from using a small erroneous base utilization in prediction and projection. Correction is made by making another utilization check nearer the end of the grazing period, and by adjusting the stocking on the basis of results obtained. Overuse cannot be corrected if allowed to occur. Careful check observations, made as grazing proceeds, will prevent an error of this type. The second error results from a shift in use to, or away from, the principle forage species concerned, after the base stocking and utilization values have been observed and the stocking capacity computed. The disappearance or appearance of ephemeral herbaceous plants, or a shift in grazing because of seasonal changes in relative palatibility of forage species, may cause this type of error.

Another method of attaining prescribed use on a range area consists of locating plots to be grazed to the prescribed use over the pasture which will receive use equal to or in excess of the prescribed use sought. Utilization appraisals have to be made on these plots as grazing proceeds, and each plot closed to grazing when the prescribed use for the plot is reached. The plots may be opened to grazing at the beginning of each growing season and the process repeated for a period of years. Care in locating the plots and stocking the pasture is necessary in order that utilization in the general area of the plots equals the highest degree of use sought in an experiment. This method, obviously, is applicable only in experimental work concerned with determining the influence of grazing intensity on the range. Of course, intensity will be confounded with period of grazing. The reflected influence of range use on livestock condition and production cannot be determined since in any one year one group of livestock is producing all degrees of use on the study plots and on the general pasture as well.

METHODS OF OBTAINING UNIFORM GRAZING PRESSURE

Two general types of uneven grazing are (1) spot or patch grazing, and (2) a progressively decreased intensity of grazing, associated with increasing distance from water or other places of livestock concentration.

Spot or patch grazing has two principal causes. First, it is the usual concomitant of light grazing. Under light use some plants, either single plants or groups, will be fully or nearly fully used, while other plants or groups of the same species in close proximity will be entirely ungrazed. In reality, there may be little or no uniform light use of all plants; instead, the light use of the range is an average of nonuse and full or nearly full use of individual plants through repeated use of the same plants. Since this is the natural manner of grazing by animals, it cannot be completely eliminated.

When grazed and ungrazed plants are both well dispersed over a range, either as individual plants or as small groups, the condition may be correctly regarded as essentially even use. Utilization plots of large size will reflect relatively even use. However, small plots, especially compact ones, may include mostly nonused or heavily used plants, and thus reflect patchiness of utilization, when in fact the range may be as evenly grazed as possible under light use. An increase in stocking will not change the grazing pattern but merely increases utilization in all areas. The same preferred spots continue to be grazed first and hardest. Although this cannot be corrected, periodic rest will safeguard against damage.

As grazing continues over a period of years, spotty or patchy grazing will give rise to a fixed pattern, and permanent "islands" of light or nonuse and heavy use develop. Unused vegetation generally decreases in palatability and tends to interfere with use of new growth in subsequent years. Unutilized old growth may be removed by occasional mowing, burning, or high intensity grazing. Since these practices alter the condition of simple light use as an experimental treatment, they may not be desirable on that account. A choice exists between using one or more of them and recognizing that the experimental treatment has been modified in that way, or not using them and recognizing that the development of patchy grazing may be one of the consequences of continued light use.

A second cause of patchy grazing is the occurrence of forage plant species of markedly different palatability on the same range area. If these different species are well intermingled, the resulting utilization condition is somewhat similar to that first described under light use. If, on the other hand, species of different palatability occur in distinct vegetation types or subtypes, uneven use may result from the outset. Correction cannot be made without excessive and damaging use of the more palatable plants. Mowing or burning will not correct the unevenness, since the fundamental cause of the differential grazing has not been corrected.

The problem of uneven use caused by mixed types may be met in either of two ways. First, it may be avoided by laying out experimental pastures in only one vegetation type or subtype, or, second, it may be partially corrected by rotating the season of use among years. This latter method would be of value if palatability varies with growth or season. Where these are not possible, utilization determinations may be recorded separately by forage types or subtypes, theoretically producing relative uniformity of use within a type or subtype. Under this plan, attention is concentrated on only one of the forage types in a pasture. Ordinarily, this will be the "key" forage species on the range under study.

The distance-graduated type of uneven grazing use occurs in varying degrees on all ranges, especially those with large pastures and limited water development, and on mountainous terrain. Factors other than water distribution and topography may induce uneven grazing use. For example, flies and gnats may cause livestock concentration and heavy use along the windward side of pastures.

Hauling water, developing temporary waters, salting and feeding, establishing insecticide-treated rubbing posts, fertilizing outlying range, mowing and burning unused feed, herding and riding, constructing trails and drift fences, and intensifying stocking as in rotation grazing, may all help reduce uneven grazing and should be considered for use in most experimental pastures. The practice of feeding proteinaceous or carbonaceous feed supplements self-regulated by salt content is a particularly effective method of reducing uneven grazing.

The decision to use any method of reducing unevenness of grazing in an experiment should be made on the basis of the specific objectives of the particular experiment and of the feasibility of using that method on the range where the experimental results are intended to apply. If, for example, an experiment has as an objective the determination of the performance of stock on a certain range type, it may be inadvisable to use supplemental feeding or rotation grazing as a method of improving distribution of experimental animals.

Effective Control of Parasites and Diseases

Animals differ from one another, not only in inherent ability to convert roughage or concentrates into meat, wool, or milk, but also in the degree and type of parasite infestation and in the presence of other disease-producing factors which might easily nullify experimental results.

To avoid complications from infectious diseases, all animals should be observed carefully for at least two weeks before placing them on experiment, and immunized against diseases enzootic in the area concerned, i.e., anthrax, blackleg, malignant edema, and bluetongue. Animals should be keep free of such external parasites as lice, ticks, and mites. An adequate fly control program should be instigated if needed. If an animal shows signs of illness, its temperature should be checked at once. Normal temperatures range from 100° to 102° F. for cattle, from 101° to 103° F. for sheep, and from 100° to 102° F. for goats. Exercise, environmental temperature, and state of fleshing may change body temperatures as much as three degrees. In borderline cases, these factors must be considered. In case of doubt, the temperatures of supposedly normal animals maintained under similar circumstances may be taken. Animals in question should be isolated until the actual cause of the abnormal temperature is determined.

Control of internal parasites is difficult if the infective stages are passed from one animal to another by means of fecal contamination. Free-living larvae of some forms are quite resistant, surviving on the ground for weeks, months, or even years. The greatest sources of parasitism are animals carrying a subclinical or reservoir infection. Eggs are constantly passed out with the feces. When climatic conditions are at an optimum for survival, the larvae population builds up at an alarming rate.

Animals placed on experimental plots should be free of internal parasites if possible. Fecal examinations should be made at regular intervals to determine the parasitic load. The choice of anthelmintic depends on the type and severity of infestation. Although flukes may be controlled to some degree by medication, the ultimate control is destruction of the intermediate host, the snail, by molluscides and drainage. Tapeworms in the digestive tract may be removed with lead arsenate. Control of the intermediate host of the broad tapeworm, a free-living mite, is difficult if not impossible under range conditions.

Nematode parasites are almost universally present in animals on pastures and ranges. Several genera and many species may exist in a given area. Practically all of those present in the digestive system have a free-living larval stage developing from the eggs passed out by an infected animal. Control measures are not available for all nematodes. *Haemonchus contortus*, the common stomach worm, and *Oesophagostomum radiatum*, the common nodular worm of cattle, are susceptible to phenothiazine, and periodic treatment with therapeutic doses, together with low-level feeding of phenothiazine, usually gives adequate control. Many of the smaller trichostrongyles and thin-neck bowel worms are not amenable to any type of treatment. Lungworms also have proved refractory to chemotherapy. A 2-gram daily intake of phenothiazine will kill larvae in the digestive tract and prevent hatching of eggs in feces. This dose is considered optimum for both sheep and cattle. Sheep usually accept it readily. Since cattle do not care for phenothiazine, difficulty is often experienced in administering the daily dosage. Often, their consumption of salt or minerals containing phenothiazine is quite erratic. Low-level feeding certainly is not a panacea, and should not replace sanitation, pasture rotation, and good nutritional practices. In certain areas and under certain conditions it may prove to be a valuable supplement. Under experimental conditions, addition of sufficient concentrates to insure an adequate daily intake of phenothiazine may prove a complicating factor.

To date a phenothiazine-mineral or salt mix palatable to cattle has not been devised. In those areas in which the vegetation is not deficient in minerals, or contains a considerable amount of salt, cattle will not always visit salt or mineral boxes at regular intervals.

Supplemental Feeding

Situations frequently arise, especially in semiarid or arid regions, or in studies designed for year-long tenure, which demand the use of supplemental feeds for animal welfare. The most frequent reasons for supplemental feeding are the occurrence of unusually severe droughts, inclement winter weather, and mineral imbalances or other nutritive disturbances which prevent experimental animals from assimilating or making full use of available herbage.

Supplements fed to correct a mineral imbalance usually consist of salt or a mineral mixture which can be supplied without either serious disruption of experimental design or major effect upon the resulting information.

Other supplemental feeding of experimental animals has an important effect upon the results of livestock grazing trials and should be avoided if possible. The effects are greatest in experiments designed to evaluate range types or to determine proper rates of stocking. In such experiments, supplemental feeding should be used only as an emergency measure to prevent death losses and to preserve continuity of experimental undertakings. Experiments designed to include different levels of supplemental feedings as treatments have been described by Harris *et al.* (1952 and 1959).

Supplemental feeding lightens the grazing load and delays the accomplishment of full or desired utilization. If feeding were allowed under only the most severe treatment, the spread between treatments would be narrowed. If range utilization continues at the normal rate in the least severe treatments and is reduced in the most severe, more uniformity in forage removal from all pastures results. As a result of the modification of the original treatment, the opportunity to study vegetation response to different levels of grazing and the recovery of the vegetation from the effects of the disturbance under different rates of stocking is lost.

Supplemental feeding changes the relation among groups of experimental animals and disturbs their expected performance under given range treatments. Too, the spread between results obtained by vegetative sampling and by animal grazing methods is widened.

When confronted with the necessity for providing supplemental feed, the most desirable procedure is to feed all lots for the shortest possible period of time at the level required to prevent weight loss in the groups receiving the most severe treatment. Should the necessity for supplemental feeding continue beyond the time when full or desired utilization of range vegetation has been attained, active grazing should be discontinued and the experiment held in inactive status until normal conditions return. This technique retains the maximum number of experimental animals and preserves the intended spread between grazing treatments. The effect on range vegetation and soils is the desired one, and any apparent reaction to grazing treatment or recovery therefrom can be considered legitimate.

One alternative to supplemental feeding would be to discontinue the experiment and move the livestock either to another range or to a feed lot. Of course, continuity is disrupted by this procedure, and the question of what might otherwise have happened remains unanswered. Some measure of the effect of drought, winter weather, or other disturbance is afforded. The number of grazing animals also can be reduced drastically during drought periods.

If animals must be fed supplements in a livestock grazing experiment, the questions of what to feed and how to feed become important. Choice of feeds will depend on the type and size of experiment, the type of range, local management procedures, and kind and class of livestock involved. Selection of a feed commonly used locally is desirable.

The feeding of common salt and various other minerals has become firmly established throughout the range livestock industry as a sound nutritional practice and is seldom omitted from either experimental or operational procedures if mineral deficiencies are known to occur.

Commercial concentrates usually are provided in the form of cubes, cakes, pellets, meals, sirups, and pulps. Most animals require a conditioning period to learn to eat the feed before the test period.

Feeds may be fed free-choice by use of boxes, troughs, or feeders placed strategically in areas ordinarily receiving light utilization. Distribution of grazing use can be regulated to a degree by judicious location of salt and by periodic relocation of the bunks or boxes.

Supplemental feeding is likely to cause severe concentration of experimental animals on the feed ground, resulting in heavy damage to range vegetation and soil through trampling. Also, experimental animals quickly change their grazing habits under such a system and tend to depend more on the supplemental feed and correspondingly less on range vegetation. Individual animals will spend many hours each day just waiting for the feed to which they have become accustomed. This undesirable habit can be minimized by shifting the time and place of feeding.

Taking hay or other native roughages to a different location each day is another widely used feeding practice. This system will prevent animals from concentrating unduly or becoming accustomed to waiting for feed when grazable vegetation is available. Some disturbance of vegetation and soil may result from the use of a truck or other vehicle on the experimental range.

Another means of preventing concentration is to construct feeding pens outside the experimental area to which the animals may be moved each day for feeding. This system involves some extra cost and requires daily handling of the animals. Also, a tendency to concentrate and wait for release to the feeding pens may develop. When certain groups must be rounded up for feeding, all groups should be rounded up at the same time, whether fed or not, to insure equal treatment between groups.

WEIGHING PROCEDURES

Forage yields seldom can be converted accurately to livestock production because of differential forage palatability, nutrient content, differential digestibility, forage loss due to trampling, weathering, insects, rodents, and physiological processes such as translocation and oxidation, and many other factors. Consequently, live-weight gain per head or per acre is of major importance in range research.

Accurate individual animal weights should be obtained at the outset, at regular intervals during, and at the end of grazing investigations. Statistical control and interpretations are greatly facilitated. Erratically gaining animals can be detected early.

Factors to be considered in obtaining accurate weights include regional acclimatization of the animals, their familiarity with the specific experimental forage and environmental conditions, reduction of differentials in forage and water fill, careful handling during the weighing period, distance from the scales, and the use of accurate, well-designed, and durable weighing facilities, together with an efficient weighing routine.

One initial weight seems to be sufficient if animals are allowed a leveling off or fill period of a week or 10 days on reserve pasture before they are weighed and introduced into the experiment. Little precision is gained by weighing animals more than once on a given date providing they are held off feed for 12 hours or more before weighing.

Periodic weights usually are taken at monthly or 28-day intervals but may be taken more often. Some advantages of monthly weighings are that climatic and phenological records usually are maintained on a monthly basis, and that interpretation of the animal data in relation to other factors is somewhat easier for both the researcher and the rancher. A disadvantage is that the work falls on different days of the week, including week ends and holidays, and that the months vary from 28 to 31 days in length.

Before obtaining initial weights in a study, the experimenter should allow the animals one or two weeks to become accustomed to the experimental forage and environment. This practice will increase accuracy of actual weight gains by reducing the effect of previous treatment and any differential forage fill. Of course, it cannot be used when the pretreatment period might influence initial weights, i.e., where various supplemental feeds or widely different seeded pastures are being studied. In studies of area gains, a reserve pasture similar to the experimental area usually will be necessary for the pretreatment period to prevent unmeasured use of the experimental pastures.

Differentials in forage fill generally will not be large if the periodic weights are taken at the same time of day. However, severe storms just before or at the time of weighing may prevent animals from obtaining their normal fill. If type of forage or forage conditions change radically between weighings, weight data should be interpreted cautiously. False weight gains occur in spring just at the time of rapid spring growth, or at any time of the year when animals are changing from dry to lush green forage. Likewise, false weight losses occur during fly season, hot weather, and the transition period from luxuriant or highly palatable to poor forage conditions.

Variations in water fill may be held to a minimum by dry-lotting the animals for 12 to 24 hours before weighing, or by leaving them on grass but off water. The latter practice disturbs the animals least, but does require facilities for keeping them off water. Nine-hundred-pound steers may lose up to six pounds of body weight per hour for the first three to four hours when dry-lotted.

The animals should be weighed with the least possible disturbance and excitement, preferably in early morning. Excessive use of whips and electric goads, and loud shouting should be discouraged. Expeditious routes to the scales should be selected. The order of weighing the various lots should be randomized at each weigh day. No particular order is necessary for animals within the treatments. The animals should be returned to grass as soon as possible.

EQUIPMENT FOR HANDLING AND WEIGHING LIVESTOCK

Good equipment and facilities are essential if errors are to be minimized. Facilities that permit livestock to be quickly handled and weighed are most useful. Procedures and equipment that cause excessive handling contribute to inaccurate results and should be avoided if possible.

Many makes and types of scales are now available. Permanent scale installations in corrals need to be housed to prevent error from wind pressure. Scales accurate to the nearest two pounds are adequate except for unweaned calves. Portable scales also have an important place in range research projects. Scales built on a trailer unit can be towed easily behind a car. Other types can be loaded in a pickup and set up for operation at the desired location. Scales that print the exact weight on a ticket are useful for eliminating the human errors due to incorrect reading and recording of weights.

Convenient cutting or sorting alleys and pens to handle cattle before weighing will help reduce shrinkage in handling. Corrals and scale should be located near the center of the range in order that all stock can be trailed about the same distance before weighing. Cattle that are trailed five miles to a corral will shrink considerably more than cattle trailed only a mile.

An efficient corral system developed at the Ft. Robinson Beef Cattle Research Station, Crawford, Nebraska (Koch 1955) is shown in figure 1. This system is much too large for experimental setups, but could be easily scaled down. Pens 1, 4, 7, 8, 9, and 10 will hold about 125 cows and calves, and pens 2, 3, 5, and 6, about 62. Pens 1, 2, and 3, plus the chutes and lane, may be adequate for herds of 100 to 125 cows. Several small pens instead of a few large ones keep the back and forth movement of cattle to a minimum. Because of the diagonal fences, cattle move through gates much more easily and quickly than in the usual square-corner type of corral. Cattle can be cut 8 to 10 different ways from a single gate. When fewer cuts are required, some of the division fences may be eliminated.

Convenient equipment is just as important for sheep and goats. Workable cutting chutes speed the handling and increase the accuracy of results.

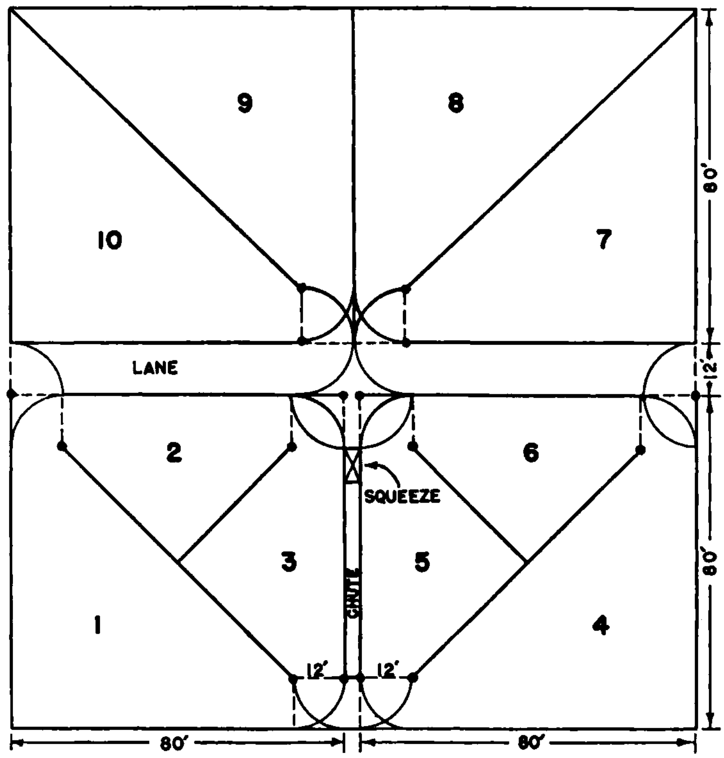

FIGURE 1. Corral system at the Ft. Robinson Beef Cattle Research Station, Crawford, Nebraska *(Koch, 1955).*

Sheep will work better in a chute that goes uphill. Portable scales are especially useful for weighing sheep and goats. Often, it is desirable to take the scale to the sheep rather than trail them to a central corral with a permanent scale installation. Portable dial scales and a weighing crate for sheep were described by Harris *et al.* (1952).

In addition to cutting chutes, sheep corrals should be designed with a four-foot alley that can be used for individual examination and selection. Such an alley permits a more thorough inspection of the animals than when they are moving along a narrow cutting chute. A dog properly trained and supervised is an invaluable aid.

BODY SCORES AND MEASUREMENT TECHNIQUES

Greater uniformity between lots of animals in grazing experiments may be had if consideration is given to body scores and measurements. Scores are useful in evaluating condition. Body measurements may be used in conjunction with weights to assess growth more accurately and to obtain an estimate of relative changes in bone, muscle, and fat.

Any one of several scoring procedures may be used for evaluating condition or fatness. The range of scores used should provide at least 10 to 12 classes as objectively defined as possible. The accuracy of scoring generally can be increased by averaging the scores of three or more independent observers working at the same time, in which case only four or five classes are needed.

A system of scoring sheep adopted by the United States Department of Agriculture uses the basic scores from one to five for excellent, good, medium, fair, and poor, respectively. Plus and minus values indicate the upper and the lower third of each score. This system is readily adaptable to a wide variety of traits. Numerical and descriptive values of these scores are shown in table 3. Column 5 gives a numerical value assigned to each score for computational purposes. Theoretically, scores 6 to 10 should be included, but they occur so infrequently that they are put in the score "5." Factors such as year, season, age, sex, type of birth, and age of dam affect condition scores and should be taken into account in statistical analyses.

TABLE 3. Typical methods of scoring

Score	*Per cent of perfect*	*Descriptive term*	*Market term*	*Numerical value*
1+	98.3			15
1	95.0	Excellent	Choice	14
1−	91.7			13
2+	88.3			12
2	85.0	Good	Good	11
2−	81.7			10
3+	78.3			9
3	75.0	Medium	Medium	8
3−	71.7			7
4+	68.3			6
4	65.0	Fair	Common	5
4−	61.7			4
5+	58.3			3
5	55.0	Poor	Cull	2
5−	51.7			1

Equipment for measuring is relatively simple. A metal bar, calibrated in centimeters and millimeters, with two bars sliding at right angles (with locks) is useful for width and depth measurements. Built-in levels allow the bar to be held in exactly vertical or horizontal positions. A large metal caliper is useful for taking length and width measurements and can be read by laying it alongside the measuring bar. A flexible steel tape, calibrated in centimeters and millimeters, is convenient for circumference and over-all length measurements. When inches and pounds are used, they should be recorded to the nearest tenth, rather than to some other fraction.

Measurements obtained from animals in fleece or from enlarged photographs generally are less accurate than those obtained from sheared animals. Photographic measurements in beef cattle are quite highly correlated with body measurements.

Wool production is difficult to measure accurately for periods of less than a year's growth. Both fineness and length of wool are influenced by environmental conditions. Although amount of clean wool is the best measurement of response to experimental treatment, wool clipped from a measured area has a useful relation to the clean weight. Since small samples have limited accuracy at best, actual shearing should not be ruled out in experiments of four months or less. Staple length alone is a useful measure of wool growth. Too, the wool fiber diameter reflects the health and plane of nutrition in the period when growth was made.

Wool fineness or grade generally is obtained by visual inspection in conjunction with standard grade samples. Wool generally is graded in numerical grades or spinning counts which often are grouped into "blood" grades. General agreement concerning these groupings does not prevail. Objective methods of measuring fineness or fiber diameter are given in the American Society for Testing Materials Standards for Textile Materials, January 1956.

Blood Chemistry and Mineral Nutrition in Grazing Experiments

The primary use of blood chemistry in range studies is to differentiate between health and disease in animals and to get a measure of possible range deficiencies. In healthy normal animals, the various blood constituents should fall within certain specified limits. In practice, this is not always the case. Factors such as physiological state, age, and nutritional treatment may cause deviations from these values.

Requirements of the animal during gestation and lactation differ markedly from those during growth or fattening. As a result, the blood composition may vary widely at different times. In order to use blood chemistry most effectively, normal values must be established for the various physiological states.

A number of nutritional deficiencies can be detected by determining constituents of the blood. For example, the vitamin A content of blood will definitely establish whether a deficiency of this nutrient exists. Specifically, in pregnant cows the vitamin A content will indicate whether a strong or weak calf will be dropped. Carotene content of the blood varies directly with intake.

Aphosphorosis can be detected before actual symptoms appear by determination of inorganic phosphorus in the blood. In order to maintain normal phosphorus levels in lactating cows, more phosphorus must be supplied in their diet than is required for either dry cows or heifers.

In certain instances, health depends on the ratio of two or more elements in the body. For example, deficiencies of iron, copper, or cobalt can cause anemia. The blood content of these elements along with hemoglobin determination is of value in determining if a deficiency exists and in prescribing the proper therapy. Many other combinations of elements are necessary for health. Because certain of the chemical determinations are difficult, skillful and carefully trained personnel are required. The trace element content of the blood can only be determined by special procedures, and by specially trained analysts. Laboratory facilities must be adequate. Special types of equipment are necessary to carry out the complex determinations. As many blood components are unstable, the blood samples must be analyzed before chemical changes can occur. Special handling is often necessary.

A definite limitation of the use of blood chemistry is lack of a knowledge of normal values of blood composition under widely different conditions. Complete blood analyses of different species in different geographical locations and under varying conditions of nutrition and management must be made. Large numbers of samples must be analyzed in order that the averages and range will have real significance.

Cumulative Effects of Grazing On Growth, Reproduction, and Longevity

Studies designed to measure cumulative effects upon breeding stocks are of long duration. Under range conditions, a minimum of three years is needed to replace a group of cows with daughters from the same herd. An actual turnover of 20 per cent is more typical of normal range practice. In general, generation intervals average from four to five years in cattle and from three to four years in sheep.

A minimum of three generations is recommended to measure cumulative effects. A shorter length of time would be required if it were possible to subject the first generation to treatment differences during the prenatal and preweaning periods. Treatment differences may be obscured by maternal effects in the second generation. In general, a minimum of from 12 to 15 years is required for cattle and 9 to 12 years for sheep.

Cumulative environment effects are difficult to measure, especially when treatment differences are not wide. Genetic variation should be minimized, not only between treatments but also between generations. Production records should be employed to select animals of similar productivity for breeding stock. A satisfactory method of sire replacement is to use sires from moderately inbred lines, i.e., closed lines in which coefficients of inbreeding change only slightly between generations. The productivity of replacement sires should be the same as that of the original sires.

Differential growth between treatments may be appraised by periodic weights throughout the test period, body and wool measurements, and carcass evaluations of meat quality and bone structure. Differential reproductive rates between treatments are measured by (1) number born alive, (2) number of stillbirths and abortions, (3) number of progeny reared to weaning, and (4) death loss after weaning. Critical autopsy data for stillborn calves and other unexplained deaths should be obtained throughout the course of the experiment.

Normally, longevity is measured by the lifetime of an individual. A more practical measure is the age at which individual production levels start to decline. For improved accuracy, progeny records should be adjusted to a mature age. Since the improvement achieved through selection is speeded up by turning generations at a rapid rate, the importance of longevity as a selection criterion may have been overemphasized.

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Chapter 7

Methods of Studying Watershed Aspects of Range

INTRODUCTION

THE RANGE management specialist has a vital interest in the behavior of water as it is deposited, infiltrated, or lost from the soil. Retention of some moisture is necessary for forage growth. Downstream ranchers and farmers are dependent upon water yields for irrigation, and urban dwellers for domestic water supplies. Conversely, excessive runoff creates erosion hazards and flood damages. It is only natural, therefore, that range research includes studies of infiltration, runoff, and erosion.

To appraise watershed problems of rangelands intelligently, the researcher should be aware of interactions between atmosphere, water, soil, and vegetation as precipitation is received and disposed. This is a specialized field in itself, and the researcher will do well to consult experienced hydrologists and soil conservationists. Little more can be done here than state basic concepts, enumerate some of the principal methods and pieces of equipment, and direct the reader to original publications for details of watershed research methods.

INFILTRATION

Definitions

Infiltration

Infiltration is the "downward entry of water into the soil" (Soil Sci. Soc. Amer. 1952). This involves two associated phenomena: the passage of water through the soil surface *(intake)* and the movement through the soil mass *(percolation)*.

Intake is a surface phenomenon, governed by conditions in the upper layer of soil, usually only a fraction of an inch deep, which when exposed is subject to direct modification by the weather. Transmission of the water through the profile depends upon internal conditions independent of those governing intake. A soil's capacity to transmit water is called *permeability*, as distinguished from its *intake capacity*.

During the course of wetting, changes in the soil progressively lower the possible rate of infiltration. Raindrop impact puddles and seals the surface to reduce intake capacity. Soil colloids swell upon wetting, thereby reducing the size of pores through which the water can percolate. When muddy water enters the soil, the suspended particles are filtered out at lower levels, clogging passageways and further reducing permeability.

The rate at which water can be transmitted in the soil depends upon the hydraulic pressure gradient of that water, or the change in waterhead divided by the distance between the surface and the wet front. As the distance to the wetting front increases, the hydraulic head decreases and the rate of intake and transmission of water correspondingly decreases. Also in many soils, a horizon several inches or even feet below the surface is considerably less permeable than the material above it. When water fills all the pore space above this layer, the rate at which infiltration can occur is reduced to the percolation rate of this restrictive layer. For these and other reasons, the potential infiltration rate after several minutes of rain usually is much less than at the beginning. Eventually the infiltration rate reaches a minimum which remains essentially constant for the remainder of the storm. As the soil drains and dries, its capacity to take in and transmit water is restored. The typical trend of infiltration rate when the supply of water on the soil surface constantly exceeds its infiltration capacity is illustrated in figure 1. Any study of infiltration must take into account this fundamental relation of rate and time.

Measurements of Infiltration

Ordinarily infiltration cannot be measured directly. It can only be deduced from other measurements of precipitation (or water applied), surface runoff, and possibly other factors. Correct interpretation of these data requires an understanding of the normal hydrologic occurrences during a rainstorm. Detailed descriptions of these occurrences in relation to infiltration and runoff have been given by Horton (1940), Sharp and Holtan (1942), and others. Measurements of infiltration ordinarily are expressed as depth in inches of water over the watershed or plot area. In the following discussion, water artificially applied is spoken of as rainfall or precipitation.

The principal means of disposition of total *precipitation* (P), and the quantities which can be measured or estimated in the order of occurrence, are the following:

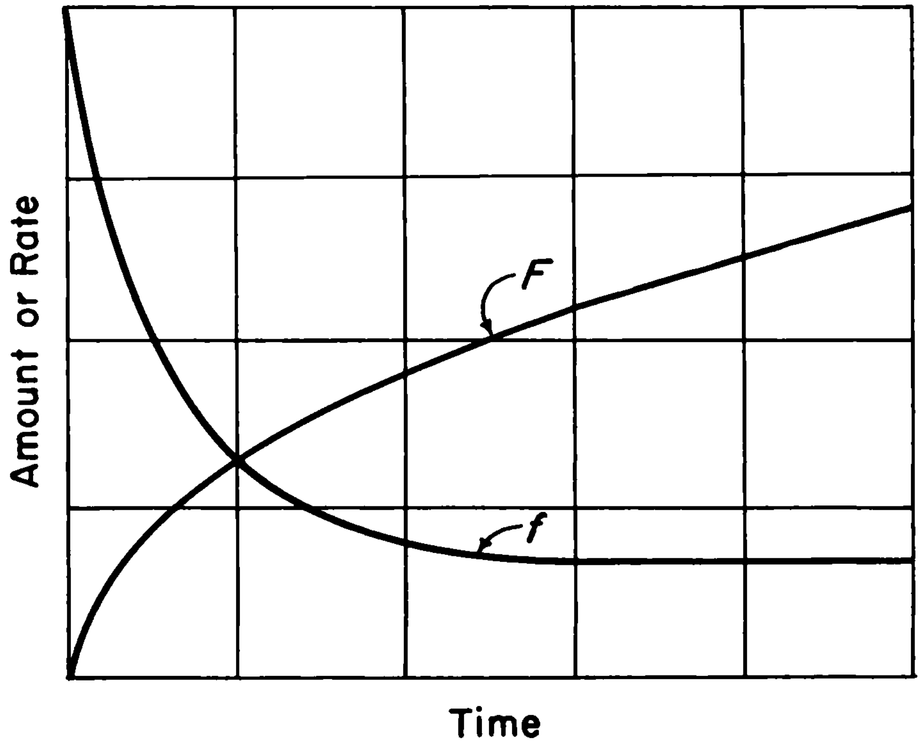


FIGURE 1. Infiltration curves. F, mass or cumulative amount of infiltration; f, infiltration rate.

(1) *Interception.* Before precipitation reaches the soil surface it may wet the surfaces of plants, litter, and other objects. The amount intercepted is variable and depends upon the vegetation and intensity and duration of the precipitation.

(2) *Stemflow.* A portion of the precipitation intercepted may move to the soil along branches and stems of plants.

(3) *Evapo-transpiration.* A part of the rainfall evaporates before or after reaching the vegetation, litter, or soil, and plants may continue to transpire during the storm. The quantity varies with type of vegetation, nature of soil, position of water table, and exposure of site. It would be noticeable only in a study of large watersheds during extended storms.

(4) *Infiltration.* Water usually begins to soak into the soil immediately upon contact. During the early part of the storm, while infiltration capacity is high and the amount of rainfall is small, all the water is absorbed and there is no surface accumulation or runoff. This infiltration is referred to as *initial infiltration* (F_i). The potential infiltration rate (f_p or infiltration capacity) at any moment declines from an initial value (f_o) to a final minimum *constant* value (f_c). An approximate *average* infiltration rate (f_a) can be obtained

by dividing the mass infiltration (F_c) that occurred during the time rainfall intensity exceeded infiltration capacity by the time during which infiltration occurred at capacity rates.

(5) *Depression-storage.* When the effective rate of rainfall exceeds the infiltration rate, part of the excess rainfall collects in depressions and adheres to the soil surface. After the rain ceases, part of this water infiltrates and part evaporates.

(6) *Detention.* As depressions fill, water accumulates in excess of depression storage and begins to spill over to lower levels. This detention water is the hydraulic head affording the motivating force for runoff. Its quantity depends upon the extent to which rainfall rate at any moment exceeds the combined infiltration and runoff rates. After rain ceases, part of the detained water evaporates and infiltrates while the remainder continues to run off.

(7) *Surface runoff.* Simultaneously with the accumulation of detention, water begins to flow over the ground surface. That leaving the area is called surface runoff.

(8) *Retention.* The sum of all the foregoing except surface runoff is referred to as retention. The difference between precipitation and runoff is retention. On small plots where interception, evapo-transpiration, depression storage, and surface detention are negligible, retention may be considered equivalent to infiltration. On large areas and watersheds, the other elements in retention must be accounted for to get reasonable values for infiltration.

(9) *Storage* in the soil. The infiltrated water fills the pore space in successive horizons of the soil as it moves downward. That held against the pull of gravity by capillary attraction in the soil mass is *retention storage.*

(10) *Percolation.* After water enters the soil mass it moves through the various layers in accordance with their respective permeability rates. As the successive horizons become saturated, the one with the least permeability restricts the rate of percolation, causing water to back up on the surface and resulting in reduced infiltration and increased runoff. After rain ceases, water not held by surface tension continues to drain from the soil until a state of quasi-equilibrium termed *field capacity* is reached.

(11) *Subsurface runoff.* The percolating water may reach impervious layers which divert it laterally to the surface downslope from its point of entry, or into streams. Here it joins the surface runoff and may be measured as such at the outlet of the area under study.

(12) *Ground water.* The infiltrated water which is not held by retention storage and does not reappear as surface runoff ultimately reaches the water table and contributes to ground water.

The relationships of the principal surface phenomena are illustrated by superimposing a hydrograph (a plotting of rate of runoff against time) onto a similar plotting of rainfall intensities (figure 2) for a particular storm.

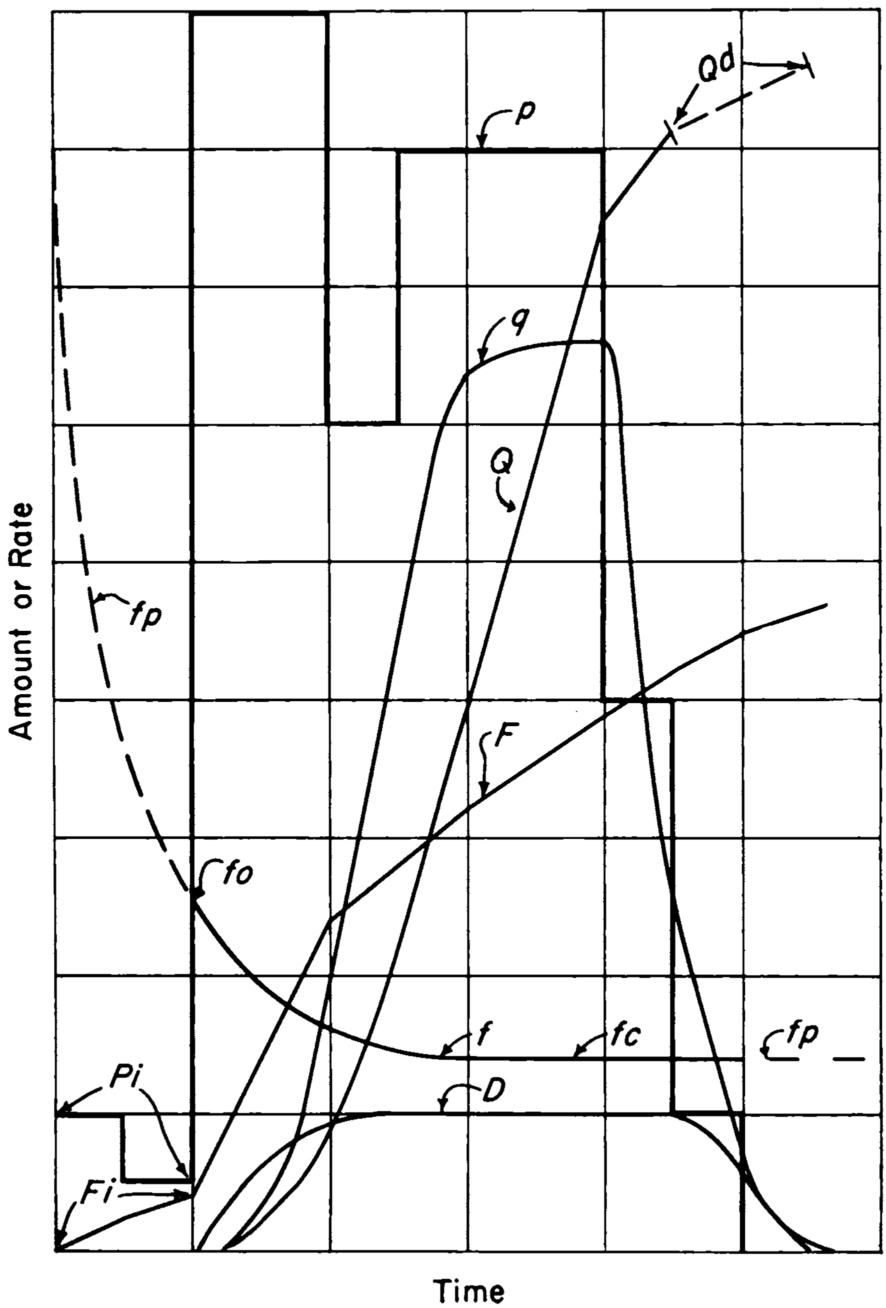


FIGURE 2. Comparison of hydrograph of a storm with rainfall intensity and infiltration curves. *D*, surface detention; *F*, mass infiltration; F_i, initial infiltration; *f*, infiltration rate; f_p, infiltration potential (capacity); f_o, initial infiltration rate; f_c, constant infiltration rate; *p*, precipitation rate; P_i, initial precipitation; *Q*, mass runoff; *q*, runoff rate; *Qd*, runoff from surface detention.

Methods of Field Study

Amounts and rates of infiltration can be determined by two general methods: (1) Measurements of natural rainfall or artificial applications of water, and associated runoff, by means of infiltrometers, and (2) analysis of rainfall and runoff data from natural watersheds. A combination of the two methods may also be used.

Plot Studies

Plot studies are especially significant in yielding information on the intake and storage of water for plant use and the proportion of excess rainfall escaping as runoff and causing erosion and floods. Small plots lend themselves to the comparison of effects of different soil and cover conditions on infiltration.

The early part of the infiltration curve (f_o) is of special importance to moisture storage and surface runoff on rangelands. In much of the range country, most rains are brief and fall on dry soil. The growth of range plants depends upon the capacity of the soil to take in and store a maximum of this meager rainfall. Furthermore, these small rains frequently are of high intensity. Correspondingly high infiltration rates, normal during the initial phase of a storm, reduce the possibility of flash floods and erosion damage.

Plots give valuable information on the water intake and runoff characteristics to be expected under natural field conditions when water is applied in a manner simulating the duration and magnitude of local rainstorms.

On the other hand, the infiltration constant (f_c), or the minimum rate that prevails after the soil is thoroughly wet, is the critical factor in predicting flood hazards and calculating watershed runoff. This value is obtained in plot studies by means of the "wet run," a second application of water to the same plot, usually 24 hours after the "initial run" (Rowe 1940; Free *et al.* 1940). Infiltration curves or indices from both runs on the same plot give the most complete picture of the water intake and runoff characteristics of the site being sampled.

Three types of equipment are used for plot studies: lysimeters, flooding devices, and sprinkling devices.

Lysimeters

Lysimeters are containers holding a quantity of soil which is exposed to natural rainfall, or to which a known quantity of water is applied. Some are arranged to enable intermittent weighing of their contents. Approximate infiltration can be determined from the increase in weight. Others permit measure-

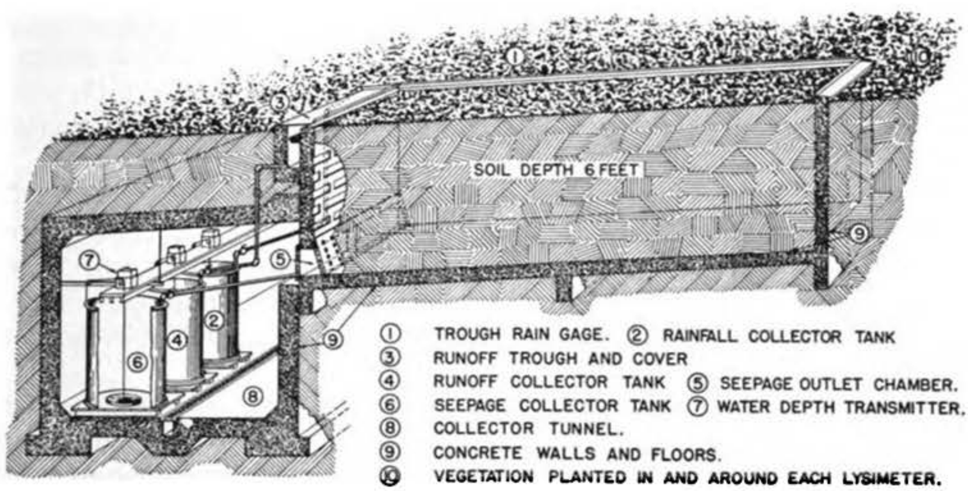


FIGURE 2A. Diagram of a San Dimas lysimeter *(Colman and Hamilton, 1947).*

ment of the water percolating through the soil or running off the surface. Kohnke *et al.* (1940) classify lysimeters into three major types: (1) monolith, or undisturbed soil block; (2) Ebermayer, and (3) filled-in.

In the monolith type, a case is built around the sides of a block of soil as it is found in the field, a partly open bottom is attached, and the percolate is conducted to receiver tanks. Tenth-acre lysimeters of this type using concrete walls and impervious base rock for the bottom have been used successfully at the Sierra Ancha Experimental Forest.

In the Ebermayer type the soil is left in site and a percolate collecting funnel is placed under it but no side walls separate a definite soil block from the adjoining soil. A tube attached to the funnel conveys the percolate into a receptacle.

The fill-in lysimeter consists of a container which has vertical sides, an open top, and a bottom that provides for percolation and is filled with soil that has been moved from its original location. In some lysimeters of this type the tops of the side walls are completely covered with soil so that the ground is level with the surrounding surface. This permits natural runoff and minimizes border effects.

There are numerous variations from these three types, and the researcher should review previous studies before deciding on the type to use. Review of Kohnke *et al.* (1940), Colman and Hamilton (1947) and Harrold and Dreibelbis (1951) would be helpful.

Flooded Plots

Flooding methods make use of tubes, rings, or frames to confine the water on the surface until it soaks into the ground. Water is usually applied at a rate to keep a constant supply or "head" on the soil surface. The quantity of water absorbed is measured as it is withdrawn from the supply container, either by a recording gauge or by noting the contents remaining in the container, at specified time intervals. The measured intake is plotted against time to give the infiltration rate curves.

Tubes: Auten (1933) used brass tubes 2 inches in diameter and 12 inches long, forced into the ground only far enough to prevent escape of water under the tube and through the surface soil. Measured amounts of water were poured into the tubes and the time required to complete absorption noted. This simple device gave comparative values for different soils, but did not permit an analysis of infiltration trends.

Musgrave (1935) and Free, *et al.* (1940) used batteries of tubes forced into the soil and water supplied from calibrated burettes to study infiltration capacities in relation to physical characteristics of soils. These tubes were of galvanized steel, 9 inches in diameter and 18 to 24 inches long. They were jacked into the soil to penetrate the B horizon, leaving a few inches protruding above the surface. A 1,000-cc. dispensing burette was mounted above each tube with the outlet about ¼ inch above the soil surface. This established a constant head of water ¼ inch high in each tube. The amount of water withdrawn from the burettes was read at intervals (5 minutes during the first half hour to 1 hour during the latter part of long runs) and later converted to inches. Ordinarily 6 to 12 units were installed for each determination. If wet runs were to be made, the equipment was left in place until the next day after the initial run.

Rings: Lewis (1937) and others have used metal rings or frames pressed into the soil only far enough to prevent escape of the water through the surface soil. These devices are simple to use, but frequently are too shallow and allow lateral movement of the water in the topsoil. Primarily, they measure the intake rate of the soil without reflecting the full effect on the infiltration curve of lower percolation rates of subsurface horizons.

Partially to eliminate the error of lateral movement, some workers use pairs of concentric rings. The smaller rings, 6 to 12 inches in diameter, are placed inside the larger, 18 to 36 inches in diameter. Water is applied simultaneously in both rings and kept at the same level. Only the data from the inner ring are taken as indicating infiltration, it being assumed that the wetted zone beneath the larger ring serves as a buffer to reduce lateral movement of water entering from the inner ring. Standardized equipment and procedures for this method are described by Haise *et al.* (1956).

Kohnke (1938) modified equipment to get separate readings from 16 compartments of the plot. Data from the four inside compartments were used for replication. The outside compartments served as buffers to reduce the error of lateral movement.

Cox (1952) described an apparatus using concentric rings with a float-

FIGURE 3. Concentric-ring type infiltrometer with automatic water supply recording gauge. The rings alone are frequently used with manual application and measurement of water. *(U.S. Soil Conservation Service photo)*

valve control of the water supply and a recording rain gauge to provide an automatic continuous record of infiltration.

Pearse and Bertelson (1937) used a 1-square-foot plot, 19.3 by 7.5 inches enclosed by baffle plates forced gently into the soil. Water was supplied from a 1-gallon container through a perforated tube which spread it uniformly over the uphill side of the plot. Rate of application was regulated to maintain a constant flooding of the plot with continuous runoff. The runoff was caught below the plot and measured in a tipping bucket. The difference between the amount applied and runoff caught was considered infiltration.

Sprinkled Plots

By spraying or sprinkling water on the plots, results more nearly like those occurring in natural rainfall are possible. Since the late 1930's, the Soil Conservation Service has developed a series of rain simulators in cooperation with the Hydraulics Laboratory of the National Bureau of Standards. Simultaneously, the Forest Service produced two models especially adapted to use on rough terrain in the western United States. With these different infiltrometers it is possible to apply water at varying rates to plots ranging in size from 1.5 square feet to 0.01 acre.

With all these devices, water is applied at rates in excess of infiltration capacity and the runoff is collected and measured. Infiltration is calculated from the difference between application and runoff; allowance is made for depression-storage and surface detention on the larger plots. For precise results, the soil is separated from the water in the runoff before measurement. The amount of soil is an indication of erosion hazards on the plots.

These infiltrometers differ principally in plot size and the drop size of the spray. The latter feature is especially important, since the impact of the drops on the soil is significant in changing the intake rate during a rain.

The principal models which have had wide use in the field are described briefly below. Specifications and instructions for operation are included in the publications cited, or can be obtained from the originating agencies.

Type D-1 infiltrometer: The sprinkler system of the type D-1 infiltrometer of the Soil Conservation Service series consists of 4 stationary Grinnel 1.-"Mulsifyre" nozzles mounted on an overhead frame to apply water to a 6- by 24-foot plot surrounded by an 18-inch buffer zone. With 2 nozzles operating, the apparatus applies about 3.3 inches per hour, with 4 operating, about 6 inches per hour, of a large-drop spray.

The study plot is enclosed on three sides by six-inch boundary plates extending four inches into the soil. The lower end-plate is modified to collect and discharge the runoff into calibrated measuring tanks. The entire apparatus is protected from wind by a canvas tent.

Water is supplied from tanks mounted on a truck. It is first allowed to flow to a sump tank where the water is maintained at a uniform level by a float valve. From here it is pumped to the applicator under a constant pressure regulated by valves.

Check runs are made at each site to determine the exact rate of application. This is accomplished by covering the plot with a waterproof canvas which directs the entire rainfall into the measuring tanks for a period before and after each infiltration trial.

Beutner *et al.* (1940) used this equipment in runoff and infiltration experiments with Arizona desert soils at Tucson. A hydrograph was plotted for each run, and analyzed by methods described by Horton (1939).

Type E infiltrometer: This infiltrometer uses a long plot, 72.6 by 6 feet (0.01 acre). It was designed especially for the study of the effect of slope on runoff and erosion (Borst and Woodburn 1940). A double row of nozzles are mounted along each side of the plot 9 feet above the ground, to spray inward. Soil and water are caught as they run from the lower end of the plot. The spray is considerably finer than in the other rainfall simulators; the drops are smaller than in natural rains of the same intensity.

Type F infiltrometer: A widely used large-plot infiltrometer is the type F, of the Soil Conservation Service series, which resembles the type D-1 in construction and operation. The distinguishing feature is the nozzles, which were especially designed to provide a high-energy spray, comparable to a typical thundershower, with drops falling nearly vertically. Application rate is varied by changing the number of nozzles. The spray oscillates to give even distribution. The plot is 6 by 12 feet (or some other multiple of 12 feet in length), surrounded by a buffer zone of about 3 feet. A metal "rain pan" is used to cover the plot to measure rate of application before and after infiltration tests.

North Fork infiltrometer: Designed by the Forest Service, the North Fork infiltrometer was developed to provide mobility and ease of operation, precision of measurements, and adaptability to various slopes for work on rough terrain (Rowe 1940).

The plot is 12 by 30 inches, horizontal measurements. The equipment is adjustable to slopes of up to 100 per cent. Water is sprayed on the plot by a pressure pump and a four-nozzle assembly at the lower end of the plot. The fog-type nozzles have removable brass screens to permit varying intensity from 0.75 to 10 inches per hour. Runoff is measured in the collection tank

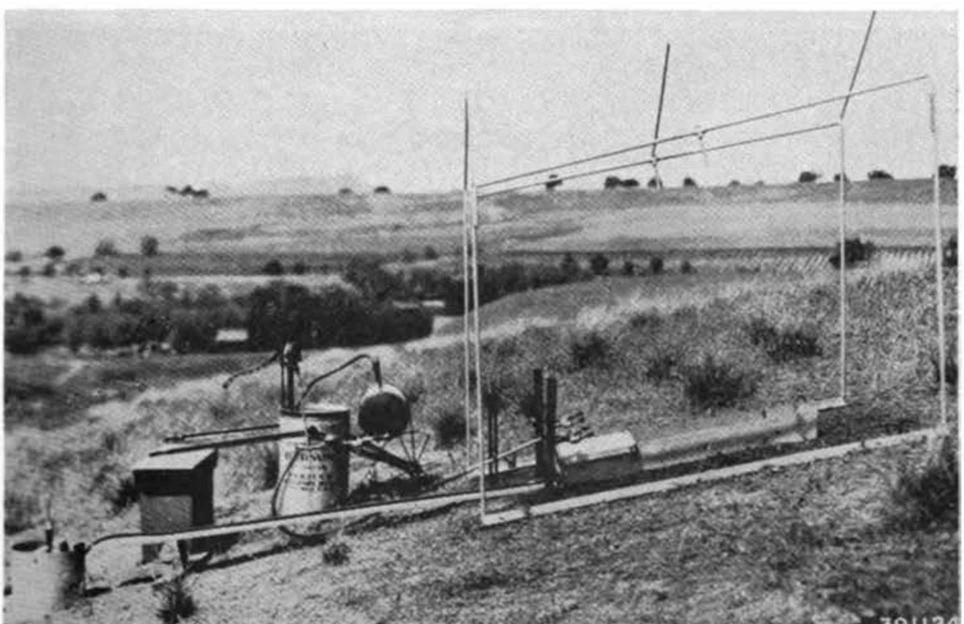


FIGURE 4. North Fork infiltrometer, an example of the sprinkled-plot type of apparatus. *(U.S. Forest Service photo)*

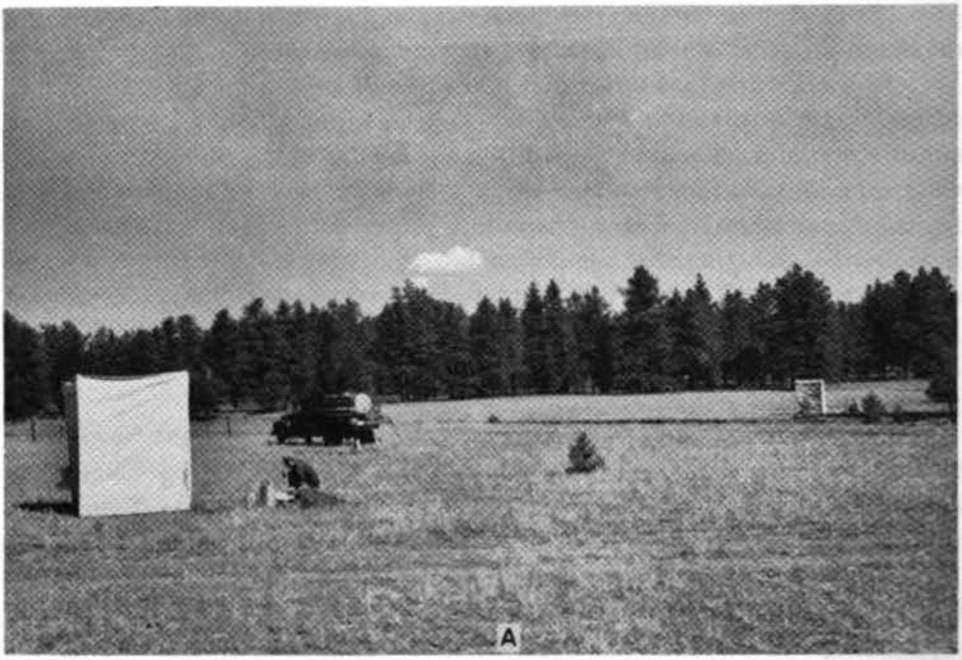


FIGURE 5. Rocky Mountain infiltrometer. *A*, in field use. *B*, closeup of apparatus. *(U.S. Forest Service photos)*

with a point gauge which permits readings every 30 seconds. The procedures described permit determinations of total infiltration, infiltration capacity, surface runoff, depression-storage, and surface detention.

Type FA infiltrometer: The Soil Conservation Service type FA infiltrometer is a modification of the North Fork instrument, using some of the features of the type F. It uses one type F nozzle mounted at the side of the plot and supplied by a power pump. The North Fork plot instrumentation is used, either in size 1 by 1½, or 1 by 2½ feet.

Rocky Mountain infiltrometer: The Rocky Mountain infiltrometer originated from the type FA, but differs in being simplified and lightened for ease of handling and carrying (Dortignac 1951). All equipment, including a 500-gallon supply tank, is carried on a 1½ ton truck.

The plot measures 12 by 30½ inches, an area of approximately 2.5 square feet on which 6,000 cc. of water equals a depth of 1 inch. A plot frame 6 inches deep is set 3 inches into the ground. A trough at the lower end collects runoff and soil and discharges them through tubes to 1-gallon containers. Rain troughs 1 by 30½ inches are mounted on both sides of the plot and discharge into a separate container, thereby providing a continuous measurement of rate of application throughout the test.

Water is sprayed upward from three type F nozzles mounted on a pipeline system to one side of the plot. The collection cans are quickly changed at intervals to permit separate measurements and calculation of runoff and infiltration rates.

Other raindrop applicators: To account for the effect of drop impact on infiltration rates during tests, a special type of rain simulator is needed with which the size and fall velocity of the drops can be controlled. These are called "raindrop applicators" because of the special control over the characteristics of the individual drops.

Type C of the series developed by the Soil Conservation Service accomplished this by using a horizontal sheet of muslin with many short pieces of yarn hanging from the lower side to convert a spray above the cloth into large drops which form and fall from the tips of the strands. The size of the yarn regulates the diameter of the drops and the distance of fall controls the velocity at the point of impact.

Investigations by Laws (1941) established a complete scale of fall velocities for different sized drops from different heights. Thus the impact energy of any test application can be regulated to any level by varying rainfall intensity, drop size, and distance of fall. Impact energy can be completely eliminated by lowering the drip-screen until the tips of the yarn strands touch the ground.

To adapt this equipment to field studies on rangeland in Texas, a mobile raindrop applicator was mounted on a one-ton truck (Osborn 1950) (fig-

FIGURE 6. Texas model of raindrop applicator. *(U.S. Soil Conservation Service photo)*

ure 6). The muslin drip-screen is supported on a one-inch mesh chicken wire rigidly mounted in a telescoping canvas-covered tower. Water is supplied to the spray head through a flexible hose from a pressure tank mounted on the truck. The 12- by 18-inch plot is located in the middle of the wetted area 6 feet in diameter. Runoff is discharged directly into a collection jar below the plot. Although the Texas equipment was designed primarily for study of splash erosion, it serves equally well as an infiltrometer (Osborn 1952).

Significance of Plot Data

Plot studies cannot be expected to give results directly applicable to watershed areas. Variations in soil, cover, and other factors which affect infiltration rates preclude this. Data from small plots are most useful in studying the relation of infiltration to selected individual factors, in establishing normal infiltration characteristics of particular soils, and in comparing relative characteristics of different areas.

Influence of method: In interpreting plot data, the effect of the experimental method itself on the results must be kept in mind. For example, flooding-type infiltrometers generally indicate higher infiltration rates than sprinkler types, since with the former the water enters the soil under a constant head and without drop impact. Rings generally yield higher values than tubes because there is greater opportunity for lateral movement of water in the soil.

The degree of control over lateral movement of infiltrated water affects the measured results with different equipment. The character of the soil studied and the degree to which it offers opportunity for lateral movement likewise affect results. In natural rainfall covering a large area, this variable is largely eliminated. Many infiltrometers provide wetted buffer zones around the study plots to reduce this source of error.

In plot studies where lateral movement is not controlled, the plot size affects the magnitude of the measurements. Marshall and Stirk (1950) in a study of this problem found that when no buffer zone was used the minimum infiltration capacity (f_c) of a soil decreased with the plot size and there was a corresponding increase in the fraction of applied water remaining beneath the plot at the conclusion of the trial. Buffer zones around flooded plots reduced lateral movement somewhat, but results were subject to considerable error; sprayed buffer zones around small plots were generally effective. The authors concluded that data from flooded plots could be corrected by a factor proportional to the fraction of the applied water remaining beneath the plot at the end of the trial, as determined from moisture samples before and after the test.

A comparison of three rain simulators by Wilm (1941) indicated that any one could give only a relative estimate of true infiltration. The results obtained with any of the instruments (Type F, Rocky Mountain, and North Fork) agreed relatively well among themselves, but were not comparable to other infiltrometers. The Pearse square-foot plot infiltrometer (a flooding type) gave consistently higher results. Such variation in quantitative measurements by different equipment on the same soil undoubtedly is characteristic of all plot measurements of infiltration.

Influence of soil: An effort to correlate the great mass of data obtained from a wide variety of infiltrometers on many different soils was made by Krimgold and Beenhouwer (1954) by grouping all soils into four categories based on relative infiltration capacities. This principle is carried further in developing a "hydrologic grouping" of soils (Musgrave 1955) for use in the hydrologic analysis of watersheds. This grouping uses available knowledge of profile characteristics to classify soils first on the basis of similarity of texture and other properties known to influence infiltration. The relative infiltration capacities of these groups are then deduced from available infiltrometer data from examples of the groups used in experimentation.

Musgrave lists the soil factors affecting infiltration rate as: (1) surface condition and amount of protection against the impact of rain; (2) internal characteristics of the soil mass, including pore size, depth or thickness of the permeable portion, degree of swelling of clay and colloids, content of organic matter, and degree of aggregation; (3) the moisture content and degree of saturation; and (4) season of the year and temperature of soil and water.

Influence of vegetation: On rangeland, vegetation greatly affects infiltration. In plot studies, this factor must be standardized to eliminate it as a variable, or it must be measured so it can be considered as an independent variable in the correlation of results.

Vegetation affects infiltration in two ways: (1) directly, as the plant cover intercepts part of the rain, protects the soil from compaction by the raindrops, or detains the water on the soil surface, thereby allowing more time for infiltration, and (2) indirectly, as the plants have influenced soil conditions and modified the soil factors previously mentioned.

Sealing the soil surface by raindrop impact especially affects infiltration during the early part of the storm. The presence of plant cover reduces this effect to about the same degree that it prevents soil splash (Osborn 1952). Total plant cover, including living plants and litter, is more significant than the kind of plants (Duley and Domingo 1949, Osborn 1954).

Soil conditions are profoundly influenced by vegetation. These influences affect the entire range of infiltration capacities of a soil, including the final constant rate (f_c) where it is not limited by shallow rock or other impervious material. Lassen and others (1952) have summarized these soil-plant-water relationships.

Watershed Studies

From records of surface runoff from a watershed and recording rain gauge data, the infiltration capacity of the area can be determined. The computations are involved (Horton 1937, 1939, Sharp and Holtan 1940, 1942), however, and are primarily within the province of the hydrologist. Such problems are closely related to the study of runoff and are discussed in more detail in the following section of this book. The Hydrology Handbook of the American Society of Civil Engineers (1949) is a good reference on this subject.

The simplest index to infiltration capacity of a watershed is the average rainfall intensity which causes runoff, or the intensity above which all rainfall is runoff. This index includes both infiltration and surface detention, and is highly variable with changing cover and soil conditions.

More significant is the *retention* rate, which is the difference between rainfall rate and runoff at any time. If the amount of water held in storage on the vegetation and the ground surface can be determined, this amount subtracted from the retention rate gives the infiltration rate (f). Methods of calculating these elements of retention are discussed in the publications mentioned above.

Where a true infiltration rate curve for a storm can be plotted, the average infiltration rate (f_a) can be obtained by dividing the mass infiltration (F_c) by the time during which rainfall exceeds infiltration capacity. This is a good summary index to the infiltration characteristics of a watershed.

Several infiltration rate curves for different storms on the same watershed can be integrated into a standard infiltration curve for the watershed, for purposes of forecasting either water yields or flood hazards.

Infiltration data obtained from watersheds of more than a few acres are of little value in revealing the influence of specific soil or cover conditions on infiltration capacities because of the great variability of these factors in any natural area. However, infiltrometer plot data can be used to interpret results obtained from watersheds.

A combination of small-watershed and plot measurements can be used to good advantage to analyze large complex watersheds (Rowe 1940). This requires subdividing the large watershed into several areas, each homogeneous as to topography, soils, vegetation, and other features which influence infiltration and runoff. A series of infiltrometer measurements is made within each area to establish characteristic infiltration capacities. Infiltration and runoff to be expected of typical rains are calculated for each area from these values, and combined to give a total for the watershed.

The method is widely used in flood-control surveys by the Department of Agriculture. An example of such a study on a range area was reported by Lull (1949).

Soil Compaction

Soil compaction can be defined as the packing together of soil particles by instantaneous forces exerted at the soil surface resulting in an increase in soil density through a decrease in pore space. The more intensively rangelands are used, the greater the opportunity for soil compaction. Sheep or cattle trails and bedding grounds are areas of greatest compaction.

From the standpoint of soil and water conservation, compaction can be harmful. Its effect is to increase the density of the soil by reducing pore space. This slows water movement into and through the soil; surface runoff may occur more frequently and may increase in volume; surface runoff starts erosion, and erosion once begun may be difficult to stop.

Compaction may also reduce growth of vegetation through its deleterious effects on soil aeration, infiltration, and soil moisture supply. In coarse-textured soils where moisture is limiting and aeration adequate, a certain amount of compaction may be beneficial by increasing the moisture content and nutrient supply per unit volume of soil.

The effect of compaction can be measured directly by comparing bulk densities of the soil before and after trampling and noting changes in oven-dry weight of the soil per unit volume, or indirectly by comparative measurements of pore space or rates of infiltration or percolation.

As the major effect of compaction is on infiltration, infiltration tests, before and after compaction, may be most revealing. Trampling generally compacts only the soil surface, usually the upper inch or two. These thin compacted layers are difficult to sample in the undisturbed state so that indirect measurements of soil compaction by infiltration tests or pore space measurements are more sensitive indicators of its effect.

Bulk density samples are usually obtained with a cylinder of known volume which is driven or pushed into the face of a soil pit. Samples should be taken when the soil is near field capacity. The oven-dry weight of the soil sample divided by the cubic centimeters of its volume gives the bulk density value. Bulk densities of most mineral soils range between 1.00 and 1.50.

In stony soils where sampling cylinders cannot be driven into the soil, bulk density may be measured by digging a small hole with a trowel, oven-drying and weighing the material removed, and measuring the volume of the hole either by filling it with a measured volume of sand or thick oil, or by filling it with plaster-of-Paris and determining the volume of the cast by weighing it in air and water. Procedures for measuring bulk density have been described by Lutz (1944), Baver (1956), Hoover *et al.* (1954), and Broadfoot (1954).

Compaction also affects soil porosity. Total pore space is reduced with the large pores, the non-capillary portion, most greatly affected. Total pore space may be estimated from bulk density assuming a specific gravity for mineral particles of 2.65. A soil with a bulk density of greater than 1.325 would have, for instance, a total pore space of something less than 50 per cent. Non-capillary pore space can be determined in the laboratory by subtracting the per cent volume of water held in a soil core at 60 centimeters tension from the volume held at saturation (Hoover *et al.* 1954). In a recent study by Read (1957) this technique was used to determine the effect of heavy grazing in shelterbelts on soil porosity with the following results:

	Heavy grazing	*Protection*
Bulk density	1.22	1.01
Total pore space (per cent)	51.7	57.3
Non-capillary pore space (per cent)	7.6	14.1

The change in non-capillary pore space provided the most sensitive indicator of compaction effect.

Relative compaction could likely be measured with the type of penetrometers that have been used to determine the location and depth of compacted plow layers (Baver 1956). Here again stoniness may present a problem by inhibiting penetration of the instrument. Also variation in soil moisture content may present problems because penetrability is closely associated with soil wetness.

Radioactive probes have been developed for determining both soil density and soil moisture (Van Bavel 1958, 1959). Measurements are based on the varying degree that radioactivity is scattered when placed in contact with materials of different density or soil moisture content. The density probe uses a cesium-137 gamma ray source and the moisture probe a radium-beryllium source of fast neutrons to provide the radioactivity. Radioactive counts are made and converted to density in pounds per cubic foot or percent moisture by volume by reference to calibration tables.

Compaction can be a transitory effect and may best be measured in the season in which it occurs. This would be particularly necessary where soil surface is loosened by frost. A soil surface, compacted in the fall, may through winter frost action appear quite porous the following spring.

Regulation of stock to obtain a known-trampling force over small experimental plots is difficult. To obtain a range of trampling effects on infiltration plots, Packer (1953) pounded the soil with a steel bar. Different degrees of trampling were simulated from plot to plot by varying the spacing and number of impacts.

RUNOFF

Runoff is that water received as precipitation that leaves the area as surface runoff or flow, or subsurface flow. The range manager is usually interested in the effects on runoff of such practices as different intensities, periods, or systems of grazing; harvesting or burning vegetation; removal of undesirable plants by chemical or mechanical methods; seeding, pitting, or other treatments of deteriorated rangelands; and water spreading.

Methods of Measuring

Quantity of runoff is usually expressed in cubic feet, depth in inches over the watershed, or acre-feet delivered at a point in a designated period of time. Flow in streams is usually expressed as a rate of discharge—cubic feet per second (c.f.s.), often abbreviated to second-feet. On a unit-area basis, discharge is frequently calculated as second-feet per square mile (c.s.m.).

Streamflow is more than surface or overland flow. It represents a composite of runoff including, in addition to surface runoff, subsurface flow and contributions from ground water. Measured streamflow does not always account for all runoff at a given point. Subsurface water may pass through pervious strata below the measuring site and appear as surface flow at some point downstream.

In range studies most workers have used relatively small areas from which runoff is received as intermittent overland flow. Occasionally techniques have been used for obtaining a separate measure of water percolating into the ground and moving laterally as subsurface flow. Some studies have been made in natural drainage areas sufficiently large to produce sustained streamflow representing all segments of runoff.

A common method of determining runoff in grazing experiments is by measuring the volume accumulated in one or more catchment tanks. Usually this is done after each storm. In some cases where runoff is expected to exceed the storage capacity of the tanks, weirs of known capacity are installed and

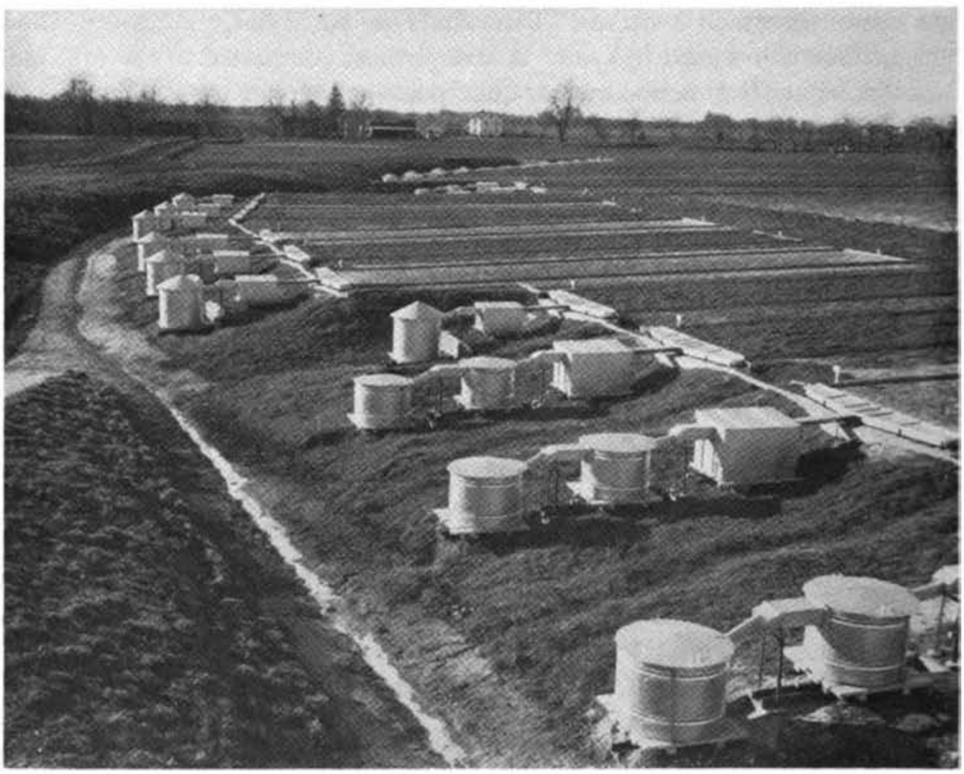


FIGURE 7. Permanent plots for studying runoff and erosion at a conservation experiment station. Below each plot is a silt box and one or more storage tanks. Between the box and tanks are divisors to take aliquot samples of the runoff. *(U.S. Soil Conservation photo NJ-R2-39)*

equipped with recording charts to measure flow. Where experimental watersheds are large enough to produce seasonal or perennial stream-flow, standard gauging methods are employed using weirs or flumes to arrive at a rate of discharge (Dils 1953, and Johnson 1952).

Quantitative information on runoff in range investigations can be obtained from either watersheds or plots. Plots fall into two general categories: permanent and portable. Plots can be designed to measure the effects of treatments either on surface runoff alone or both surface and subsurface runoff. With watersheds it is frequently possible to measure all segments of runoff: surface, subsurface, and accretions from ground water.

Permanent Plots

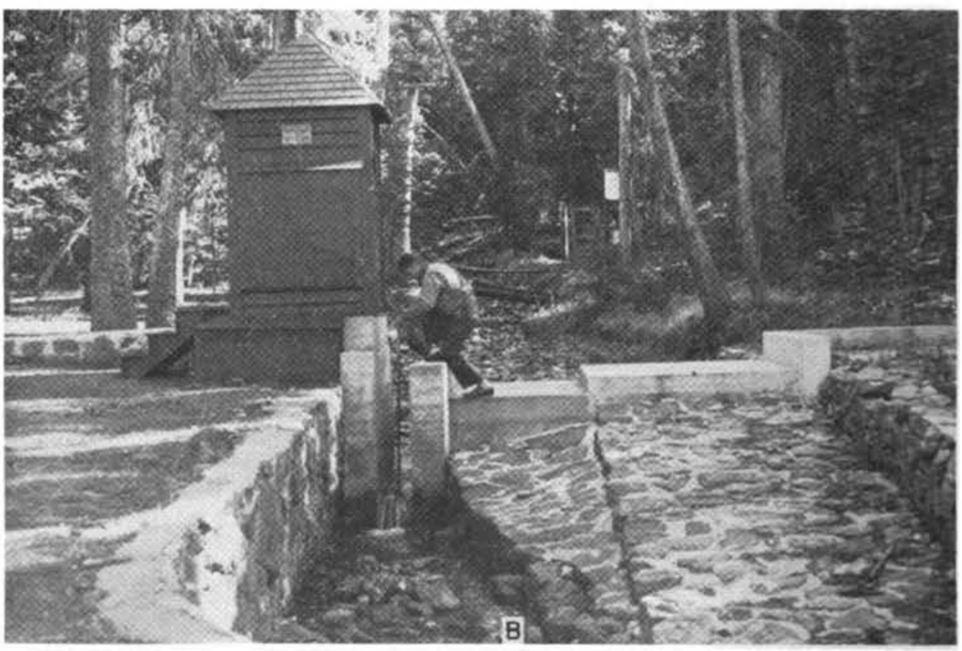
Permanent runoff plots are useful to evaluate changes associated with time. They permit careful and continuous records of the effect created by an applied treatment, as well as the influence of associated factors such as seasonal variations in climate, precipitation, and forage production. Plot sites are selected to represent an important range type. Permanent plots are costly and, therefore, the ideal number of samples required to evaluate the variable conditions normally found on the range can seldom be achieved. Offsetting this drawback, permanent plots provide continuous records of time variation under different treatments or management practices.

Most permanent plots used in range research have been patterned after installations employed by Duley and Miller (1923), Lowdermilk (1930), Conner *et al.* (1930), and Nichols and Sexton (1932). These investigators measured runoff from agricultural land, pastures, and brushland (figure 7). They were concerned with the effects of various treatments on runoff for variable slope gradients, slope lengths, and rainfall intensities. Plots are enclosed by galvanized iron or concrete barriers or earthen berms to exclude runoff from outside the plot and to confine runoff inside so it can be collected and measured. Surface flow drains into tanks or vats located at the downslope end of the installation. Natural rainfall supplies the source of runoff in most instances, but in some cases water is applied by artificial means to simulate rainfall.

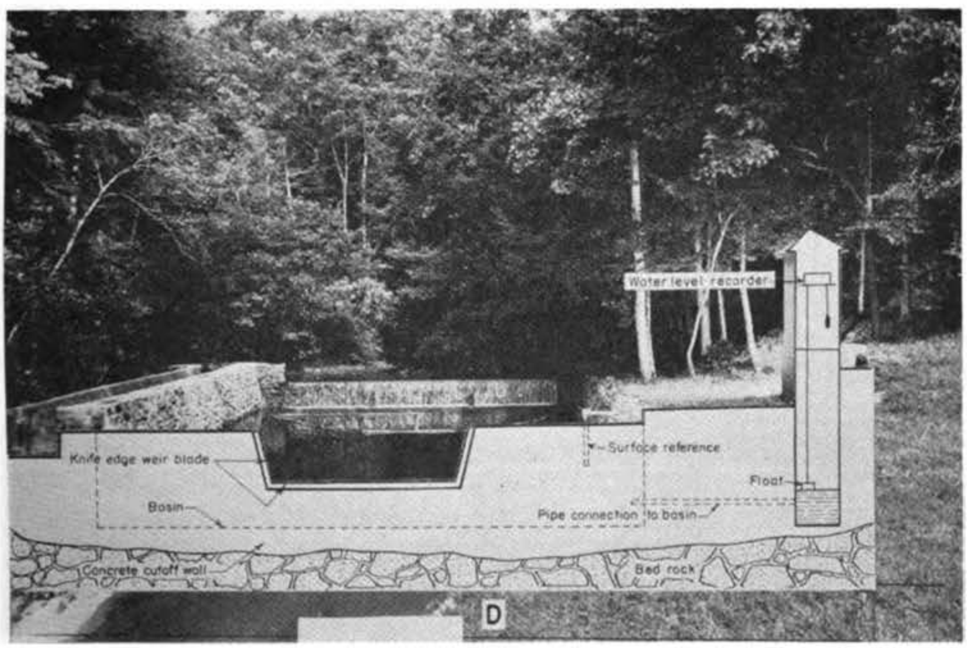
Extensive investigations of runoff and erosion have stimulated the development of special equipment for measuring runoff (Harrold and Krimgold 1948, Carreker and Hendrickson 1952, and Parsons 1954).

Runoff from plots and small watersheds nearly always is intermittent. After intense rains, runoff rates rise rapidly to peaks that usually last only a few minutes, and the flow ceases soon after the end of precipitation. Runoff from agricultural areas and heavily used ranges often carries considerable amounts of floating debris and eroded material. Measuring devices must be adapted to such conditions.

FIGURE 8. Four types of stream gauges. *A*, 90-degree, sharp-crested weir suitable for measuring small flows accurately where low temperatures are expected. *B*, One-foot San Dimas flume suited to passing sediment-laden flows. *C*, Trapezoidal flume suited



for passing sediment-laden flows with wide range of flow volume. *D*, Sharp-crested weir designed for measuring larger quantities of water than any of the other three types shown. *(U.S. Forest Service photos)*



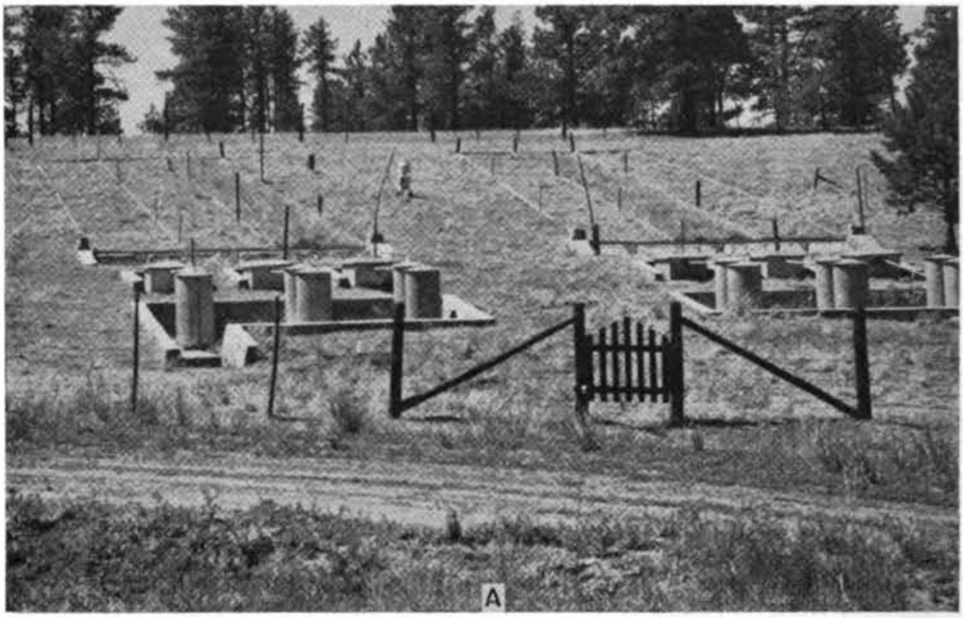
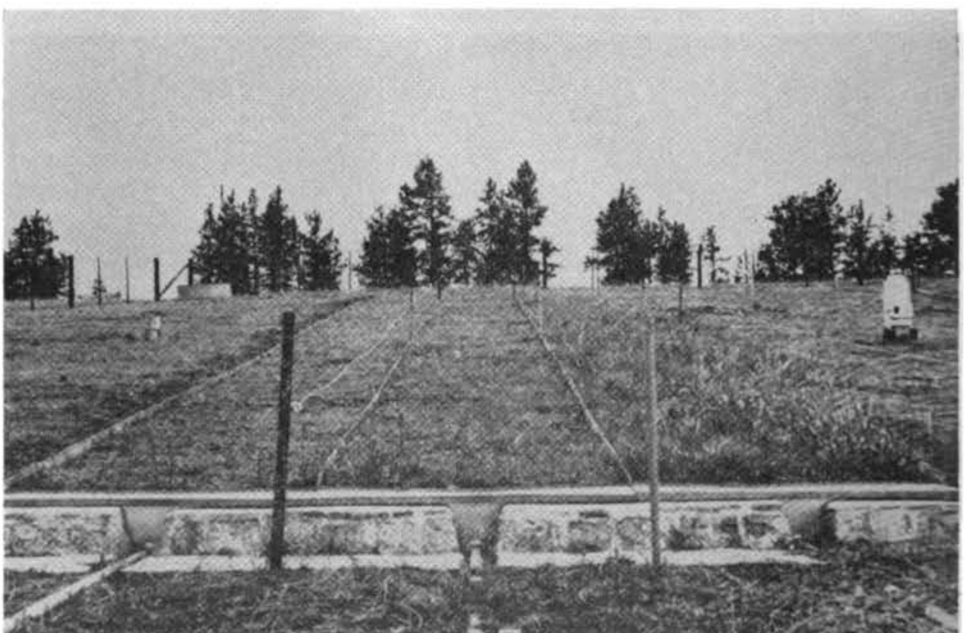


FIGURE 9. Runoff plots to study the effect of grazing at different intensities on runoff and erosion. *A*, General view of a pair of 3 plots showing collection tanks. *B*, Closeup showing how grazing is regulated by electric fense. *(U.S. Forest Service photos)*



Wherever data on rates of runoff are desired, flow from plots and small watersheds, as well as low flows from larger ones, are measured by flumes or special weirs developed and calibrated in hydraulic laboratories. A continuous record of depth of flow (stage or head) is obtained from water-level recorders (figure 8). The stage records are converted into rates of flow from laboratory rating tables developed for each type of measuring device, or by current-meter calibrations for the larger areas. Total runoff for any period is calculated by integrating the rates of flow during the period.

Where only the total amount of runoff from plots or small areas is of concern, the entire flow, or an aliquot of it, is collected in a calibrated tank. The aliquot devices are also used where samples are desired for determining the amount of sediment associated with the runoff. These devices are described in the section on Erosion.

Similar methods have been used effectively in determining the influence of range treatments on runoff by Croft and Monninger (1953), Dunford (1954), Weaver and Noll (1935), and others (figure 9).

Normally, permanent installations of this type are dependent upon natural precipitation. Rain and snow gauges are used to determine amounts received. Intensity and time of occurrence of precipitation are usually determined from recording rain gauges, with supplemental measurements of total catch obtained from standard 8-inch gauges.

Data are most useful when related to individual storms causing runoff over a period of years. Runoff can be compared with amounts of precipitation causing it by converting volumes of runoff water to inches depth over the plot. Supplemental data on temperature, wind movement, evaporation, and soil moisture often are recorded at these installations.

Lysimeters can measure all runoff including both surface and subsurface flows (figure 10). Somewhat artificial techniques are required, since, in most cases, the soil being tested must be transferred to a tank fitted with a drainage device for removing and measuring percolated water. Lowdermilk (1930) was one of the earliest investigators to use lysimeters. He was interested in the effect of burning litter on surface runoff and percolation in three distinct soil types. Soil was taken up in shallow layers and repacked in tanks by layers in their original order and approximate original volume. Duley and Hays (1932) made use of a similar device to determine effect of slope on runoff.

Natural or "in place" lysimeters are an extremely useful modification where soils are not too variable and a well-defined impervious layer can be found below the soil surface. The Base Rock lysimeters on the Sierra Ancha Experimental Forest in Arizona are an example (Martin and Rich 1948). Water percolates through an undisturbed soil mantle to impervious quartzite bedrock. It flows over the surface of the bedrock to the lower edge of the plot where it is collected and measured as subsurface flow.

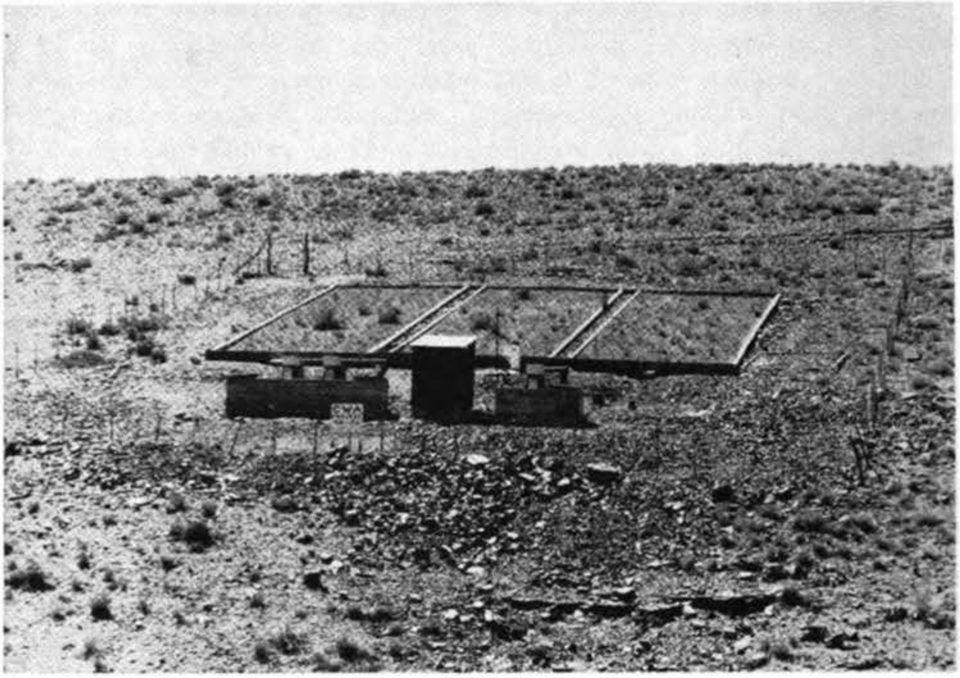


FIGURE 10. A battery of three lysimeters used to measure both surface and subsurface flow. These lysimeters were constructed in place; they have bedrock bottom and concrete sides. This permitted studying of treatments on undisturbed soils. *(U.S. Forest Service photo)*

Portable Plots

In contrast to permanent installations, portable plots enable the investigator to sample runoff from a wide variety of range conditions within a relatively short time. An essential feature is the use of artificial or simulated rainfall which may be applied to the plots at a controlled rate and a uniform velocity of impact. Amounts actually delivered on the plots can also be measured by standard gauging methods or various modifications, depending on plot sizes.

Portable plots have been used in sizes ranging from a square foot to 0.02 acre in area. The latter size has been used with the so-called rainmaker developed by the Forest Service (Craddock and Pearse 1938, and Johnson and Niederhof 1941). Simulated rainfall is applied from an overhead sprinkling arrangement to a plot 6.6 $\times$ 33 feet. Plot boundaries are formed by galvanized sheet metal baffles, which can be moved from place to place. "Rainfall" delivered to the plots and runoff collected from them are measured by recording tipping bucket gauges.

Runoff data have also been available from various infiltrometers, already described. Infiltrometers have been developed for the primary purpose of determining infiltration capacity, but determination of surface runoff rates is a necessary part of the measurements.

Watersheds

Natural watersheds or drainage areas have been used in range-watershed research, but not as widely as small plots. The principal reasons have probably been the high cost, long-time nature of watershed experiments, and scarcity of ideal sites. Also, some technical difficulties are encountered in measuring runoff occurring as intermittent flow. In the semiarid western ranges, it is difficult to find watersheds with permanent flow and yet small enough to provide relatively uniform vegetation cover and soil conditions. Changes in runoff behavior resulting from rangeland treatments are apt to be masked out by variations in soil and vegetation type usually existing in watersheds a square mile or more in area.

Despite these difficulties, natural watersheds can provide a desirable research tool. They have been used to good advantage in testing the effect of sheep grazing on surface runoff in the Wasatch Plateau of Utah (Forsling 1931). In North Carolina grazing effects have been tested on watersheds having perennial flow which is measured by normal stream-gauging procedures (Dils 1953, and Johnson 1952). Surface runoff from small watersheds can be measured in tanks equipped with V-notch weirs to gauge overflow. Runoff from larger watersheds must be measured by stream gauges that record automatically the rate and amount of flow.

Experimental Methods of Measuring Runoff

Studies of runoff in range research can be classified into two general procedures described by Wilm (1952). The first consists of methods for determining the influence of present and past range practices where the investigator measures variables as he finds them. The second is by controlled experimentation in which natural variations are carefully segregated to minimize their effect on evaluation of treatments which the investigator wishes to test.

In using the first of these methods, refinement can be added by segregating the variables involved in the problem into classes, each of which is relatively homogeneous with respect to runoff. For example, Johnson and Niederhof (1941) used the "rainmaker" to test runoff rates from three important cover types. Information was obtained for 10 per cent and 40 per cent slopes with simulated rainfall rates of 2½ and 4 inches per hour. Similar measurements were made by Craddock and Pearse (1938) using two rainfall intensities on four range types and two slope gradients. This type of information and a knowledge of grazing practices leading to the existing conditions enable the investigator to make inferences about the influence of grazing on runoff.

A further refinement can be introduced by supplementary measurements of variables not readily subject to classification. Packer (1951) measured surface runoff and erosion with an infiltrometer on two range cover types and within each sampling plot measured additional site characteristics thought to be associated with surface runoff and erosion. From the data he was able to test statistically the factors which are correlated with runoff and to make recommendations on range conditions needed to control surface runoff.

When making use of the second method, both permanent and portable plots, as well as watershed techniques, can be used effectively. It is necessary that plots be arranged in such a manner that applied treatments are given equal chance to exert their influence without confusion from extraneous variations. An example of such an arrangement is the randomized block design which provides an opportunity to segregate and account for variations such as soil and slope differences, and slope variations. Several grazing management experiments have been patterned after this design (Driscoll 1955, and Johnson 1953). Runoff data may be obtained from each pasture, either from plot measurements or from natural watersheds if entire drainage units can be found within the individual pastures.

Some controlled studies of runoff are being conducted as part of grazing management tests. However, pastures of the size needed for grazing management trials usually contain more heterogeneity than is desirable for measurement of runoff. Comparison of runoff from pasture to pasture is easily obscured by variabilities in soil and cover. For this reason, most tests have been conducted on relatively small and closely spaced runoff plots or watersheds having uniform soil, slope, and cover. Frequently, a set of two or more such sample areas are replicated to determine the effect of more than one soil, slope, or cover type.

Runoff on rangelands is influenced most by changes which affect the density and vigor of the vegetative cover and the porosity of the soil. Controlled experiments may be designed to show the effect of changes in these two basic factors which can be introduced experimentally. Tests have been conducted to determine how runoff is affected by various intensities of grazing by cattle and sheep, by simulated trampling of the soil, clipping or burning of vegetation, removal of litter and tree cover, and revegetation of bare areas. Studies of this kind are reported by Colman and Hamilton (1947), Croft and Monninger (1953), Dils (1953), Dunford (1954), Forsling (1931), Lowdermilk (1930), Marston (1952), Martin and Rich (1948), Packer

(1953), and Weaver and Noll (1935).

A general procedure is to compare runoff from a treated plot or plots with that of an adjacent check plot. If the experiment is carefully designed, provision is usually made for a "calibration" period before testing treatment effects. Calibration is desirable to determine any pretreatment variations in runoff indicating inherent differences among plots. If significant variation in runoff is discovered before treatment, these differences need to be taken into account in evaluating post-treatment results.

One notable modification of this general pattern has been employed on the Wasatch Plateau (Forsling 1931). Two adjacent small watersheds began with vegetation densities of 16 per cent (watershed A) and 40 per cent (watershed B) in 1915. For 5 years these densities were maintained by controlled sheep grazing. During the next 5 years the vegetation density on watershed A was raised from 16 to 40 per cent by eliminating all grazing and reseeding where needed. During the third 5-year period watershed A was again opened to moderate grazing on a deferred system to maintain the 40 per cent already achieved. These manipulations made it possible to study the influence of fluctuating densities in one watershed with a second which remained unchanged during a 15-year period.

In another watershed study, data on runoff were collected from a single drainage (Johnson 1952). Streamflow was measured for a seven-year calibration period before cattle were grazed on the area. The effect of grazing was based on a comparison of streamflow behavior before and after the beginning of grazing.

Grazing treatments also have been successfully introduced on small runoff plots. In Colorado, cattle were grazed at moderate and heavy intensities on 1/100-acre surface plots (Dunford 1954). Movable electric fence was used to control cattle movements. In Arizona sheep were grazed on 1/50-acre natural lysimeters with equally good results (Martin and Rich 1948). In general, however, runoff data from plot tests of this type have more value as relative indicators of treatment effects than as absolute measures of runoff which can be expected from large areas of similar grazing land. Of necessity, the treatments on plots must be applied under somewhat artificial conditions. Grazing, for example, has been conducted under confined conditions and for concentrated periods, resulting in somewhat unnatural effects.

Controlled studies are often useful in providing information on factors other than range treatments which are related to runoff. Measurements of rainfall, for example, have shown how intensity and amount are associated with runoff (Dunford 1954, and Martin and Rich 1948). Kittredge (1954) has also demonstrated a relation between runoff and antecedent rainfall, a measure of the moisture already held by the soil. These data often help explain variations in runoff which cannot be attributed to treatment.

EROSION

Methods of Evaluating

Erosion on rangelands can be estimated by inspection of eroded areas or by measurement of the eroded material itself, either in transit or accumulated at some point.

Inspection of eroded areas is the more direct approach because it is done at the point of soil detachment. Quantitative determinations of soil volume removed can be made by comparing surface profiles with known points of reference. Though less specific, extent of erosion can also be classified by adjective references such as slight, moderate, and severe. These are usually based on erosion indicators which relate in a qualitative way to relative amounts of soil removed. Amounts are expressed in units of depth, volume per unit area, or weight per unit area. Soil material in transit as suspended sediment in water can also be expressed in terms of parts per million of the water tested. Flowing water transports eroded material in suspension or by pushing, rolling, and skipping of the heavier soil and rock particles along the channel bottom (bed load). The most common method of evaluating erosion in transit is by observation of suspended sediment in streamflow. Bed load and heavier materials in suspension for short periods generally are collected in a basin or depression where the accumulated material can be measured by weight or volume.

Wind erodes soil by much the same process as flowing water. Particles in transit can be trapped at various points or deposited material can be sampled and measured.

Sampling Methods

On Eroding Areas

A reliable quantitative procedure is the periodic remeasurement of established profiles using fixed reference points or bench marks to determine successive changes in profile elevation. The method can be used with a fair degree of success with a level and rod in locations where changes are fairly rapid, such as active gullies, streambanks, or roads.

Sheet erosion is difficult to detect by periodic remeasurement of established profiles. Refinements in measurement are needed, such as using graduated erosion pins or carefully measuring the distance to the ground surface from a fixed frame or tapeline stretched between two permanently established points. Sampson (1944) used steel stakes 18 inches long with their tops extending 4 inches above the soil surface as reference points to determine amounts of soil piled up or removed. Such methods, however, give only relatively crude measures of a change in surface elevation which normally occurs slowly and in minute dimensions. Furthermore, changes in elevation may be obscured by factors other than erosion such as frost heaving, colloidal swelling of the soil, or changes in bulk density due to compaction. This latter might be particularly the case on rangeland and especially on previous forest or brushland soils cleared for range.

Soil loss sometimes can be estimated from natural reference points such as grass clumps and pedestalled rocks and twigs. Cooperrider and Hendricks (1937) estimated soil erosion on quadrat plots by determining the average depth in inches between the eroded profile and a plane defined by the tops of humps held in place by grass. Pickford and Reid (1942) estimated soil loss in the green fescue type by arriving at an average height between eroded surfaces and the tops of soil blocks maintained by grass clumps. In making such determinations, it must be remembered that wind-deposited soil frequently can build up the level of soil held in place by grass clumps, thereby accentuating the indicated soil removal.

Erosion Surveys

Soil surveys by the U.S. Department of Agriculture and cooperating state agencies include information on accelerated soil erosion. Standard criteria for estimating and classifying erosion are set forth in the Soil Survey Manual (U.S. Dept. Agr., Soil Survey Staff 1951). Erosion on rangelands can be mapped by these standards. The methods are also applicable to range research where erosion is to be estimated by inspection rather than measured.

The Soil Survey Manual classifies erosion as follows:

By water

Class 1.—Up to 25 per cent of the original A horizon, or original plowed layer in soils with thin A horizons, removed from most of the area.

Class 2.—Approximately 25 to 75 per cent of the original A horizon or surface soil lost from most of the area.

Class 3.—More than 75 per cent of the original A horizon or surface soil, and commonly part or all of the B horizon or other underlying layers, lost from most of the area.

Class 4.—The land has been eroded until it has an intricate pattern of moderately deep or deep gullies. Soil profiles have been destroyed except in small areas between the gullies.

By wind

Class 1.—About 25 to 75 per cent of the original A horizon, or surface soil in soils with thin A horizons, removed from most of the area.

Class 2.—All the A horizon or surface soil and a part of the B horizon or other lower lying layers, removed from most of the area; an occasional blowout area may be included.

Class 3.—Most of the soil profile removed; blowout holes are numerous and deeply carved into the lower soil or parent material, and areas between blowouts are deeply buried by soil material from the blowouts.

Besides these classes for removal, two classes are used to define areas on which significant amounts of material have been deposited by wind:

Class 1a (Overblown).—Recent deposits of wind-drifted material cover the soil in layers thick enough to alter its characteristics significantly up to 24 inches.

Class 2a (Wind hummocky).—Recent deposits of wind-drifted soil material in a fine pattern of hummocks or low dunes.

Special classes of erosion may be needed to describe unusual forms, such as land slips and combination of slips with water or wind erosion.

Various indicators of soil displacement have been used qualitatively to gauge the extent of erosion. Ellison *et al.* (1951) have established some useful criteria for judging erosion as a part of a general assessment of range condition and trend. Important indicators were found to be: cover condition, amount of bare soil, observed soil movement, trampling displacement, relics of original soil surface, erosion pavement, lichen lines on rocks, active gullies, wind-scoured depressions, wind and water deposits, and rill-channel ridges formed by grass rows invading old rills and becoming exposed ridges as a result of further erosion.

Reid and Love (1951) used per cent of bare soil as a criterion for classifying sheet erosion hazard (erosiveness) into four categories: none, slight, moderate, and severe. These categories were based on per cent of bare soil that had previously been related to relative erosiveness by infiltrometer tests.

Parker (1951) recommended a combination of observations on a 100-foot transect and a 100- by 150-foot plot. Soil stability is rated in 5 categories: excellent, good, fair, poor, and very poor developed from a classification score ranging from 0 to 30. Half of this score is based on a proportion of the 100 observations made along the transect which are recorded as having ground cover. The other half is a qualitative estimate of current erosion on a plot 100 by 150 feet, bisected by the transect. Current erosion is classified as none, slight, moderate, advanced, and severe—each class being assigned by a numerical rating ranging from 0 to 15.

Croft *et al.* (1943) sampled erosion and soil at 100-foot intervals along 3 transects 8,000 feet long. Erosion at each sampling point was classed in terms of deviation from normal: none, moderate, and severe. To augment the data additional soil was sampled by erosion classes within a zone 200 feet wide along each transect.

Garrison and Rummell (1951) used transects with 1/10-acre sample plots located at 5-chain intervals. In each plot, the area of soil disturbance was estimated in three categories: deep, shallow, and slash covered. Deep disturbance was regarded as an important factor in erosion.

Cooperrider and Hendricks (1937) sampled erosion by use of chart quadrats varying in size from one to six square meters. Chart quadrats are time consuming and have been largely replaced by estimating methods.

Measurements of Eroded Material

Several methods have been devised for measuring eroded material while it is being transported by flowing water. However, the best methods are only approximations. Most accurate determinations of suspended sediment are obtained by carefully weighing the residue after filtration or evaporation of the water in the sample.

Determinations of this type are obtained from samples of sediment-carrying streamflow which can be obtained simply by dipping a container into a stream at a selected point. Several sampling devices have been developed to give added refinement. One now in common use is the DH-48 depth-integrating hand sampler (U.S. Federal Inter-Agency River Basin Committee, Subcommittee on Sedimentation 1952). Water is collected in a bottle inserted into an aluminium case provided with a small filler inlet. The bottle is filled slowly, allowing the operator time to obtain a representative sample of streamflow at all depths.

Adequate spot sampling of suspended sediment is difficult because of variations in precipitation, volume of stream discharge, upstream land use, and time of sampling. Many of these difficulties can be overcome by continuous automatic sampling and several devices are being tested to meet this need. In order to relate sediment measurements with stream discharge where gauging stations are not installed, Anderson (1941) has developed a combination sampler and current velocity meter from which discharge at the time of sampling can be calculated.

A rough estimate of suspended sediment can be obtained from turbidity observations (American Public Health Association 1955). These are optical determinations based on interference of the suspended matter to the passage of light rays. When compared with standard samples of recorded turbidity, a gross approximation of suspended sediment can be obtained. It must be remembered, however, that ingredients other than suspended sediment can cause turbidity and this absence of a direct relation can cause errors which are unacceptable in precise experimentation (Benedict 1945).

Not all eroded material can be accounted for in suspended sediment. Considerable amounts of the heavier material are in suspension for a relatively short period, or are simply moved along the beds of water channels and gullies. This bed-load material commonly is measured by collecting it in a basin or depression in the watercourse. For small watersheds, debris or sediment catchment basins can be constructed at relatively low cost and provide useful means for measuring accumulations volumetrically. Basins are most successful in natural drainages where runoff can be impounded by a dam. Suspended material can also be trapped by this method, but its proportion to the total carried by the stream depends on the relation of storage capacity to the volume of streamflow.

A more refined version has been frequently employed in range research where erosion is being studied on a plot or small-watershed basis. Catchment tanks used for collecting runoff from the plots serve also to accumulate eroded material. Some examples where this system has been used in studies of different kinds are found in the following references: Conner *et al.* (1930), Craddock and Pearse (1938), Croft and Monninger (1953), Duley and Hays (1932), Duley and Miller (1923), Dunford (1954), Johnson and Niederhof (1941), Kittredge (1954), Lowdermilk (1930), Marston (1952), Martin and Rich (1948), Nichols and Sexton (1932), Osborn (1952), and Packer (1953). Installations designed to contain all runoff from intermittent storms provide the best measure of erosion since all transported material is caught. Some suspended material is lost, of course, from tanks where overflow provisions are installed.

Accumulated material can be measured in several ways depending on the catchment method and the refinement of measurement needed. Deposits in debris basins can be measured by recording successively rising elevations of the incoming material. In most natural watersheds of 10 acres or more, it is difficult to relate deposition of eroded material to individual storms; seasonal or yearly measurements are generally considered sufficient. Eroded material from plots received in catchment tanks is generally measured after each storm or simulated rainfall application. The usual method is to allow suspended matter to settle, and siphon or decant the clear water. In some instances a flocculating agent has been used to hasten the settling process (Davis 1937). The residue of eroded material is then measured volumetrically and samples of known volume air-dried or oven-dried to determine dry weight. Erosion is usually expressed in terms of dry weight per unit area from which it is received.

Devices to take proportional samples, or aliquots, of the runoff and its content of eroded material can be used on plots too large for all the runoff to be collected.

One of the most widely used is the Geib multislot divisor. This installation consists of a silt box, where the heavier particles of the runoff settle and the trash is sieved out; a series of divisor boxes, each with an uneven number of identical slots in the discharge end; and a storage tank. Sediment-laden water discharges from the silt box into the first divisor, where the discharge from the center slot is directed into another divisor, and so on until the aliquot is a convenient amount to hold in the storage tank (Harrold and Krimgold 1948).

Another type of runoff sampler was developed at the North Appalachian Experimental Watershed at Coshocton, Ohio. In this sampler the discharge from the measuring flume falls directly upon a water wheel (figure 11). A sampling head with a narrow opening along its top is mounted on the wheel. With each revolution of the wheel, the slot cuts across the jet from the flume and extracts a small portion of the flow. The sample falls through the sampling head into a collecting pan below the wheel, and thence to the storage tank (Parsons 1954).

On larger plots and field-size watersheds a combination of flume and

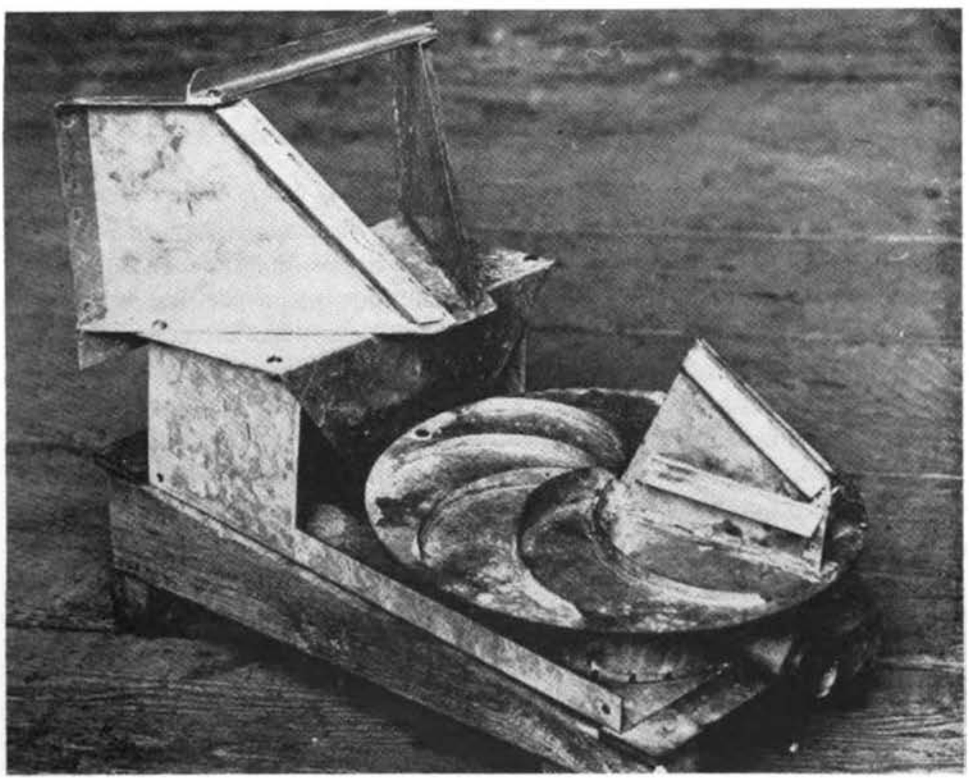


FIGURE 11. Coshocton-type runoff sampler. The wheel rotates in the jet from the flume and takes a sample at each revolution. *(U.S. Soil Conservation Service photo NM-R3-6624)*

FIGURE 12. A spud is used to bring up samples of sediment from bottom of reservoir. *(U.S. Soil Conservation Service photo NY-881)*

silt sampler commonly is used. By this method the runoff flows through the flume, where a recording gauge registers the depth and time of flow. The water with its load of eroded material discharges into a silt box, where the heavier particles settle out. The water then flows over a rectangular weir into an outlet ditch. As it passes over the weir, a small amount flows through a slot into a divisor box, and thence into a storage tank.

Long-term sediment yields of watersheds can also be determined by measuring the accumulation of sediment in reservoirs of known age (Gottschalk 1952). Special equipment has been developed to determine the thickness of deposits and volume-weight relationships of the sediment (figure 12). The volume of sediment is measured by standard hydrographic survey methods. These measurements can be converted to weights on the basis of the volume-weight relationships of the deposits.

Experimental Methods for Measuring Erosion

Erosion studies in range research can be segregated into two general classifications. First are those which the investigator measures and classifies as he finds them. The second are experiments designed to evaluate the results of applied treatments.

A considerable body of knowledge concerning erosion on rangelands has been accumulated from the first of these methods. The most useful has been that which has led to a correlation of erosion severity with associated range use.

A few examples are illustrative. Cooperrider and Hendricks (1937) classified degrees of erosion into normal, moderate, advanced, and excessive. These were found to be associated with low, medium, or high degree of vegetation deterioration.

Renner (1936) classified erosion into four classes: none, sheet, shallow-gully, and deep-gully. He then related these classes with observed gradients, aspect, soil plant types, density of vegetation, rodent infestation, and accessibility to livestock. From these associations, he determined some easily recognizable range characteristics and land-use practices which are conducive to erosion.

Investigations of the physical properties of soil have also revealed some usable relationships with erosion and erosion hazards. Croft *et al.* (1943) used a 3-stage classification based on deviation from normal geologic erosion: no deviation, moderate, and severe deviation. Soil associated with each class was sampled at 0- to 1-inch and 1- to 6-inch depths to determine the relation of erosion severity to content of organic material, moisture equivalent, and total nitrogen. They found that organic matter in the surface inch of soil is strongly and inversely related to accelerated erosion. Johnson and Niederhof (1941) analyzed soils in "rainmaker" plots to determine percent of sand, gravel, silt plus clay and colloids, from which they drew conclusions on the relation of soil porosity to erosion.

Infiltrometer measurements over a wide variety of cover types and soils have demonstrated some useful relations between percentage of bare soil and relative amounts of erosion. Reid and Love (1951) used this type of information to estimate sheet erosion hazard. Packer (1951) used this same type of information to determine the minimum requirements of cover to hold erosion in check. An infiltrometer survey led to the conclusion that a 70- to 75-per cent ground cover was needed for effective control of storm runoff and erosion in areas subject to high rainfall intensities (Marston 1952).

Investigations of this type can aid materially in establishing criteria for classifying erosion hazards and soil protection requirements. However, Wilm (1952) points out some of the hazards of interpreting results of these studies in terms of practical land management. The investigator always risks the possibility of bias and the confounding of variables.

Controlled experiments offer an alternative when the risk of bias is one the investigator is not willing to take. In making this choice, the investigator adds to the cost of his investigation and delays the results.

Plots and watersheds designed for testing runoff from range areas almost always have included provisions for measuring erosion as well. The principles of experimentation described for runoff investigations likewise apply to studies of erosion.

Treatments used in plot and watershed studies of erosion are designed to alter soil stability and porosity, to change the degree of mechanical protection by vegetation and litter, and to alter the quantity of surface runoff. Treatments have been accomplished in numerous ways: by actual grazing or simulated grazing; by burning (Blaisdell 1953); by revegetating bare and eroding areas; and by mechanically removing vegetation and surface litter.

Compaction effects were studied by Packer (1953) to determine what levels of trampling disturbance step up stormflow and erosion beyond safe limits. For this purpose he used a hand-operated steel "hoof." Degree of trampling was controlled by varying the spacing and the number of impacts of the hoof from plot to plot to simulate light, moderate, and heavy trampling.

The effects of natural grazing can also be determined under carefully controlled conditions. Effects of grazing by sheep were determined in a test on the Base Rock lysimeters at Sierra Ancha Experimental Forest in Arizona (Martin and Rich 1948). Cattle grazing was regulated with good results on 1/100-acre runoff and erosion plots in the Front Range of Colorado (Dunford 1954). In this case a movable electric fence was used to exclude grazing from two plots intended for checks, to restrict use on two others to a moderate intensity, and to permit heavy grazing on two others.

Studies of Wind Erosion

Erosion by wind may be more prevalent than erosion by water on rangeland in arid and semiarid regions. Yet little research has been devoted to it. Most investigations of wind erosion have been on cultivated land of the Great Plains. Methods used on croplands, however, could be applied to rangeland.

A portable wind tunnel has been used to test erodibility of cropland soils and protective effects of cover much in the same way that rainfall applicators have been used to study erosion by water on small plots (Zingg 1951). Chepil and Woodruff (1954; with Zingg 1955) describe the measurement of these factors and present a formula for expressing their average relationship.

Stallings has summarized information on the mechanics of wind erosion (1951) and wind-erosion control (1953) which might suggest approaches to the study of wind erosion on range watersheds.

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Chapter 8
Economic Research in Range Management

Introduction and Purpose

Economic research in range management is concerned with management decisions by people in relation to the goals they desire. Its task is to observe and record facts relevant to decision making, and to organize and analyze these facts so that answers to pertinent questions can be provided or the hypotheses tested. The questions usually relate to specific entities, such as a firm or individual ranch, a grazing association or other group, or even society as a whole. Usually, also, the questions are in terms of maximizing or minimizing something. The questions and the decision making are conditioned by the economic and social environment of our society.

Physical and biological research in range management, however, focuses mainly on relationships between or among things—between intensity of grazing and plant composition, root development and rates of plant growth, fertilizers and forage yields, season of grazing and reproduction of certain species, to name only a few. Discovery of these relationships reveals what can be done under conditions defined by the research. Relationships between cause and effect permit prediction or extension of results into situations other than those observed in the course of the research.

A distinction commonly made between physical-biological research and economic research is that one asks the question, "Will it work?" whereas the other asks, "Will it pay?" A more accurate distinction is that one deals with what can be done, whereas the other deals with what people choose to do. To be relevant, economic research must be directed toward questions that will help people decide on a course of action.

"Will it pay to reseed sagebrush range?" is a typical question of this order. The answer is seldom a simple "yes" or "no." The answer may be "yes," if the cost is low, forage production is increased, livestock can make greater gains or use the range for a longer season, the money to pay the costs is available, the livestock can be managed so as to make best use of the reseeded range, and the range itself can be controlled. These and many other factors affect the decision.

Economic decisions are made most frequently by an individual and in terms of his goals. Economists usually assume that the goal of the individual is to maximize net profits over some given time period. Often this is the case, but other goals may exist. For instance, the individual may want to achieve a certain minimum income with the smallest amount of labor or maximum income with a given amount of investment.

Two concepts that are pertinent to an understanding of economics and economic research are involved here. One is the concept of the firm, the other is the concept of maximization. As used in economics, a firm is a business entity under a single management. It may be an individual farm or ranch, or it may be a corporation or group that acts as a unit. Decisions are made in terms of the goals desired by or from the unit. The concept of maximization is basic to economics in that usually the goals of people are in terms of maximizing something—gross returns, net profits per dollar invested, net returns per hour of labor, maximum profits to managerial efforts, net returns per acre of land, or others. Both the concept of the firm and the concept of maximization are used and expanded later.

Theory and Methods

The use of theory in economic research is similar to its use in other subject-matter disciplines. Whatever the subject to which it relates, theory is used for three separable functions: (1) To help in describing events that occurred in the past, (2) to develop criteria for appraising these events, and (3) to suggest questions or hypotheses which concern predictions about events that may happen in the future. These three functions apply to ecology as well as economics.

Research requires that theory be made specific to particular problems. These problems are set apart by a process of abstraction that makes it possible to investigate one problem while "fixing" others by means of assumptions, presumably on the basis of the best available estimates. These abstractions (in this instance, basic economic concepts), are of strategic importance in understanding the function of economic theory in research.

Basic Economic Concepts

In economics, a ranch is conceived to consist of two entities, a firm and a household. The firm is the business unit, or the group of resources used together, about which decisions are made. The household is the site of decisions that relate to the disposition of earnings from the firm. Here it is decided whether and in what way to spend for current consumption or current production, or to save for future investment in production or future consumption.

Economic theory gives us a few basic concepts or principles relating to the firm. The first of these is the principle of diminishing returns. At first, successive units of any factor used in the firm for production will give increased output for each unit added. After a certain point, additional units of input will give added output, but at a decreasing rate. Finally a point is reached at which additional inputs actually decrease output. Increasing numbers of livestock added to a given area or range will increase total production up to a point, but continued increases in numbers will decrease total output. This principle gains relevance in economics when prices or values are associated with the inputs or resources used in production and the outputs or products that result from the production process.

Resources used in production—rangeland, hayland, cattle, labor, and others—may be combined in different ways. Number of cattle per area of land, amount of labor per unit of livestock, acreage of hayland per section of range, and other combinations of inputs to the ranch may be varied one with the other. When costs of the various factors used in production are compared with the volume and the value of product, a most profitable or most desired combination can be determined. Generally, the cheaper factors per unit of output are used more generously.

Knowing that the product obtained by successive additions of an input will decrease if enough inputs are added and that inputs can be combined in different proportions permits an approximation of the "best" combinations for any given firm. The best may be the combination that results in the greatest net profit for a given period, or maximizes returns to some one factor, or maximizes returns over a period of years. The best solution must be found in terms of the goals held by people who are making decisions regarding the firm under observation.

Economic Behavior of Firms

The term "optimum" is encountered frequently in economics literature. Ordinarily, it describes a solution to a particular type of problem which must be solved as a step toward the ultimate goal set for the firm (for example, maximum of net ranch income). In fact, "economics of the firm" consists of little more than specifications for a series of optima, in which the criteria are logically consistent and best in terms of the goal or goals set by managers of the firm.

The simplest criterion is maximization of net income. This is achieved when three optimum conditions are met

(1) An optimum proportioning of the resources that can be varied for

a given level of production in each enterprise in the firm

(2) an optimum level of production for each enterprise, given these proportions of the variable resources; and

(3) an optimum allocation of resources among the various enterprises.

These three optima must be specified for particular time periods. As of a given moment in time nearly all resources are fixed, but the longer the period of time the more resources are variable within respective enterprises and, for that matter, allocable among enterprises.

Solutions for the optima require two types of data: (1) Physical data and (2) price or market data. For rigorous analysis, the physical data must be in terms of functional relationships, not simply estimates of single points on functions.

Let us return to the first optimum listed above. To obtain a maximum net ranch income, the cost of resources that can be varied (for example, those for which decisions remain to be made) must be at a minimum for each level of production within a given enterprise. As is shown in numerous economics textbooks, this is achieved when the marginal rate at which one resource substitutes for the other is equal to the inverse price ratio of the two resources.

In an experiment with commercial fertilizer, Hoglund (1952) has shown forage production (measured in air-dry feed) to be functionally related to inputs of nitrogen (N) and phosphorus (P_2O_5). These data (table 1) suggest that forage output is related to quantities of each fertilizer in diminishing returns and that a given quantity of forage can be produced with several combinations of N and P_2O_5.

TABLE 1. Pounds of air-dry feed per acre of annual range types at selected levels of N and P_2O_5 fertilization

Pounds N per acre	*Pounds P_2O_5 per acre*			
	0	*65*	*129*	*172*
0	1,601	1,903	1,910	1,799
32	2,757	3,129	3,298	3,256
61	3,837	4,253	4,486	4,494
84	4,500	4,970	4,477	4,952

Data in table 1 may be "fitted" or described in a functional relationship so that a quantity of feed can be calculated for each combination of fertilizer ingredients (Heady and Pesek 1954).[1] When this is done, we find, for

[1] For the range forage experiment the function fitted was:

$$\log \hat{Y} = 3.265 + 0.0577 \log N + 0.0136 \log P_2O_5$$

where $\hat{Y}$ is calculated production in air-dry feed per acre,
N is pounds of nitrogen, and
P_2O_5 is pounds of phosphoric acid

example, that 3,600 pounds of air-dry feed can be produced with each of the combinations of P_2O_5 and N given in the first two columns of table 2. The marginal rate at which P_2O_5 substitutes for N to maintain the 3,600 pounds of forage is given in the third column of table 2.

TABLE 2. Substitution rates of P_2O_5 for N to produce 3,600 pounds of air-dry feed on an acre of annual range

Lbs. P_2O_5	*Lbs. N*	$\Delta N/\Delta P_2O_5$
0	65	
40	47	−0.450
80	40	−0.175
120	36	−0.100
160	34	−0.050

TABLE 3. Optimum proportions of P_2O_5 and N to produce 3,600 pounds of air-dry feed on annual range

	Price of N					
Price of P_2O_5	.10	.12	.14	.16	.18	.20
.02	77/41	84/40	97/38	107/37	114/37	120/36
.04	47/46	57/44	64/43	69/42	73/41	77/41

For example, the figure —0.175 in the third column means that as N is reduced from 47 to 40 pounds per acre, it takes on the average for this change an increase of 0.175 (7/40) pounds of P_2O_5 to sustain production at 3,600 pounds per acre of air-dry feed. This change entails (1) a reduction in the cost of N and (2) an increase in the cost of P_2O_5. It is clear that if the increased cost of P_2O_5 is less than the decreased cost of N, it would be a profitable change in resource proportions. The *optimum* proportions are found by equating the marginal rate of substitution (in this example, $\Delta N/\Delta P_2O_5$) with the ratio: price of P_2O_5 ÷ price of N.

Although the intervening steps are not shown, the resulting optima are given in table 3. Each figure in the body of this table represents an "optimum" for the respective prices (per pound) of P_2O_5 and N given in the headings of the rows and columns. For example, if N costs 10¢ per pound and P_2O_5 2¢ per pound applied, the optimum quantities to produce 3,600 pounds of feed would be 41 pounds of N and 77 pounds of P_2O_5. This example demonstrates the use of functional relationships in arriving at optimum solutions (this one simply minimizes the costs of fertilizer for a given quantity of forage) and the fact that the optimum changes as prices of each resource change. Methods of solution for the other two optima given on page 196 are similar to the one described.

For an optimum level of production in each enterprise, optimum (2), the enterprise is expanded until the point is reached at which further increments in returns (given simply by price of product) are equal to increments in cost. Such a point is reached only because of diminishing returns to the individual variable resources. The top row of table 1 illustrates this type of relationship with P_2O_5 as the individual variable resource.

There are two possible reasons why optimum (2) may never be reached in actual ranch situations. A shortage of resources may prevent the rancher from expanding a given enterprise to a size at which incremental costs and returns are equated, or a second enterprise may divert resources from the first before it has expanded to its optimum size. This is possible as the second enterprise must promise only a net increment to income greater than zero (above the cost of allocable resources). Optimum (3) specifies the conditions necessary to the solution of this type of problem (Hopkin 1954).

Problem Formulation as a Step in Research

These three optima serve at least two useful functions. First, they are logical notions of "constructs" with which to test decisions made by the rancher for consistency with goals affirmed for the use and development of resources within the ranch firm. But second, and important from a research viewpoint, they serve as idealized situations or "models" to guide a search for data useful in the solution of economic problems.

The importance of problem formulation as an integral part of the research process is hard to overstate. Without a problem concept, why would the investigator be interested in combining relationships to achieve results such as those given in table 3? A pure search for facts would give, perhaps, (1) only response estimates in range forage product to N or P_2O_5; or (2) a historical series of prices for N or P_2O_5 or both. But when a problem involves optimizing the proportions of N and P_2O_5, it becomes reasonable to relate the two phenomena.

The example of the effects of nitrogen and phosphorus on forage production used in the preceding sections may have limitations as an illustration applied to range management, but it serves to demonstrate the logic involved in economics research. The "problem" might be stated: Ranchers are not making as much net profit from the use of N and P_2O_5 as they believe they should. One hypothesis then becomes: Net profits can be increased by using relatively greater quantities of nitrogen. This latter statement can be verified by observation. Statements of the problems in range economics research and of the hypotheses that suggest solutions to them are almost infinite in number. At this point, we shall not attempt to list or classify them in any way, as it is not necessary to do so in our exploration of research methods and techniques.

Evidence Needed to Analyze Economic Problems

It has been suggested that physical, price, and market data are required for analysis of economic problems. The physical production processes and the prices or costs associated with the resources used and the product obtained are basic to economic analysis. Given the necessary technical input-output relationships, it is possible to derive the solutions necessary for rational economic decisions. Whether obtained from surveys, experiments, or from other sources, the input-output coefficients provide the technical data that apply to the particular set of resources and conditions defined in the hypothesis.

The type and form of data needed for economics research will depend on the hypothesis to be tested. If the need is to establish the effects on aggregate income of following a particular production program, average values for inputs and outputs will serve. But if the need is to determine the effect of a change in resource inputs, singularly or in multiples, to a given body of fixed factors, marginal data are usually more appropriate. For example, data relating to only one rate of fertilizer application or one rate of stocking are not adequate. To be most useful for economics research, data on the independent variables should cover a range wide enough to permit establishment of marginal values.

Physical input-output data are basic to economics research. Average or marginal quantities, depending upon the hypothesis to be tested, are needed for inputs (things going into the production process) and outputs (products resulting from the process). In addition to physical quantities, values or prices must be associated with them for the solution of economic problems.

Although it is difficult at times to obtain the input part of the data, it causes economists relatively less difficulty than the output part. Acres of land, hours of labor, numbers of livestock, tons of hay, and other factors going into a production process can be quantified. Many of the factors have a price, established in a market, that can be used with confidence. Factors that have no market price, family labor for example, still may be assigned a value based on their worth in some alternative use. If the economic problem under study, such as a conservation problem, involves a long-time period, projected prices or values can be assigned to the factors based on analysis of observable trends in the economic system. The input data required in range-economics research can be obtained more easily and used more confidently than output data.

Frequently, the output from rangeland is difficult to measure and may be even more difficult to price or to value. Range forage is one of the main products from rangeland, but frequently it has value only as it is grazed and converted into an economic good such as beef or game. The value of range forage then becomes a function of the livestock management systems and practices used on it as well as of the land-management systems. The question then arises, how much forage is produced, that is, produced in an economic sense? Furthermore, how is the best way to determine values of, or set prices for, the range forage produced (North Central Farm Mgt. Com. 1955). Range forage that can be used as a steer pasture may be evaluated readily in terms of the gains in marketable weight on the animals. The same forage used for dry cows kept in a breeding herd does not have a readily identifiable value. This problem of establishing values of range forage is particularly difficult in seasonal range areas where the feed is usable only at a given season. It may have little value unless it is used with other range and feed supplies, when it may become an important part of the annual feed supplies of the ranch.

Range produces products other than forage for domestic livestock, some of which are even more difficult to evaluate. Big game is one product of rangeland which people want under certain circumstances, so it has value. But it has no price, in the usual economic sense, because it is not exchanged in a market in which people can express willingness to spend for it (Upchurch 1954). Many attempts have been made to evaluate game in terms of expenditures by sportsmen. Usually, these attempts were unsuccessful from an economic viewpoint, because their results provide no basis for functional relationships between the costs of producing game and its value.

One way to approach the problem of value of game in economics research is through the value of some other product, such as domestic livestock, which is not produced because of the game. For example, if the opportunity to produce 500 sheep is foregone in order to produce 200 deer, then the 200 deer are worth at least as much as the 500 sheep. Two major difficulties attend this approach. One is the difficulty of establishing the physical relationships between deer and sheep in their use of range feed. The other is the fact that deer and sheep are "produced" by different economic firms—an individual rancher in the one instance, the state in the other. As decisions on economics must be made in the context of a firm, two different levels of decision-making are involved. An optimum solution for each firm does not solve the economic problem of allocating range use between deer and sheep.

Most frequently, the firm involved in an economic study in range management is a livestock ranch operated under a single management. It may be individually owned, a partnership, an estate, a corporation, or any other form of business unit. For the firms studied, the researcher needs to know something about their management, organization, size, nature of resources available, which resources are fixed and which variable and to what degree, and the tenure or degree of control over resources, especially land. These and other factors help to set the stage for economic analysis and indicate, to some extent, the range within which solutions must be sought. They help to establish and identify the goals of management of the firm and in this way help the researcher to specify relevant hypotheses required to guide the inquiry.

Even though the individual ranch generally is the firm on which economics research is focused, this need not be the case. A firm may be a national forest, a grazing district, a grazing association, a sportsmen's organization, a state, or even the federal government. The only requirement in economic research is that the firm be an entity through which management decisions are formulated with respect to production of economic goods. Regardless of the nature of the firm, the factors listed in the preceding paragraph must be known or ascertained in the course of the research. Much economic research could be sharpened and made more meaningful by a clearer definition of the firm or firms to which the research is intended to apply.

Sources of Data

Data used in economics research can be obtained from many different sources. The kinds of data, and to some extent their source, depend on the nature of the hypothesis to be tested.

Records existing in public offices frequently are fruitful sources of data needed. For example, records in national forest and grazing district headquarters contain a wealth of information about rangeland, the kind and extent of use, the nature of the firms that use it, the price for its use, and the product obtained (at least in terms of animal months of grazing). In addition, they may contain data on range improvements, including costs and results, and data resulting from special range use studies of many different kinds.

Records in county and other local offices may contain useful data. County tax offices contain data on land ownership, assessed values, and taxes levied. County Agricultural Stabilization Committee offices often contain useful data on range improvements, including costs of practices eligible for cost sharing under the Federal agricultural conservation programs. Local offices of the Soil Conservation Service may have valuable information on rangeland use and conservation practices. This is not an exhaustive list, but it is enough to show that a great deal of information useful in range economics research does exist from secondary sources.

Results of technical research often have direct application to and are highly useful in economics research. This is especially true of experiments dealing with range production practices and their results when such experiments have been made in locations and under conditions relevant to an economic problem under investigation. Usually, however, range experiments are not designed to test an explicit economic hypothesis so use of their results for this purpose is coincidental. Economists rarely have the facilities to carry on controlled experiments of their own. Results of experiments designed by other technicians for other purposes must be used. The universe to which the experiments apply may not be adequate for the economic purpose, the range of variation tested may not be appropriate, the variables measured may not be adequate, and the results obtained may not be applicable to real firms or ranches. This in no way reflects on the usefulness of the controlled experiments for the purposes for which they are designed; it is intended to put the researcher on guard when using experimental results in economic research. Greater cooperation between economists and other range technicians in selecting, designing, and operating controlled experiments would be beneficial to the work of both groups.

Many demonstrations of range use and improvement practices have been made. Frequently, they have resulted in data useful for economic investigation. Their limitations are that they may not be "typical" or applicable to a relevant universe; some important variables may not be accounted for or controlled; inputs and products may not be carefully measured or recorded; and the range of conditions tested may not be great enough to permit determination of economic optima. Nevertheless, demonstration plots sometimes provide the only relevant data to be had and they can be used meaningfully if their limitations are properly recognized.

Economists usually depend on surveys from which they obtain much of the data required in economic analysis. Surveys may be of many types. The proper design of a survey depends upon the nature of the problem under study and the hypothesis to be tested. When aggregate magnitudes are desired (such as determination of total returns to all ranches from a given practice), a random sample that meets prescribed limits of reliability for all ranches in the universe is required. When relations among firms with different characteristics are under scrutiny a stratified sample based on relevant differences is required.

Surveys are expensive. They may be less costly per datum obtained than controlled experiments, but nevertheless they are expensive enough to place much responsibility on the researcher. He must make sure that the data to be obtained from a survey cannot be gotten by cheaper means, and if not, that the survey, schedules, and questionnaires be designed to produce acceptable results. More than ordinary care and skill must be exercised in defining the problem, in formulating hypotheses to be tested, and in designing surveys that will produce the required data.

Analytical Techniques

Analytical techniques in economics research are subject to considerable controversy and continual discussion among economists. Frequently, these discussions arise not because of differences of opinion concerning the worth of the techniques themselves, but because of implicit differences in the task the techniques are supposed to perform. Many of these discussions could be resolved by making the hypothesis to be tested explicit and by agreement as to the degree of precision required to accept or reject the hypothesis.

In economics research, as in other subject-matter fields, the techniques for collecting and analyzing data must meet the rigorous standards of scientific inquiry. The degree of precision required in the analysis, however, depends on the hypothesis to be tested and on the kind of decisions expected to be made from the results. For example, the hypothesis under scrutiny may be that a reduced rate of stocking would be more profitable than present rates on given range sites. The inquiry may proceed to a point at which this hypothesis can be accepted without room for doubt. For this purpose, the data and analysis may not need to be precise enough to determine *the* most profitable rate or the exact amount of increased profit. On the basis of this information, a rancher could decide to move in the direction of increased profits without knowing exactly how far he would have to go to achieve the greatest profits. Formulation of other hypotheses and perhaps different data and more precise techniques of analysis would be required for the latter.

Statistical techniques common to other branches of science are widely used in economics research. For example, the problem of fertilizer application on rangeland may be viewed as one of selecting, from among different kinds and quantities of fertilizer, the kind and quantity that would produce the greatest economic return from the land. One hypothesis might be that there is no significant difference in the yields obtained from different quantities of fertilizer. The proper statistical tool for testing this hypothesis would be analysis of variance of mean yields of the different treatments (Snedecor 1956).

An example more commonly encountered in economics research involves an estimation of the physical production for successive quantities of various combinations of the fertilizer elements. In this instance, a continuous functional relation is visualized. Experiments designed to estimate successive points on the production surface permit the use of regression analysis with single or simultaneous equations. The standard error of estimate would be used to determine fiducial limits to the regression line or surface, while the t-test would be used to determine whether or not the regression equation differed significantly from zero (or some other hypothetical value).

For problems that involve several independent and dependent variables, a tentative exploration of the relationships by means of tabular analysis or by graphic regression analysis before the more complex task of mathematical regression is undertaken will usually prove to be worthwhile. Some of the possible combinations of variables might be rejected on the basis of this tentative arrangement of data. Further, the relations suggested by tabular and graphic analysis usually will suggest the form of mathematical equation to be used in further analysis.

The Single Enterprise

All too frequently, economic relations are measured, analyses made, and conclusions drawn only in terms of the rangeland or the livestock of the ranch, each considered as a separate enterprise. Information for the enterprise approach often is obtained from controlled experiments. When this is not possible, information on costs and returns of the particular practices in question can be collected from ranchers who have applied them. If the cost of a practice is less than the increased returns from it (as measured by the expected increased volume of product from the particular plot of rangeland multiplied by the expected price of the product) the practice is advocated.

The limitation of the enterprise approach is that it does not consider the ranch as a producing unit, that is, a firm for which management decisions are made. Thereby, it ignores alternative uses of the scarce resources that might return more to the rancher if used on some other enterprise or in some other way. Also, it ignores many secondary effects that changes in the single enterprise might have on other factors that affect ranch income. For instance, by increasing the carrying capacity of an early spring range, the summer range and winter feed might be used more effectively, or by improving the quality and yield of the late summer and fall pasture the calf crop might be increased. Competitive and complementary effects are ignored in the enterprise approach.

The Ranch or Firm

A more accurate appraisal of the economic relationships in range management is obtained when the entire ranch unit or firm is considered. In using this approach, one must decide *which* ranch unit to use.

The case method: This method is followed frequently in range economics research. A single ranch on which a range improvement, for example, is being applied is selected as representative in some important way of ranches encountering the problem under study. This ranch is then studied in detail. Records of physical inputs and outputs, as well as records of costs and returns, are collected over time. These records show the economic picture before the range-improvement practice was applied, the economic situation existing during the transition brought about by the practice, and the situation after the practice was established. From this information, conclusions are drawn concerning the profitableness of the practice on the particular ranch. Inferences to other ranch situations are subjective. This approach may include several different cases selected for their similarities or differences with respect to the situation under study.

The advantage of the case method is that it provides a real working environment in which to conduct the research. The sample (one firm) remains intact throughout the study and all forces (anticipated or unanticipated, identified or confounded) operate freely and influence the results. The case approach is useful in appraising cause-effect relations within the firm. Also, it might become an effective demonstration unit in extending the conclusions to other ranchers.

Disadvantages lie in the fact that with only one observation the influence of the manager and of many other unmeasurable factors applicable to that particular firm only might influence the results so strongly that erroneous conclusions and inferences might be made. The approach does not result in conclusions that can be generalized, as no estimates of the population can be made.

The survey method: Another procedure followed in range-management research is to make an economic survey of the ranchers who, for example, are following a management practice in question. Information relevant to the study is gathered from each of the ranchers or from a random or stratified sample, depending upon the data required. Inventories of resources and production practices, physical inputs and costs, production and monetary returns, and others are obtained by means of questionnaires or from ranch records if they exist. This information is pooled and some measure of central tendency for each variable is used in "constructing" a ranch that is "representative" of the population or "typical" of a stratum of the population studied. The analysis then proceeds on the firm or ranch approach, using the representative or typical ranch as the model.

The advantage of this method is that the influence of particular managers tend to "average out" and thus do not exert an undue influence on the conclusions. This can be said also of other unmeasurable and random forces. Consequently, inferences from the model to ranches in the area are usually on safer grounds than when the case method is used.

The disadvantages of this method are that the average of any series might not represent any single member in the series and that important characteristics may be obscured because observations within the sample contradict each other. Based strictly on an average of the ranches, odd combinations and sizes of enterprises might occur in the model. To use these "average" situations as models might yield results that would be applicable to no particular firm.

This limitation of the survey method can be overcome when the survey averages become only guides to the researcher in setting up a synthesized model of a firm for purposes of analysis. Based on the survey and other information at his disposal, the researcher can construct a working model to represent the ranches to which inferences are to be made. He then proceeds to analyze what might happen to his model when the treatment in question is and is not applied. This approach is smilar to the case method except that in this instance the "case" is idealized.

Methods of Analysis

Regardless of the level of aggregation desired (whether the single enterprise, the ranch, a group of ranches in a small watershed, a community, or a river basin area) the economic analysis must proceed in such a way that the meaningful hypotheses can be tested. In economics research this usually means comparisons of costs and returns of each of the meaningful alternatives so that the most profitable, or otherwise most desirable, one can be selected.

The procedure ordinarily used for this analysis is the partial budget. It is nothing more than a systematic arrangement of the data on resources used, costs, production, and income for each alternative course of action (Caton 1957). In partial budgeting, those costs and returns that are the same for each alternative (such as fixed interest charges, taxes, depreciation on buildings and equipment required for each alternative) can be omitted from the tabulations without affecting the conclusions. Thus, changes in the variables can be observed and measured easily. After the most promising alternative has been selected, a complete budget can be prepared to illustrate total costs, total returns, profits, and other characteristics.

The use of the budget as an analytical technique has many advantages, not the least of which is its flexibility. Costs and returns for alternative practices, alternative organizations of the enterprise or firm, or for different time periods may be tabulated in budget form. Each budget for each alternative is independent and each can reflect realistic relations among cost items and between these items and income, limited only by the skill and time of the researcher and by the data available. A series of budgets may be made to reflect incremental changes in some one factor or group of factors, thus facilitating the search for the most profitable or otherwise most desirable combinations of resources and practices (Black *et al.* 1947).

For purposes of illustration, summaries of two budgets for a South Dakota farm are included (tables 4 and 5). These budgets show that net income for labor and management remains about the same whether the major enterprise is cattle or sheep. The sheep farm requires a little more labor, while the cattle farm requires more capital. Therefore, an operator with a good supply of labor and limited funds would find it to his advantage to raise sheep while an operator with a good supply of capital and limited labor probably would prefer cattle, other things being equal. Budget summaries such as these, if prepared for each relevant alternative, will tell the researcher or the ranch manager a great deal about the consequences and requirements for each situation under study.

In recent years, considerable attention has been given to linear programming as a mathematical technique for determining solutions to limited resource allocation problems (McCorkle 1955 and Charnes 1953). It has been widely used for analysis of problems that involve cost minimization for a specific output and factor allocation among alternative enterprises or processes for maximum profit in the short run. The technique requires that one or more factors used in production, such as land or capital, be limited. Results are

TABLE 4. Budget summary for 682-acre cattle-hog partly irrigated farm with slaughter cattle as a major enterprise, central South Dakota, projected prices

Crop	Land use					Crops sold		
	Acres	Yield	Unit	Production	Farm use	Amount	Price	Value
							dollars	*dollars*
Dryland								
Corn	20	16	Bu.	320	320			
Wheat	39	15	Bu.	585	59	526	1.55	815
Alfalfa	7	1.4	Ton	10	10			
Native pasture	291	.81	AUM	236	229			
Irrigated								
Corn	160	47	Bu.	7,520	3,985	3,535	1.20	4,242
Wheat	52	24	Bu.	1,272	80	1,192	1.55	1,848
Alfalfa	43	3.5	Ton	150	148			
Alfalfa pasture	64	7.0	AUM	448	448			
Other	5							
TOTAL	682							6,905

Livestock and livestock products sold

Item	Grade	Number	Av. weight per head	Total weight	Sold		
					Amount	Price	Value
			pounds	*pounds*	*pounds*	*dollars*	*dollars*
Steers, yearling	Choice	22	950	20,900	20,900	22.00	4,598
Heifers, yearling	Choice	13	950	12,350	12,350	20.95	2,587
Cows	Medium	10	1,050	10,500	10,500	12.50	1,312
Hogs		150	230	34,500	34,500	16.65	5,744
Sows		30	350	10,500	10,500	14.45	1,517
Stags		2			2		80
Poultry		75	5	375	375	.20	75
Eggs		100 hens	120 eggs	1,000 dz.	1,000	.30	300
TOTAL							16,213

Continued on following page

TABLE 4.—Continued

Financial summary

Expenses		*Receipts*		*Inventory value*	
Seed	$ 582	Crops	$ 6,905	Land and bldgs.	$37,360
Fertilizer	1,229	Livestock	16,213	Bldg. and impr.	(3,996)
Feed	1,581	Total cash rec.	$23,118	Mach. & eqpt.	7,944
Taxes	996	Change in inv.	—	Livestock	21,117
Water, O&M	1,600				———
Water, const.	960	Total Income	$23,118	TOTAL	$66,421
Machinery oper.	2,464				
Building repairs	142	Cash receipts	$23,118		
Labor	879	Less cash exp.	10,760	*Inventory No.*	
Other	327		———	Beef cows	48
	———	*Net cash income*	$12,358	Sows	30
Cash oper. exp.	$10,760			Hens	100
Machinery depr.	795	Change in inv.	—		
Building depr.	120	Less depreciation	915	*Labor req'ts*	
	———	*Net farm income*	$11,443	Operator M/da.	277
Total depr.	915	Less int. on inv.	3,238	Hired M/da.	187
Int. on invest.	$ 3,238	Net labor and			—
Total expenses	$14,913	mgt. income	$ 8,205	Total	464

Adapted from Rex. D. Helfinstine, "Economic potentials of irrigated and dryland farms in central South Dakota," S. Dak. Agr. Exp. Sta. Bul. 444, Stat. supplement, 1955.

TABLE 5. Budget summary for 682-acre sheep-hog partly irrigated farm with fat lambs as a major enterprise, central South Dakota, projected prices

Crops	*Land use*					*Crops sold*		
	Acres	*Yield*	*Unit*	*Production*	*Farm use*	*Amount*	*Price*	*Value*
							dollars	*dollars*
Dryland								
Corn	20	16	Bu.	320	320			
Wheat	39	15	Bu.	585	59	526	1.55	815
Alfalfa	7	1.4	Ton	10	10			
Native pasture	291	.81	AUM	236	229			
Irrigated								
Corn	160	47	Bu.	7,520	3,843	3,677	1.20	4,412
Wheat	53	24	Bu.	1,272	80	1,192	1.55	1,848
Alfalfa	46	3.5	Ton	161	159			
Alfalfa pasture	61	7.0	AUM	427	427			
Other	5							
TOTAL	682							7,075

TABLE 5.—Continued

Livestock and livestock products sold

Item	*Grade*	*Number*	*Av. wgt. per head*	*Total weight*	*Sold Amount*	*Sold Price*	*Sold Value*
			pounds	*pounds*	*pounds*	*dollars*	*dollars*
Lambs, fat	Good	275	95	26,125	26,125	20.30	6,303
Ewes	Good	53	120	6,360	6,360	8.55	544
Bucks		5			5		75
Wool		416	9	3,744	3,744	.45	1,685
Hogs		150	230	34,500	34,500	16.65	5,744
Sows		30	350	10,500	10,500	14.45	1,517
Stags		2			2		80
Poultry		75	5	375	375	.20	75
Eggs		100 hens	120 eggs	1,000 dz.	1,000	.30	300
TOTAL							15,323

Financial summary

Expenses		*Receipts*		*Inventory value*	
Seed	$ 582	Crops	$ 7,075	Land and bldgs.	$37,360
Fertilizer	1,229	Livestock	15,323	Bldg. and impr.	(4,096)
Feed	1,460			Mach. & eqpt.	7,944
Taxes	835	Total cash recp.	$22,398	Livestock	10,422
Water, O&M	1,600	Change in inv.	—		
Water, const.	960	Total Income	$22,398	TOTAL	$55,726
Machinery oper.	2,464				
Building repairs	145	Cash receipts	$22,398		
Labor	949	Less cash exp.	10,648	*Inventory No.*	
Other	424			Ewes	400
		Net cash income	$11,750	Sows	30
Cash oper. exp.	$10,648	Change in inv.	—	Hens	100
Machinery depr.	795	Less depreciation	918		
Building depr.	123	*Net farm income*	$10,832	*Labor req'ts*	
		Less int. on inv.	2,596	Operator M/da.	298
Total depr.	$ 918			Hired M/da.	202
Int. on invest.	2,596	Net labor and			
Total expenses	$14,162	mgt. income	$ 8,236	Total	500

Adapted from Rex. D. Helfinstine, "Economic potentials of irrigated and dryland farms in central South Dakota," S. Dak. Agr. Exp. Sta. Bul. 444, Stat. supplement, 1955.

obtained in terms of optimum combinations of resources required to make full use of the limited factors. This characteristic raises some doubt as to the usefulness of the technique for solution of problems that involve long time periods because all input resources can be varied within limits over time. This is brought out in greater detail in the following discussion on problems that involve conservation.

The programming technique as commonly used further requires the assumption that output is proportionate to input at all levels of production of a given enterprise; profit per animal is the same whether 50 or 100 animals are involved. This characteristic does not invalidate the technique for static solutions within fairly narrow ranges of variability. It does, however, cast doubt on the accuracy of results in problems that involve optimum scale of enterprises. Moreover, the technique requires that a finite number of units of each process or enterprise can be applied. This too places some limitations on the techniques, as is seen later.

Agricultural economics literature has included many illustrations in recent years of the application of linear programming to various types of economic problems. A discussion of the mathematics and computational procedures is available in a number of sources (Boles 1955, McCorkle 1955, and Koopmans 1951). To work through a problem for illustrative purposes in this chapter would be too voluminous and it is unnecessary for the purposes here.

None of the techniques for analyzing economic data provide a method of blind manipulation that will furnish an infallible answer. None can be more reliable than the basic data that go into it. The purpose of analytical techniques is to provide an organized and orderly way of testing hypotheses so that better economic decisions can be made.

SPECIAL PROBLEMS IN RANGE ECONOMIC RESEARCH

In the preceding sections, some of the logic and methods of economics research have been discussed. The function of economics research as a tool to help people decide how they will use resources in the production of economic goods has been emphasized. The most common application of this tool is to analyze alternatives available to the manager of a firm or ranch so that he may obtain maximum profits or maximum achievement of other rational goals. At times, a few special problems are encountered in economics research. Some of these problems are discussed briefly in the sections that follow.

Problems That Involve Scale of Operations

If all of the factors or inputs used in range production were infinitely divisible, determination of an optimum scale or size of operations would be simple. The same procedure used in arriving at the optimum level of production for an enterprise would apply in arriving at the optimum scale of operation for the firm. Assuming no arbitrary limits on capital or other resources, additional resources would be added until the return from each increment just equaled the cost of the resources. At this point, the most economical combination of resources and the most efficient scale of operations is achieved.

In practice, however, many resources are available only in "lumps." Rangeland is added by sections, or parts of sections, and not acre by acre. Usually, an additional worker is employed by the day, month, or year. Ordinarily, the managerial services of the operator are available for a full year once the decision to engage in ranching has been made. Once a "bundle" of resources has been committed, the additional cost of using it to capacity over using it at less than capacity is small.

The problem of determining the optimum scale of operations is one of determining the optimum combinations of "lumpy" inputs. In most parts of the range region, labor is one of the most costly input factors and one that is not readily divisible because of scarcity of alternative employment. On most ranches, the minimum efficient scale of operations is that which results in full employment of one man for one year. As many operations cannot be performed by one man, some seasonal labor is required also. The number of other resources required to provide the man with full-time employment varies with type of ranch, location, and other factors.

Once the scale of operation is expanded beyond the size that one man can handle, a new optimum size is established which approaches full employment of two men. As additional men are added, a point is reached beyond which profits or other advantages fail to increase with additional labor. This usually results because the managerial ability of the person making the decisions is spread over such a large area that his contribution to the production process becomes the limiting factor to further increases in size.

If managerial ability of the operator ultimately sets the economic limit to increase in scale of operation, it becomes difficult if not meaningless to attempt to establish an optimum scale of operation for all firms within an industry. Actually, there is an array of optimums varying with the characteristics of the manager.

Problems That Involve Assumption of Risk

Management of a ranch, or any other firm using rangeland, includes the process of deciding on a course of action and putting the plan into operation. In ranching, as in other types of business, many factors can cause the actual results to deviate from the expected. Seldom can the result of a course of action be predicted with complete certainty (Northern Great Plains Committee on Tenure, Credit, and Land Values 1953).

The term "risk" is commonly used to describe any deviation of the realized results from the expected. However, in this sense, risk can be classified into two useful categories for purposes of economic study. These categories are useful since they permit a distinction to be made in the recommended course of action. The word "risk" is applied to one and the word "uncertainty" is applied to the other.

In some instances, the probability of outcome from a large number of events can be established. For example, the number of barns that will burn, the number of automobile accidents that will occur, and the number of farmers who will suffer from hail damage in the United States during the next year can be predicted with a high degree of accuracy. Likewise, a rancher with a large number of cattle and long experience can predict the death loss in his herd with a reasonable degree of accuracy. The term "risk" applies to those events for which the probability of outcome can be established.

In other instances, the probability of outcome cannot be established. For example, in an economy in which prices are free to fluctuate, there is no basis for establishing empirically the probability of realizing a given price for an agricultural product. The term "uncertainty" refers to those events whose outcome cannot be predicted.

As risk is predictable in the aggregate, many risks are now insurable. Fire, hail, accident, and other kinds of insurance are available to most ranch operators. The cost of an occasional loss can be translated into a smaller cost periodically in the form of insurance premiums. The ranch operator must decide whether he will insure against the risk or bear it himself, that is, whether he chooses a certain small cost in the form of insurance payments or an uncertain large cost in the form of losses. An operator who believes his chance of loss is less than average, or who has adequate financing, may choose to bear the risk and "average out" over a series of events or a series of years.

A rancher is faced with many types of uncertainty. Often he cannot predict with any degree of accuracy the prices he will receive for his products, crop and livestock yields, results of reseeding, actions of a landlord, or forthcoming technological innovations. As these events are not predictable, they cannot be translated into an annual cost of insurance. Survival under these conditions requires that the operator consider a series of possible outcomes in planning his operations. The ability to adapt to changing events as they occur permits him to use the additional information gained as time passes. Flexibility of operations is the only "insurance" against uncertainty.

Economic research can aid farm and ranch operators by providing the data required for rational decisions pertaining to assumption of risks or adjustments to uncertainty. In some instances, a compilation and analysis of existing data will help operators to appraise the alternatives open to them. In others, new areas of research must be undertaken to provide the data needed. All too frequently, economic analysis rests contentedly on average or normal input-output relations without making allowance for the costs required to assume risks or the possibility of recurrence of uncertain events. To obtain realistically useful results these factors must be included and accounted for in most economic studies that involve rangeland.

Problems That Involve Kind of Livestock

Most range research as well as most management decisions by ranchers and administrators of public land have assumed that specific rangelands were best suited to one kind of livestock, that is, that a range was either "cattle range" or "sheep range," but not both. The fact is that most rangelands can be used by either cattle or sheep, or by both. Sheep may eat many summer grasses only sparingly, especially as they become stemmy in late season, whereas cattle may prefer the stemmy grasses to the forbs and shrubs. Thus, the most economic use of many ranges may be obtained by some combination of sheep and cattle.

Consider a range on which only cattle are grazed. When the intensity of use is such that none of the grasses is overused, most of the forbs and browse may be underused. If this condition exists, it should be possible to add a substantial number of sheep by removing only a few head of cattle and still leave the range in an unimpaired condition. As long as the added numbers of sheep bring in more profit than is lost by the cattle that are removed, total profits will increase.

The economic problem of determining the combination of sheep and cattle that will maximize revenue or profit turns on two basic relationships that need to be estimated: (1) the physical relationships, showing the various combinations of sheep and cattle that will give approximately the same degree of range utilization, and (2) the expected price relationships between sheep and cattle.

The physical relationships required for economic solutions can be derived in two ways. First, they may be obtained from controlled grazing experiments when sufficient combinations of sheep and cattle are observed over time so that a relation may be expressed as a curvilinear regression. Obviously, results from grazing experiments of this kind are obtained slowly. When experimental results are not available, production obtained from grazing various combinations of sheep and cattle can be estimated in the same ways as grazing capacity for one type of livestock. Once a physical relation between two different uses of the same resource can be established and expressed as a function, a rational economic decision can be made using the principle illustrated earlier in the fertilizer example.

If cattle and sheep use the same range, it is possible to determine, theoretically at least, the numbers of each which together would produce maximum revenue and maximum net returns (Hopkin 1954). Maximum revenue is achieved simply by finding that point on the functional relationship that results in the greatest sum when the quantity of each product is multiplied by its price.

Maximum net returns from combinations of products (cattle and sheep in this instance) are more difficult to determine because economies of scale distort the net returns from each unit of each product as the quantities change. If it could be assumed that the net return per head of cattle or sheep remained constant with changing numbers, the optimum solution would be relatively simple, but usually this is not the case. Nevertheless, a theoretical solution can be achieved by first determining the relation between numbers and net profits for each kind of livestock. The sum of net profits from both cattle and sheep can be calculated for any point on a curve that expresses the relation between the two in range use.

Problems That Involve Multiple Use of Resources

Multiple use of the range is the production of two or more products from the same resource or group of resources. The most common products of this multiple use are forage, timber, water, big game, and recreation. Forage may be used by cattle, sheep, goats, or big game, singly or in various combinations. Water has multiple uses and recreation takes many forms. These products may be competitive in use of range resources, such as sheep and deer competing on an early spring range where more deer mean fewer sheep. Or they may be complementary in use. Both sheep and cattle may graze a range to produce more total product than either grazing it alone. Careful management of timber may actually increase yields of water whereas no timber cutting may decrease the yield of water for irrigation. But excessive timber cutting or grazing may destroy the value of water for irrigation or domestic use.

Formal economic analysis has been little used in the solution of multiple-use range problems. These problems are difficult to handle methodologically and the data required, especially the values of non-marketable products, do not exist in precise form. Nevertheless, some creditable work has been done in developing the logic for solutions of multiple-use problems (Ciriacy-Wantrup 1941). Most of this work is based on use of production functions in which the costs (inputs) are compared with the value of the products (outputs) at various levels of production (Robinson 1955). Determination of economic optima for two products, as discussed in the previous section, is easier than for three or more, which must be handled mathematically without the option of graphic analyses. Pairs of products may be analyzed as partial solutions in a series of several. However, choosing first the optimum combination of cattle and game, then the best association of forage users with timber production, and finally analyzing this coalition jointly with recreational or watershed uses and values, is not realistic. Yet it offers a way of approaching the solution of a complex problem.

Despite recent progress in economic methods, several important issues remain to be resolved before economics can contribute materially to decisions that involve multiple use. One issue is that of establishing values for non-marketable products. No valid economic comparisons can be made without them. Another issue is that of establishing functional relations between and among the products jointly produced. Here the responsibility rests mainly with range, forest, and other technicians who have the resources and skills to perform the needed controlled experiments and to make the needed observations under field conditions. A third issue involves improvement of analytical techniques to produce optimum solutions under conditions of multiple inputs and multiple products. These techniques are fairly well advanced in farm-management research, but they may need to be adapted to problems of multiple use of rangeland.

A fourth issue involves the determination of optimum combination of inputs and products when different firms are to be considered. The main contribution from economics to multiple land use problems has been in the area of the theory of joint costs. The construct is useful mainly for solution of problems for a single firm. If only ranchers, only irrigators, only deer hunters, or only lumbermen had to be considered, optimum solutions could be found for each. However, many different firms are involved in the use of rangeland, and the optimum solution for a rancher may conflict with the optimum solution for deer hunters. In situations where economic optima for different firms are in conflict, economic research does not yet have the methodology for precise analysis.

Moreover, each firm or each type of firm has a different relation to rangeland as determined or defined by its tenure on the land. Ranchers may own, lease, or have permits to graze land. Irrigators have rights to the water flowing from the land through appropriations. Deer may graze nearly all accessible land by virtue of their "ownership" by the state. The institutional arrangements through which each interest group (firm or type of firm) has access to land define the nature and limits of the resources it may put into the production and the way in which it may share in the products. Under conditions of multiple land use, each firm or group may contribute inputs to the complex production process from which come a number of commodities. Each firm or group may share in the complex of products, but its share in the output may not bear a direct relation to its share in the input—as is generally assumed in economic analysis. Here, then, is a problem in economic methodology that is yet to be solved before economic research can make its full contribution to decision-making on multiple range use problems.

Problems That Involve Conservation of Range Resources

Time is a factor in economic decisions. The essential problem involved in conservation is the distribution of resource use over time. The economics of conservation is concerned with the *when* of production from natural resources (Ciriacy-Wantrup 1951 and 1952).

The type of decision that must be made in range management on the distribution of use over time does not differ conceptually from the decision that must be made with respect to multiple use of range resources. In the economics of conservation, the joint products are differentiated by their occurrence in different intervals of time rather than by their physical characteristics alone.[2]

In reality, management decisions that affect the physical and the temporal characteristics of products are interrelated. For example, decisions that affect a change in the vegetative composition of range among grass, brush, and trees, and thereby the physical characteristics of the final product between grazing and browsing animals and between animals and timber, change also the time distribution of the final products. For analytical purposes, it is well to focus on the latter change separately. This change has technological, economic, and political aspects of its own, and it is of particular concern in range management even when only one product, for example, beef, is produced.

Decisions as to the distribution of production over time—"conservation decisions"—are a part of all business planning. However, in range management with its complex association of resources and products, the deferred effects of management practices[3] on costs and revenues are larger relative to the immediate effects than in agriculture generally. In range management, the deferred effects are characterized in a general way by cyclical oscillations. Frequently, it takes many intervals—decades or even generations (in terms of clock time)—until stability is reached. Sometimes the effects are economically irreversible. Problems that involve conservation, therefore, are a special challenge, but also a promising field for research in range economics.

The Economic Objective of Conservation Decisions

The economic objective of management decisions is usually defined in terms of maximizing profits or other values. With respect to conservation decisions, it is well to emphasize that the main usefulness of the maximization principle consists in its being a construct to help the range operator, the researcher, and the policymaker to understand: (1) the significance of making

[2] An "interval" is defined as that period of time within which changes of rates of production and of other economic variables can be neglected in the analysis. For many problems of range economics, 12 consecutive months, or the "grazing season" constitute a suitable clock-time extent of the interval. For some problems, however, a longer or shorter period is more suitable —for example, a full breeding cycle comprising several years or the period of finishing expressed in weeks rather than months.

[3] A "practice" is defined as a technologically interrelated combination of "productive services" or "inputs"—for example, labor, feed, fertilizer, tractor hours, and fencing materials. Such a combination may be distributed over more than one interval. For example, controlled burning, reseeding, different degrees of stocking ,and rotation grazing may be interpreted as practices.

choices between alternative time distributions of production; (2) the reasons why and in what direction—toward the future or toward the present—a given planned time distribution of production should (in terms of the defined objective) be changed under assumed changes of the economic environment; (3) why, viewed historically, range operators, taken individually or as groups, have realized certain time distributions; and (4) what public policy measures might induce range operators to adopt practices that will result in a time distribution which appears to be desirable "in the public interest."

Use of the maximization principle in economics does not mean that a range operator actually does, should, or could maximize the present value of the expected flow of net revenue over time. (Incomes and costs occurring at different times in the future can be compared by converting them to a present value.) The actual objective of conservation decisions is more modest. It is to increase rather than to maximize the flow of values. A maximum probably cannot be realized, save by accident, but a course toward it can be steered effectively in an economic environment characterized by uncertainty and ceaseless change.

This proximate objective has significant implications for research in range economics. But such practical approximation of the theoretical objective does not invalidate the usefulness of the maximization principle as a construct to order the pursuit of economic meaning. To use an analogy familiar to range technicians, a particular "climax type" in ecology or an "adaptive peak" in genetics is difficult, if not impossible, to define with accuracy. These "maxima" do not explain an actual plant association or the developmental state of a species at a particular time and place nor do they indicate that static states are realizable or that the system under consideration is closed. Still, these concepts are helpful constructs in understanding the direction, the rate, and the conditions of change in plant associations and species. The maximization principle has a similar usefulness in economics.

Implications for Data and Tools of Research

In exploring the implications of what has been said for range economics research, one may first mention the need for more suitable—not necessarily more voluminous—data. Economic decisions in which conservation is an issue require comparison of costs and revenues of range management practices over time. To ascertain the costs of inputs is comparatively easy. To ascertain their effects in physical and monetary terms on output over a number of intervals is more difficult. The most obvious requirement for data is to "follow through" in scientific observation to make sure that all significant deferred effects of an experiment are included. In range economics, some indication of the qualitative and quantitative relation between deferred and immedicate effects of an experiment or practice is at least as important as statistical refinement in the measurement of immediate effects.

In economics of conservation problems, as in other problems of range economics, data are needed on quantity of range output (for example, pounds of beef, wool, or venison), as it relates to qantities of inputs. (Data relating to the intermediate products—forage in its many forms, stages, and quantitative expressions—are not enough. First, the final product is needed for monetary evaluation. Second, the effects of the forage on quantity and quality of the final product are economically significant.) Changes in the "inventory value" of the range itself are as much a product of production processes as the output of beef or wool and must be accounted for in the economic analysis. Deterioration in the condition of a range site (lessening of its capacity to produce over time) may be viewed as a cost to a given production system, whereas improvement of a range site may be viewed as an income.

It has been implied that marginal analysis is an appropriate tool in defining and realizing the economic objectives of conservation. Marginal analysis means thinking in changes. Changes may be finite or infinite, continuous or discontinuous. That finite differences—rather than derivatives—are used in making conservation decisions was indicated when the need for comparing discontinuous additions to total revenues and costs resulting from alternative practices was discussed earlier. Marginal analysis is independent of the maximization principle, but it may be applied to maximization of some value quantity—such as present value of assets—or to other objectives. Marginal analysis is also independent of specific mathematical concepts and techniques.

Recently, linear programming has become popular in economic analysis for management decisions. Some believe that it is superior to the proximate type of analysis commonly known as "budgeting" because a maximum can be determined accurately and cheaply in joint-production problems. At first glance, a tool of this kind would appear to be especially welcome for research in problems of time (that is, conservation) economics, which in range management are essentially joint-production problems. It is appropriate, therefore, to ask, what are the potentialities of the new tool in the economics of conservation?

As we know, the main usefulness of the maximization principle in economics research is as a construct that helps in understanding and orientation—not necessarily as a realizable objective for actual management decisions. Usefulness of linear programming for this purpose is limited. By assuming the type of discontinuity under which linear programming becomes superior (in the above respects) to alternative tools of economic planning, one also "assumes away" some of the most vital theoretical and practical problems of decision-making in time economics.

These assumptions are required by the mathematical technique (McCorkle 1957). They may be expressed in non-mathematical form as follows: (1) That some factors of production available to the firm are limited;[4] (2) that the operator can employ a finite number of production "processes" or "enterprises," which use the limited factors in given proportions and which are independent of each other in the use of nonlimited factors; and (3) that the decision of the quantity of nonlimited factors to be used per unit of each process is independent of the decision as to how many units of each process should be used.[5] The question may be raised as to whether any one of these three assumptions is tenable in time or conservation economics, especially when applied to range management.

In time economics, the differentiation between limited and nonlimited factors (as the terms are used in linear programming) disappears. Nonlimited factors are sunk over various period of economic "gestation." Limited factors can be conserved or depleted, bought or sold, and obtained or disposed of in many ways. Most factors of production can be varied over time, but for a particular production cycle—that is, one crop season—some factors are fixed and others variable.

In range management, the "processes" that have thus far been defined in the literature are interrelated through costs of nonlimited factors and sometimes through revenues. Most of these relations depend on time (Ciriacy-Wantrup 1941). To be sure, processes *can* be defined in such a way that they are independent. But if such definition focuses on the product, that is, if the processes are enterprises as in the existing literature, such independence is more likely to be found in nonagricultural industries than in range management.

The decision as to the combination of processes and the decision about the combination of factors in each unit of process in terms of "intensity" (inputs) of nonlimited factors are not independent of each other. As applied to time economics, this means that the decision about the optimum distribution of rates of production over time contains a decision as to the optimum length of time or optimum number of intervals included in the production plan (Ciriacy-Wantrup 1952). However, decisions as to the quantities and kinds of products to be produced jointly are no less interdependent in instantaneous economics.

It would seem that linear programming has definite limitations as a

[4] Sometimes the term "limitational" is used in connection with these factors. In linear programming, the term refers always to the control of the operator. Such factors are assumed to be divisible among "processes" or enterprises and among units of each process.

[5] In the terminology of linear programming, this latter decision is referred to as "resource allocation." In the economics of natural resources where rationing of resources among different individuals and allocation of costs, benefits, and income to rates of production and to individuals are significant problems, such terminology may lead easily to misunderstandings.

tool of analysis in conservation economics. When numerical accuracy in computation of maxima or minima within the restrictive assumptions and for a specific static situation is desired, linear programming may have advantages over other tools. The restrictive assumptions and the rigidity of the mathematics place considerable doubt on its use in analyzing economic problems of range conservation where data occur in fairly crude forms; relations among inputs, products, enterprises, and firms can only be approximated; and time removes or relaxes the limited nature of some factors.

Another technique that has been introduced in farm management is the calculation of a "break-even" price, that price of a factor or product at which substitution for an alternative product or factor leaves the quantitative criterion management decisions, such as total net revenues, unchanged (Carpy 1957). Although the mathematics of this tool is simple as compared with that of linear programming, the two tools have certain characteristics in common. The simplifying assumptions of linear programming must be made and a given scale of output (number of units of the two alternative "processes") must be assumed. The advantage is similar also to that of linear programming in that the price at which substitution is indicated can be determined with any desired degree of accuracy. Again, therefore, the researcher must ask himself whether he is interested in numerical accuracy under highly restrictive assumptions. For purposes of illustrating the problem of choice between alternatives in instantaneous economics without joint costs and revenues, the tool is adequate. For purposes of solving real problems in conservation economics, where products in different time intervals are always related through costs and revenues, the potentialities of the tool are less promising.

Research in Problems of Conservation Policy

Problems involved in conservation decisions by individual operators do not differ essentially from other managerial problems. Research in the former makes special demands on the type of data needed and cannot so easily employ new tools. But these are differences of degree. In the economics of the private firm or ranch, conservation involves a particular emphasis but constitutes an integral part of the established field of range management in both research and practice.

To help individual range operators in their conservation decisions is only one objective of research in problems of conservation. Even more important is an understanding of how conservation decisions by range operators taken as a group are affected by changes of income and income distribution, prices, interest rates, allowance for uncertainty, and especially by changes in such social institutions as the laws and the administration of laws concerning property, tenure, taxation, credit, and markets. Based on an understanding of these economic forces, the means and the criteria of using such forces to modify conservation decisions by private operators "in the public interest" can then be studied. This constitutes a major field of conservation policy. In range economics research, this field has been largely neglected.

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Chapter 9

Sampling Methods With Special Reference to Range Management

SAMPLING

Introduction and Basic Requirements

IN NO FIELD does the research worker encounter a more complex population for estimation than in range investigations. On a single square foot of soil area he may find species representing several genera and several families. He is required to estimate many characteristics of the forage such as the total volume or weight, the quantity used or available, the species distribution, height, and growth.

In a discussion of sampling, we should consider first the basic requirements of a sample if it is to serve the purpose for which it is drawn. Fundamentally, the purpose of a sample is to estimate the result that would have been obtained had every unit of the population been measured. This leads to the basic requirement that the sample represent the population in a known manner. If the selection of the sample is restricted in any way, this must be taken into account in estimates derived from the sample. If changes take place either in the population itself, or in the method or tools of measurement, they must be considered in analyzing data.

A feature of sampling that is often taken for granted, and often ignored, is the need for a dependable basis for evaluating or appraising the precision of estimates derived from the sample. It is assumed, but often without adequate basis, that the sample estimate is correct. In order that a sample supply the basis for evaluating the precision of the estimate, care must be taken to represent the variability of the sampling units.

General Considerations in Sampling

In identifying the sampling unit and planning the procedure for sampling the planner must study the population to be sampled: its location; size; accessibility; the nature and extent of variability; costs and accuracy of measurements; features peculiar to the specific population such as sources of possible bias; usable bases for stratification; correlated variables that may be used for increasing precision of estimates or reducing costs. Before these factors and their effects can be examined, it will be necessary to introduce and discuss the basic concept of statistical variability and its effect on precision of estimates.

Measure of Variability and Central Tendency

To make the discussion more understandable, consider a pasture of 320 acres on which the principal forage species is black grama. Let this pasture be subdivided theoretically into square milacre plots or sampling units, of which there are 320,000. Thus, N is equal to 320,000. Consider a variable X which is the plot weight, in grams, of the black grama plants above a stubble height of ½ inch. We have, then, a population of 320,000 weights. The milacres may be given identifying numbers from 1 to 320,000. We have, then, 320,000 separate and distinct values X_i ($i = 1,2, \cdots N$). This population has an arithmetic mean or average[1]

$$\mu = \frac{\sum_{i=1}^{N} X_i}{N} \tag{1}$$

The mean μ characterizes the magnitude of the values of X but gives no idea of how individual values may be dispersed or distributed relative to μ. For this purpose we calculate the population variance

$$\sigma^2 = \frac{\sum_{i=1}^{N} (X_i - \mu)^2}{N} \tag{2}$$

which is the arithmetic average of the squares of the differences between the X_i values and their mean μ. The positive square root of σ^2 is the standard deviation of variable X.

Now if we harvest a random sample of n, say 400 units of X_i, we compute the sample arithmetic mean

$$\bar{x} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{3}$$

[1] Σ is called summation sign and the subscript i is called the index of summation. The $i = 1$ below Σ indicates that the first term in the sum is found by giving i the value of 1. The N above Σ indicates that the last term in the sum is found by giving i the value of N. N is the total number of sampling units in the population.

It can be shown that $\bar{x}$ is an unbiased estimate of μ. Similarly, we compute the sample variance

$$s^2 = \frac{\sum_{i=1}^{n} (X_i - \bar{x})^2}{n - 1} \tag{4}$$

which can be shown to be an unbiased estimate of population variance σ^2.

Now, it can be shown that, almost regardless of the form of the original population, means $\bar{x}$ of n observations will have a variance of approximately

$$\sigma_{\bar{x}}^2 = \frac{\sigma^2}{n} \tag{5}$$

These relationships are of importance in statistical tests of significance and in setting confidence limits on estimates. If means of n observations tend to be distributed normally with variance $\frac{\sigma^2}{n}$, the probability that a single sample mean $\bar{x}$ will differ from the true mean μ by more than some fixed quantity "d" can be determined directly from a table of the normal distribution.

In practice, the sampler does not know σ^2 but makes a sample estimate s^2.

It has been shown that if $t = \dfrac{\bar{x} - \mu}{\sqrt{\dfrac{s^2}{n}}}$, (6)

then t follows the well-known Student's "t" distribution when samples are drawn from a normal distribution. This relation remains approximately true when the distribution from which the sample was drawn departs quite widely from the normal. As a consequence, the statement can be made that

$$\mu = \bar{x} \pm t_{.95} s_{\bar{x}}, \tag{7}$$

that is, that the true mean μ lies within the interval $\bar{x} - t_{.95}s_{\bar{x}}$ and $\bar{x} + t_{.95}s_{\bar{x}}$, where $t_{.95}$ is the t value corresponding to the 95 percent limit, and this statement has a probability of .95 of being true. In the "t" table, the value given at the .05 level of significance is the $t_{.95}$ value as applied here to the confidence interval. The standard error of the mean is calculated by the formula

$$s_{\bar{x}} = \frac{\sqrt{s^2}}{\sqrt{n}} \tag{8}$$

If it is desired to narrow the confidence interval, with the same number of observations in the sample, a smaller value of t may be used but this reduces the probability that the statement is true. Conversely, if greater probability is desired, it will be necessary to widen the confidence interval. To demonstate these relations, suppose 31 random observations yield a mean of 100 and a standard error of the mean of 5. We may make the following statements:

(1) The probability is 0.95 or 19:1 that

$$\bar{x} - t_{.95}s_{\bar{x}} \leqslant \mu \leqslant \bar{x} + t_{.95}s_{\bar{x}}$$
$$(100 - 10.21) \leqslant \mu \leqslant (100 + 10.21)$$

or

$$89.79 \leqslant \mu \leqslant 110.21$$

(a range of 20.42)

(2) The probality is 0.50, ie., a 50-50 chance that

$$(100 - 3.42) \leqslant \mu \leqslant (100 + 3.42)$$

or

$$96.58 \leqslant \mu \leqslant 103.42$$

(a range of 6.83)

(3) The probability is 0.99 or 99:1 that

$$(100 - 13.75) \leqslant \mu \leqslant (100 + 13.75)$$

or

$$86.25 \leqslant \mu \leqslant 113.75$$

(a range of 27.50)

It is assumed in the above that the sample is a small part (less than 2 percent) of the population. If the sample is a large part, the variance of the mean should be multiplied by a factor

$$f = \left(1 - \frac{n}{N}\right) \tag{9}$$

which will reduce the variance of the sample mean to the extent of the ratio of the sample to the population size.

Confidence Range or Sampling Error Relative to Magnitude Estimated

It may be desirable to express the sampling error, or range of confidence, in terms of either a percentage of the estimate or in terms of the population total. Thus, we wish to provide an estimate such as 50 animal months with a confidence range of plus or minus 3 animal months or a sampling error expressed as plus or minus 6 per cent.

The estimate of the total for a population is obtained by multiplying the average value per sampling unit by the total number of such units in the population.

Thus, if there are N milacres in a pasture, the estimated total in the pasture, say $\hat{T}$, is

$$\hat{T} = N(\bar{x}) \tag{10}$$

where $\bar{x}$ is the sample average value of X per milacre. The variance of $\hat{T}$ is

$$\sigma^2_{\hat{T}} = N^2\sigma^2_{\bar{x}}, \tag{11}$$

and the sample estimate is

$$s_{\hat{T}}^2 = N^2 s_{\bar{x}}^2 \tag{12}$$

Consider now the effect of increasing the size of the unit of observation. Let X' be the weight of a 4-milacre plot. Obviously, the population average of weights of plots this size would be 4 times as great, and in the population there would be one-fourth as many as when one milacre area is used. Now the estimate is T' and

$$T' = \frac{N}{4}\,\bar{x}' \text{ where } \bar{x}' \text{ is the average of the sample} \tag{13}$$

of 4-milacre plots. Now the variance of T' is

$$s_{T'}^2 = \frac{N^2}{16} s_{\bar{x}'}^2 \tag{14}$$

$\hat{T}$ and T' are, of course, estimates of the same population value. $s_{\hat{T}}$ or $s_{T'}$ when multiplied by the value for the probability level selected show the limit of confidence in either direction or half the confidence range. If the half range is divided by $\hat{T}$ or T' and multiplied by 100, the result is an expression of the confidence limit in terms of a percentage of the estimated total.

Size and Shape of Plot

A comparison of equations 12 and 14 shows that to obtain equal values of the variances of the totals, i.e., $s_{\hat{T}}^2$ and $s_{T'}^2$, it would be necessary for $s_{\hat{T}}^2$ to be 1/16 as great as $s_{\bar{x}'}^2$. If the 1-milacre plots making up the individual 4-milacre plots were completely independent, that is, if each could be considered to be a random sample of the entire pasture, the variance of single 4-milacre (totals of four 1-milacre) plots should be 4 times as great as for single milacre plots. The milacre plots making up 4-milacre plots are expected, however, to be less variable than if selected at random over the whole pasture. It is expected, therefore, that the 4-milacre totals would be more variable than totals of 4 randomly selected milacres, that is $s_{\bar{x}'}^2$ is expected to be more than 16 times as great as $s_{\bar{x}}^2$. To attain the same precision would, therefore, require a greater area to be sampled, i.e., more than one-fourth the number of samples using 4-milacre plots than 1-milacre plots. To offset the greater sample area requirement, however, the cost of measurement per unit of area should be less for the larger plots because of the reduced travel time and the reduced time to locate sample points. Quite possibly, then, it may cost less to use the larger sample size to obtain the same accuracy.

The shape of the plot also can be important in the efficiency and cost of the sample. It is usually found that elongated plots which are oriented with the long axis in the direction of greatest variability are more uniform from plot to plot than are square or circular plots of the same area.

To study the importance of plot size and shape, use is made of some field data. An area 100 × 160 feet in size was divided into 640 5 × 5-foot plots, and the weight of hawksbeard was obtained for each plot.

The variance of these 640 plots is 6265.66. The plots were combined into 5 × 10-foot plots, 5 × 20-foot plots and 10 × 10-foot plots. The actual variances of these plots are shown in the third column of table 1.

TABLE 1. Shape of plots, actual and estimated variance, and efficiency as compared to independent plots

Shape of unit	*Number of small plots per unit*	*Actual variance*	*Estimated variance**	*Efficiency as compared to independent plots*
(1)	(2)	(3)	(4)	(5)
5 x 5 feet	1	6,265.66	6,265.66	1.000
5 x 10 feet	2	20,630.39	12,531.32	.607
5 x 20 feet	4	46,357.23	25,062.64	.541
10 x 10 feet	4	58,539.30	25,062.64	.428

* Assuming independence.

The effect of grouping can be seen by comparing these actual plot variances to what would have been obtained by random combination of these plots. The estimated variance of the larger plot is equal to the variance of an individual plot multiplied by the number of plots. The estimated variances are shown in column 4 and were obtained by multiplying the variance of the unit plot, i.e., 6,265.66 by the number of plots shown in the second column.

The effect of plot shape can be seen by comparing the actual variance of plots 5 × 20 feet with plots 10 × 10 feet in size. The long narrow 5 × 20-foot plot is $\frac{58{,}539.30}{46{,}357.23} - 1.0 = .26$ or 26 per cent more efficient than the square 10 × 10-foot plots. In other words, 26 percent more plots of the shape 10 × 10 feet would be required to give the same error as obtained by using 5 × 20-foot plots.

The cost of obtaining kn independent small plots is usually greater than that of obtaining n large plots each having an area equal to k individual plots. For this reason, it is necessary to consider cost when deciding on plot size.

If the cost of obtaining a 5 × 10-foot plot is more than 60.7 per cent of the cost of a pair of independent smaller plots—then the small plots will give a smaller error for a given amount of money (table 1). Also, if the cost of obtaining a 5 × 20-foot plot is more than 54.1 per cent of the cost of four random small plots—then the small plots are better. However, if the cost of obtaining a larger plot is less than 54.1 per cent of that of obtaining four small plots—then the larger plots are best.

For instance, if \$5,000 is available for a survey and it cost \$10.00 to get a pair of independent 5 × 5-foot plots, the variance of the estimate would be $\frac{12{,}531.32}{(\$5{,}000/\$10.00)} = \frac{12{,}531.32}{500} = 25.0626$. If a larger 5 × 10-foot plot cost \$7.00—then the variance of this estimate would be $\frac{20{,}630.39}{(\$5{,}000/\$7.00)} = \frac{20{,}630.39}{714} = 28.8941$.

The variance for the larger plots is larger than for the pairs of random plots. This is as expected, since the cost of the larger plots was more than 60.7 percent of the cost of a pair of small plots. If the larger plots had cost \$5.50 per plot—then the variance of the larger plots would be $\frac{20{,}630.39}{\$5{,}000/\$5.50)} = \frac{20{,}630.39}{909} = 22.6957$. This is as expected, since the cost of the larger plot, \$5.50, is less than 60.7 per cent of the cost of a pair of small plots.

Sampling Plans

It will be evident from the discussion of the basic sampling designs that a large number of variants or combinations can be created. In fact, they are limited only by the ingenuity of the sampler and the material available.

Simple random sampling: The simplest form of sampling is the random selection of a set of n observations from a population of N. For instance from a total of 640 possible units, 10 are selected with each unit of this total having an equal chance of being selected.

The yield from this random sample of 10 out of a total of 640 plots can now be used to estimate the yield of all plots. The 10 random observations were 60, 0, 40, 75, 115, 95, 150, 190, 75, and 310. The total of these observations is 1110. The estimate of the mean of the population is 111.0.

The estimate of the population total is

$$\hat{T} = N(\bar{x}) = 640(111.0) = 71{,}040$$

To determine the reliability of this estimate, it is necessary to calculate the standard deviation and the standard error.

The standard deviation is calculated using a rearrangement of Equation 4:

$$s = \sqrt{\frac{\sum_{i=1}^{n} X_i^2 - \frac{(\sum_{i=1}^{n} X_i)^2}{n}}{n-1}} = \sqrt{\frac{193{,}400 - \frac{(1110)^2}{10}}{9}}$$

$$= \sqrt{\frac{193{,}400 - 123{,}210}{9}} = \sqrt{\frac{70{,}190}{9}} = \sqrt{7{,}798.89} = 88.31$$

The standard error is

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}\sqrt{1 - \frac{n}{N}} = \frac{88.31}{\sqrt{10}}\sqrt{1 - \frac{10}{640}}$$

$$= \frac{88.31}{3.1623}\sqrt{.9844} = 27.93(.9922) = 27.71$$

In this problem the use of the finite population correction factor $\sqrt{1 - \frac{n}{N}}$ has reduced the error but little, i.e., from 27.93 to 27.71.

Since $\hat{T} = N\bar{x}$ the standard error of $\hat{T}$ is

$$s_{\hat{T}} = N(s_{\bar{x}}) = (640)\ (27.71) = 17{,}734.40$$

The confidence interval for this estimate of the total is

$$\hat{T} - t_p s_{\hat{T}} \leq T \leq \hat{T} + t_p s_{\hat{T}}$$

If t_p is chosen for a probability level of $p = .95$ and 9 degrees of freedom then $t = 2.26$. The confidence interval thus is

$$71{,}040 - (2.26)\ (17{,}734.40) \leq T \leq 71{,}404 + (2.26)\ (17{,}734.40)$$
$$71{,}040 - 40{,}079.7 \leq T \leq 71{,}040 + 40{,}079.7$$
$$30{,}960.3 \leq T \leq 111{,}119.7$$

Thus, we are 95 per cent confident that the true population total T is in the range 30,960.3 to 111,119.7.

Since this range is rather large, it may be desirable to obtain a smaller confidence interval by resampling. Therefore, the sample margin of error of 7,000.0 might be selected instead of the value of 40,079.7. The sample size suggested to obtain this accuracy can be obtained from the equation

$$n = \frac{t^2(N^2s^2)}{(\hat{T} - T)^2 + t^2Ns^2}$$

which is a rearrangement of the expression for "t".

Sometimes the research worker wants to collect a sufficient number of samples to give reasonable assurance that the true mean is within a prescribed range of the sample mean. Thus suppose the confidence interval is to be 10 per cent of the mean or (.10) (111) = 11.1. Therefore, using $t_{.95} = (\bar{x} - \mu)/(s\sqrt{n})$, then $n = t^2s^2/(\bar{x} - \mu)^2$. From the example $n = (1.96)^2\ (88.31)^2/(11.1)^2$ or 243. This suggests that if as many as 243 samples are taken the population mean will not deviate more than 10 per cent from the sample mean with odds of 19 to 1 or a probability of 95 per cent.

The sample supplies the value for s. The value for $(\hat{T} - T)$ in this example is 7000, the desirable allowable error. The confidence we want to place in the allowable error is measured by the value of t chosen. If we set the confidence interval probability at $P = .95$ then from the normal curve of error we find $t = 1.96$ thus

$$n = \frac{(1.96)^2(640)^2(88.31)^2}{(7000)^2 + (1.96)^2(640)(88.31)^2}$$

$$= \frac{12,271,336,355}{49,000,000 + 19,173,963} = 180$$

If a preliminary sample is not available to supply the estimate of s, then one must use his best estimate of s.

Cluster sampling: Cluster sampling is the simplest of the restricted random sampling plans. It may be thought of in a restricted sense as random block sampling. As used here, a cluster location or block will be considered as a relatively small and compact area within which a cluster or subsample of elementary units is confined. For example, a cluster area may be a 1/10-acre circular or square area in which n (for example 2, or 6 or 16) milacre plots may be selected for measurement or observation. In cluster sampling the time or cost of making individual observations within a small area is less than when the plots are scattered at random over the whole area.

For example, returning to the population of 320,000 milacres in a 320-acre pasture, we may mentally subdivide the pasture into 3200 1/10-acre sub-areas or sampling areas. We may then select 25 of these 3200 at random and select 16 of the 100 milacres in each of the 25 as subsamples. Alternatively, we could select 10 1/10-acre areas and at random select 40 milacres in each. In either event, a sample of 400 milacre plots would be obtained but the randomization of the selection would have been restricted.

As before, the estimate $\hat{T}$ would be

$$\hat{T} = N\bar{x}$$

where N is 320,000 and $\bar{x}$ the average of the 400 milacre values. Equivalently, we could estimate

$$\hat{T} = \frac{320,000}{400} \sum_{i=1}^{400} X_i$$

which is identical but indicates more apparently that the expansion factor $\frac{320,000}{400}$ is the reciprocal of the sampling fraction.

In order to compute the sampling variance or error of T as estimated from a clustered or block sample, we must consider two sources of sampling error. Consider first the error of the sample estimate if we measured all 100 milacres on each of the 25 randomly selected areas. We then should have had a simple random sample of 25 1/10-acre plots of the 3200 available. If the true mean of plot "i" is μ_1, we shall call the variance of these means σ_b^2. The estimate of the mean 1/10 acre sub-areas would have been

$$\bar{x} = \frac{1}{25} \sum_{i=1}^{25} \mu_i$$

and its sample variance would be

$$s_{\bar{x}}^2 = \left(\frac{1}{25}\right) s_b^2 \left(1 - \frac{25}{3200}\right) \tag{15}$$

Since all of the 1/10-acre plots are not measured, variance s_b^2 cannot be computed directly by substituting in equation 4, but must be approximated by an analysis of variance computation.

The theory of this estimate will be discussed more fully in a later section.

Consider now the second source of sampling error. The value $\bar{x}_i$ as an estimate of μ_i is subject to a sampling variance equal to the variance of milacre plots within 1/10-acre plots divided by the number of sample milacres within the 1/10-acre plot and multiplied by the complement of the sampling ratio. If the variance among milacre plots within 1/10-acre plots is σ_w^2 and its sample estimate s_w^2 and if there are N sampling units (in this case 100) of which n (in this case 16) are included in the sample, then the sample variance of $\bar{x}_i$ as an estimate of μ_i is

$$s_{\bar{x}_i}^2 = \frac{s_w^2}{n}\left(1 - \frac{n}{N}\right) \tag{16}$$

$_w^2$ is computed according to formula 4, for a single 1/10-acre area as

$$s_{w_i}^2 = \frac{\sum_{j=1}^{n} (X_{ij} - \bar{x}_i)^2}{n - 1} \tag{17}$$

For the entire sample of 25, in this case, 1/10-acre plots, s_w^2 is computed as the average of the 25 values of s_w^2 by the direct formula

$$s_{w_i}^2 = \frac{\sum_{i=1}^{k} \sum_{j=1}^{n} (X_{ij} - \bar{x}_i)^2}{k(n - 1)} \tag{18}$$

where k is the number of 1/10-acre plots sampled (in this case $k = 25$). Now, the variance of $\bar{x}$ as an estimate of μ is the sum of the two variances, i.e., the variance of $\bar{x}_i$ as an estimate of μ_i and the variance of μ_i as an estimate of μ. If K is the total number of 1/10-acre plots in the population sampled,

$$s_{\bar{x}}^2 = \frac{s_b^2}{k}\left(1 - \frac{k}{K}\right) + \frac{s_w^2}{kn}\left(1 - \frac{n}{N}\right) \tag{19}$$

If, as in this case, $\frac{k}{K}$ $\left(\text{which is } \frac{25}{3200}\right)$ and $\frac{n}{N}$ $\left(\text{here } \frac{16}{100}\right)$ are near zero, the terms in parentheses approach one and may be omitted.

Allocation of subplots to clusters: It is evident from the examples given, i.e., drawing sixteen milacre samples from each of 25 1/10-acre plots, or 40 milacres from each of 10 1/10-acre plots, that the number of plots and subplots or the number of clusters and observations per cluster are not unique. A specified sampling error ($s_{\bar{x}}$) can often be obtained from a number of combinations of k and n under constant conditions of σ_b^2, σ_w^2, K, and N. Normally the most desirable combination is that which leads to the minimum cost. Let C_b be the cost associated with the cluster. This is principally travel and survey time, and establishing the necessary equipment "on the ground." Let C_w be the cost association with the observation plot. The cost of the sample will then be $C = kC_b + knC_w$. The combination that will lead to the minimum cost will be when

$$n = \sqrt{\frac{s_w^2}{s_b^2}\frac{C_b}{C_w}} \tag{20}$$

The number of plots per cluster thus increases directly as the square root of the ratio of within- to the between-cluster variance and varies inversely as the square root of the observation cost to the cluster cost. Evidently, the number of plots per cluster must be two or more if the sampling error of the survey is to be self-contained since if there is only one observation per cluster neither s_w^2 nor s_b^2 can be computed.

Tabular computation of s_w^2 and s_b^2: It is customary to compute s_w^2 and s_b^2 by an analysis of variance procedure as typified by the following table.

TABLE 2. Computation of within- and between-cluster variance

Source of variation	*Degrees of freedom*	*Sum of squares*	*Components of variance**
Clusters	$k - 1$	$n\sum_{i=1}^{k}(\bar{x}_i-\bar{x})^2$	$\sigma_w^2 + n\sigma_b^2$
Within clusters	$k(n - 1)$	$\sum_{i=1}^{k}\sum_{j=1}^{n}(X_{ij} - \bar{x}_i)^2$	σ_w^2
Total	$kn - 1$	$\sum_{i=1}^{k}\sum_{j=1}^{n}(X_{ij} - \bar{x})^2$	

* Components of variance or mean square (M.S.)

$$s_b^2 = \frac{\text{cluster M.S.} - \text{within clusters M.S.}}{n} \doteq \sigma_b^2 \tag{21}$$

This symbol, $\doteqdot$, refers to an estimate of some value.

If the sample of k clusters and n plots per cluster is an appreciable part of the population of clusters and plot per cluster then:

$$\text{Within cluster M.S.} \doteqdot \sigma_w^2 \left(\frac{N}{N-1}\right)$$

$$\text{Cluster M.S.} \doteqdot \sigma_w^2 \left(\frac{N-n}{N-1}\right) + n\sigma_b^2 \left(\frac{K}{K-1}\right)$$

The observations for six clusters of three plots each which represent the forage yield in grams of sample plots taken in an experimental pasture are given in table 3.

TABLE 3. Forage yield in grams per plot for six clusters of three plots each

	Cluster						
Plots	*1*	*2*	*3*	*4*	*5*	*6*	
1	130	139	137	152	151	157	
2	122	155	97	136	111	125	
3	202	171	13	248	199	93	
Total	454	465	247	536	461	375	2,538

The mean per plot is

$$\bar{x} = \frac{\sum_{i=1}^{k} \sum_{j=1}^{n} (X_{ij})}{kn} = \frac{2538}{(3)(6)} = 141.00$$

To estimate the error of $\bar{x}$ it is necessary to separate the total variation into two parts, among clusters and within clusters, and to estimate the variance components.

For easy calculation the expression for the sums of squares given in table 2 will be expressed in different forms. Total sum of squares

$$\sum_{i=1}^{k} \sum_{j=1}^{n} (X_{ij} - \bar{x})^2 = \sum_{i=1}^{k} \sum_{j=1}^{n} X_{ij}^2 - \frac{\left(\sum_{i=1}^{k} \sum_{j=1}^{n} X_{ij}\right)^2}{kn}$$

$$= 400{,}272 - \frac{(2538)^2}{18}$$

$$= 400{,}272 - 357{,}858 = 42{,}414$$

Sum of squares for among clusters

$$n \sum_{i=1}^{k} (\bar{x}_i - \bar{x})^2 = \sum_{i=1}^{k} \frac{\left(\sum_{j=1}^{n} X_{ij}\right)^2}{n} - \frac{\left(\sum_{i=1}^{k} \sum_{j=1}^{n} X_{ij}\right)^2}{kn}$$

$$= \frac{(454)^2 + (465)^2 + (247)^2 + (536)^2 + (461)^2 + (375)^2}{3} - \frac{(2538)^2}{18}$$

$$= 374,597 - 357,858 = 16,739$$

Sum of squares within clusters

$$\sum_{i=1}^{k} \sum_{j=1}^{n} (X_{ij} - \bar{x}_i)^2 = \sum_{i=1}^{k} \sum_{j=1}^{n} X_{ij}^2 - \sum_{i=1}^{k} \frac{\left(\sum_{j=1}^{n} X_{ij}\right)^2}{n}$$

$$= 400,272 - 374,597 = 25,675$$

TABLE 4. Analysis of variance for data shown in table 3

Source of variation	*Degree of freedom*	*Sum of squares*	*Mean square*	*Components of variance*
Among clusters	5	16,739	3,347.8	$\sigma_w^2 + 3\sigma_b^2$
Within clusters	12	25,675	2,139.6	σ_w^2
Total	17	42,414		

Thus $2,139.6 = s_w^2 \doteq \sigma_w^2$

$$\frac{3,347.8 - 2,139.6}{3} = 402.7 = s_b^2 \doteq \sigma_b^2$$

Using these estimates of the variance components the variance of the mean $\bar{x}$ is

$$s_{\bar{x}}^2 = \frac{402.7}{6} + \frac{2,139.6}{(3)(6)} = 67.1167 + 118.8667 = 185.9834$$

If the population contains 240 clusters each with 15 observations per cluster then the variance components should be estimated using the equation given below the footnote to table 2.

$$\text{Thus, } 2,139.6 \doteq \left(\frac{15}{14}\right) \sigma_w^2 \text{ or } 1,996.96 \doteq \sigma_w^2$$

$$\text{and } 3,347.8 - 1,996.96 \left(\frac{15-3}{14}\right) \doteq 3\sigma_b^2 \left(\frac{240}{239}\right)$$

$$\frac{3,347.8 - 1,711.7}{3} \left(\frac{240}{239}\right) \doteq \sigma_b^2$$

$$547.65 \doteq \sigma_b^2$$

Block sampling: A natural extension to the cluster sampling system described under the previous section is to enlarge the blocks from which samples are drawn so that samples are drawn from all blocks. This would be the same as stratified sampling where blocks represent the strata. To see the statistical effect of this extension, equation 19 is copied below:

$$s_{\bar{x}}^2 = \frac{s_b^2}{k}\left(1 - \frac{k}{K}\right) + \frac{s_w^2}{kn}\left(1 - \frac{n}{N}\right)$$

If the size of the blocks in the population or the number of blocks in the sample increases so that n observations are drawn from every block in the population, we find that $k = K$ and hence that $\frac{k}{K} = 1$ and the term $(1 - \frac{k}{K}) = 0$. Thus if all blocks are represented in the sample in the same manner as in the population sample, any variation s_b^2 among blocks makes no contribution to the sampling error of the survey.

In surveys of areas such as in pasture or range allotment samples, the block type survey has considerable intuitive appeal. Unlike a completely random survey which by the caprices of chance could result in all or the bulk of the observations falling in a quarter or half of the area, block surveys by their very nature insure that all parts of the range are sampled reasonably uniformly. The cost of this insurance is an increase in the size of the t value used in setting the confidence limits. This will usually be slight, however, since the range sampled would normally be divided into no fewer than 25-30 blocks. The gain in accuracy will usually be substantial since the variation of plots in the same block may be ¼ less than the variation in plots over the whole range sampled.

Block and cluster sampling: The principles presented in the two previous sections can readily be combined. A range allotment or pasture can be divided first into a number, say H large blocks or 40 acres each. Each of these large blocks can then be subdivided into K (here 400) 1/10-acre large plots or cluster areas, and these in turn divided into the 100 milacre plots. A sample would then consist of k 1/10-acre plots drawn at random from the K available in each of the H blocks. Within each of the k 1/10-acre plots, n milacre plots are drawn from the N (here 100) available. The estimate $\bar{x}$ of the population mean μ is now

$$\bar{x} = \frac{1}{H}\sum_{p=1}^{H} \bar{x}_p \tag{22}$$

where $\bar{x}_p$ = the mean of a block.
The variance of $\bar{x}$ will then be

$$s_{\bar{x}}^2 = \frac{1}{H}\left[\frac{s_b^2}{k}\left(\frac{K-k}{K}\right) + \frac{s_w^2}{kn}\left(\frac{N-n}{N}\right)\right] \tag{23}$$

Evidently, with this further extension it would not have been necessary to have included all H of the large blocks in the sample. Had only h of the blocks been included, a further source of sampling error would have resulted from the variance σ_s^2, say, among the true large block means. The estimate s_s^2 would have been obtained from an analysis of variance computation similar to that in table 2 where a third line would have been added (table 5).

TABLE 5. Computation of variance among blocks, among clusters within blocks, and within clusters

Source of variation	*Degrees of freedom*	*Components of variance*
Among blocks	$h - 1$	$\sigma_w^2 + n\sigma_b^2 + nk\sigma_s^2$
Clusters within blocks	$h(k - 1)$	$\sigma_w^2 + n\sigma_b^2$
Within clusters	$hk(n - 1)$	σ_w^2
Total	$hkn - 1$	

To obtain an estimate of the yield from a 100-acre pasture, the pasture was divided into 4 blocks of 25 acres each. Each block was divided into 250 1/10-acre clusters. Each cluster was divided into 198 sampling units. The sample to estimate mean yield consists of 6 clusters of 3 units in each block. These samples are shown in table 6.

TABLE 6. Forage yield in grams per plot for six clusters of three plots each in four blocks

	Cluster						
Blocks	*1*	*2*	*3*	*4*	*5*	*6*	*Total*
1	235	152	191	101	270	85	
	143	194	196	17	279	325	
	241	193	260	182	264	210	
Total	619	539	647	300	813	620	3538
2	163	205	248	215	164	234	
	198	197	124	235	236	196	
	113	221	199	166	188	186	
Total	474	623	571	616	588	616	3488
3	210	50	222	220	190	165	
	285	151	230	327	230	250	
	292	248	282	254	195	154	
Total	787	449	734	801	615	569	3955
4	298	330	161	254	345	280	
	248	143	263	183	264	274	
	225	165	255	305	189	337	
Total	771	638	679	742	798	891	4519

The variation among the 72 unit observations is due to variation among blocks, variation among clusters within blocks, and variation within clusters.

These sources of variation are separated out in an analysis of variance as shown in table 7.

TABLE 7. Block totals, sum of squares of individual observations, and cluster totals for data shown in table 6

Block	*Block total*	*Sum of squares of individual observations*	*Sum of squares of cluster totals*
	$\sum_{i=1}^{6}\sum_{j=1}^{3} X_{ij}$	$\sum_{i=1}^{6}\sum_{j=1}^{3} X_{ij}^2$	$\sum_{i=1}^{6}\left(\sum_{j=1}^{3} X_{ij}\right)^2$
1	3,538	795,242	2,227,660
2	3,488	699,408	2,043,502
3	3,955	939,413	2,703,313
4	4,519	1,200,139	3,443,775
Total	15,500	3,634,202	10,418,250

The computations are as follows:

Total sum of squares:

$$\sum_{e=1}^{h}\sum_{i=1}^{k}\sum_{j=1}^{n} X_{eij}^2 - \frac{\left(\sum_{e=1}^{h}\sum_{i=1}^{k}\sum_{j=1}^{n} X_{eij}\right)^2}{(h)(k)(n)}$$

$$3{,}634{,}202 - \frac{(15{,}500)^2}{72} = 3{,}634{,}202 - 3{,}336{,}806 = 297{,}396$$

Block — sum of squares

$$\sum_{e=1}^{h}\frac{\left(\sum_{i=1}^{k}\sum_{j=1}^{n} X_{eij}\right)^2}{(k)(n)} - \frac{\left(\sum_{e=1}^{h}\sum_{i=1}^{k}\sum_{j=1}^{n} X_{eij}\right)^2}{(h)(k)(n)}$$

$$\frac{(3538)^2+(3488)^2+(3955)^2+(4519)^2}{18} - 3{,}336{,}806 = 3{,}374{,}832-3{,}336{,}806 = 38{,}026$$

Clusters within block — sum of squares

$$\sum_{e=1}^{h}\sum_{i=1}^{k}\frac{\left(\sum_{j=1}^{n} X_{eij}\right)^2}{n} - \sum_{e=1}^{h}\frac{\left(\sum_{i=1}^{k}\sum_{j=1}^{n} X_{eij}\right)^2}{(k)(n)}$$

$$\frac{10{,}418{,}250}{3} - 3{,}374{,}832 = 3{,}472{,}750 - 3{,}374{,}832 = 97{,}918$$

Within cluster — sum of squares

$$\sum_{e=1}^{h}\sum_{i=1}^{k}\sum_{j=1}^{n} X_{eij}^2 - \sum_{e=1}^{h}\sum_{i=1}^{k}\frac{\left(\sum_{j=1}^{n} X_{eij}\right)^2}{n}$$

$$3{,}634{,}202 - 3{,}472{,}750 = 161{,}452$$

The basic computations are shown assembled in the analysis of variance in table 8.

TABLE 8. Analysis of variance for data shown in table 6

Source of variation	*Degrees of freedom*	*Sum of squares*	*Mean square*	*Components of variance*
Among blocks	3	38,026	12,675	$\sigma_w^2 + 3\sigma_b^2 + (3)(6)\sigma_s^2$
Clusters within blocks	20	97,918	4,896	$\sigma_w^2 + 3\sigma_b^2$
Within clusters	48	161,452	3,364	σ_w^2
Total	71	297,396		

$$3{,}364 = s_w^2 \doteq \sigma_w^2$$

$$\frac{4{,}896 - 3{,}364}{3} = 510.67 = s_b^2 \doteq \sigma_b^2$$

$$\frac{12{,}675 - 4{,}896}{18} = 432.17 = s_s^2 \doteq \sigma_s^2$$

The mean yield per plot is

$$\bar{x} = \frac{\sum_{e=1}^{h}\sum_{i=1}^{k}\sum_{j=1}^{n} X_{eij}}{(h)(k)(n)} = \frac{15{,}500}{72} = 215.28$$

Since each of the four blocks is sampled, the variance due to block does not enter into the calculation of the error of the mean. Thus the variance of this mean is

$$s_{\bar{x}}^2 = \frac{510.67}{(4)(6)} + \frac{3{,}364}{(4)(6)(3)} = 21.2779 + 46.7222 = 69.6001$$

The process of geographic partitioning and subsampling can, of course, be extended as far as it is profitable to do so but a hierarchy of more than 3-4 levels is rarely desirable or even practicable in most fields.

Stratified random sampling: Stratified sampling is a system by which sampling units are drawn from relatively homogeneous classes, groups, types, or conditions which are spoken of in a generic sense as strata. In range vegetation sampling, strata are usually mapped or mappable vegetation types such as meadows, grassland, and open timber. These broad condition classes may be subdivided further on the basis of species or species groups that are readily observable and can be mapped reasonably accurately. The number of sampling units selected in each stratum can be chosen arbitrarily by the sampler since the total or mean value for all strata is computed by adding stratum totals or weighting stratum mean values by the area of the stratum.

If

N_h $(h = 1,2, \cdots m)$ is the number of units in stratum h
n_h is the number of sample observations in stratum h
m is the number of strata

$$\bar{x}_h = \frac{\sum_{i=1}^{n_h} X_{hi}}{n_h}$$ is the sample mean of stratum h and

$$s_h^2 = \frac{\sum_{i=1}^{n_h} (X_{hi} - \bar{x}_h)^2}{n_h - 1}$$ is the sample estimate of the variance of observations

in stratum h, then

$$\hat{T} = \sum_{h=1}^{m} N_h \bar{x}_h$$ is the estimated total for the population, and its sampling variance is (24)

$$s_{\hat{T}}^2 = \sum_{h=1}^{m} N_h^2 s_{\bar{x}_h}^2 \qquad (25)$$

If the stratum areas are large so that n_h is an inconsequential part of N_h, or if sampling is with replacement, i.e., all sampling units have a chance of being selected at each random draw and the same sampling unit may therefore be represented more than once in the sample, then

$$s_{\bar{x}_h}^2 = \frac{s_h^2}{n_h} \qquad \text{and} \qquad (26)$$

$$s_{\hat{T}}^2 = \sum_{h=1}^{m} N_h^2 \frac{s_h^2}{n_h} \qquad (27)$$

If, however, sampling is without replacement and n_h is an appreciable part of N_h,

$$s^2_{\bar{x}_h} = \frac{s^2_h}{n_h}\left(1 - \frac{n_h}{N_h}\right) \qquad \text{and} \tag{28}$$

$$s^2_{\hat{T}} = \sum_{h=1}^{m} N^2_h \frac{s^2_h}{n_h}\left(1 - \frac{n_h}{N_h}\right) \tag{29}$$

The allocation of sampling units, however, is usually of two types: proportional or optimum (also called Neyman) allocation. These will be discussed in turn.

Stratified sampling with proportional allocation: If the sample measurement locations are selected at random (or even systematically) without regard to stratum boundaries, the sample points, on the average, will be distributed by strata in proportion to stratum areas. If stratum areas are known and proportional sampling is desired, this can be achieved by restricting the randomization accordingly.

In proportional sampling, the number of observations allocated to stratum h is equal to the total number of observations multiplied by the proportion of the population in stratum h, i.e.,

$$n_h = n\frac{N_h}{N} \tag{30}$$

where

$n = n_1 + n_2 + \text{---} + n_m$ = total number of observations in the sample, and
$N = N_1 + N_2 + \text{---} + N_m$ = total area or number of observations in the population.

Stratified sampling with optimum allocation: The equation for computation of the sampling variance of the estimate based on stratified sampling (equation 29) is valid regardless of type of allocation. From the components of this sum, it is evident that large values of N_h and s_h, particularly since they appear in the equation as squared terms, will increase $s^2_{\hat{T}}$ and $s^2_{\hat{T}}$ is reduced only by increasing n_h. If the entire cost of the survey is fixed so that only a total number of observations, $n = \sum_{h=1}^{m} n_h$, can be taken it is often desirable to allocate the observations to the strata in a somewhat disproportionate manner. When such allocations are made $s^2_{\hat{T}}$ should be kept as small as possible.

It can be shown that if we set

$$n_h = (n)\frac{N_h s_h}{\sum_{h=1}^{m} N_h s_h} \tag{31}$$

this objective will be accomplished. The following examples illustrate that when there are substantial differences in the values of s^2_h, optimum allocation enjoys a substantial advantage over proportional allocation, whereas with reasonably uniform variances the gains are negligible.

The data used in the following example were obtained from three strata: (1) dense timber, (2) open timber, and (3) meadow. From each stratum a sample of 20 random units was drawn and the mean and standard deviation of the units computed. These statistics and the total number of units in each stratum are shown in table 9.

TABLE 9. The mean and standard deviation for three strata of vegetation cover

Stratum	*Number of units in population*	*Sample*	
		Mean	*Standard deviation*
Dense timber	246	18.1	20.1
Open timber	322	105.2	69.8
Meadow	72	190.8	130.4

Using the sample data, an estimate of the population total can be made and its confidence band computed. The estimate of the population total will be made using equation (24) and the variance of this estimate by equation (29). The calculations are shown in table 10.

TABLE 10. Calculations for an estimate of the population total and the variance of the estimate for three strata of vegetation cover

Strata	N_h	$\bar{x}_h$	s_h	n_h	$N_h(\bar{x}_h)$	$N_h(s_h)$	$\frac{N_h^2 s_h^2}{n_h}$	$1-\frac{n_h}{N_h}$	$\frac{N_h^2 s_h^2}{n_h}\left(1-\frac{n_h}{N_h}\right)$
	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Dense timber	246	18.1	20.1	20	4,452.6	4,944.6	1,222,453	.919	1,123,434
Open timber	322	105.2	69.8	20	33,874.4	22,475.6	25,257,630	.938	23,691,657
Meadow	72	190.8	130.4	20	13,737.6	9,388.8	4,407,478	.722	3,182,199
Total	640				52,064.6	36,809.0			27,997,290

The estimate of the population total using equation (24) is the sum of column 6 or 52,064.6. The variance of this total is the total of column 10 or 27,997,290. In the computations note that column 8 is column 7 squared and divided by column 5. The error of the estimated total is $\sqrt{27,997,290}$ or 5,291.

Since the strata samples are not small, a t value from the normal curve will be used in determining the confidence band. For a probability of .95 the value of t is 1.96. The confidence interval becomes

$$52,065 - (5291)(1.96) \leq (T) \leq 52,065 + (5291)(1.96)$$
$$52,065 - 10,370 \leq (T) \leq 52,065 + 10,370$$
$$41,695 \leq (T) \leq 62,435$$

If the strata sample sizes had been small, for example 7, 8, and 5 for the dense timber, open timber, and meadow, respectively, the confidence interval could not be as easily computed since the degrees of freedom for selecting t are not known.

Using the same means and standard deviations the error can be recalculated using the smaller sample sizes. This calculation is shown in table 11.

TABLE 11. Calculations for the error of the estimated total for three strata of vegetation cover with seven samples taken from dense timber, eight from the open timber, and five from the meadow

Stratum	N_h	s_h	n_h	$N_h s_h$	$\frac{N_h^2 s_h^2}{n_h}$	$1-\frac{n_h}{N_h}$	$\frac{N_h^2 s_h^2}{n_h}\left(1-\frac{n_h}{N_h}\right)$
Dense timber	246	20.1	7	4,944.6	3,492,724	.972	3,394,928
Open timber	322	69.8	8	22,475.6	63,144,074	.975	61,565,472
Meadow	72	130.4	5	9,388.8	17,629,913	.931	16,413,449
Total	640						81,373,849

Error = $\sqrt{81{,}373{,}849}$ = 9,020.7

In this example the number of degrees of freedom of each class is small so the normal deviate value of t cannot be used. To choose the appropriate t value, one must have an appropriate number of degrees of freedom. For problems like this, approximation (Cochran and Cox 1950) will be used.

$$n' = \frac{\left\{\sum_{h=1}^{3}\left[\frac{N_h(N_h - n_h)}{n_h}\right]s_h^2\right\}^2}{\sum_{h=1}^{3}\frac{\left\{\left[\frac{N_h(N_h - n_h)}{n_h}\right]s_h^2\right\}^2}{n_h - 1}}$$

The basic data are obtained from the fourth and the last columns of table 11. The calculations for obtaining n' are shown in table 12.

TABLE 12. Calculations for determining approximate degrees of freedom for the estimated total when unequal sample numbers are used among the strata

Stratum	$\left[\frac{N_h(N_h - n_h)}{n_h} s_h^2\right]$	$(n_h - 1)$	$\left[\frac{N_h(N_h - n_h)}{n_h} s_h^2\right]^2 \div (n_h - 1)$
Dense timber....	3,394,928	6	1,920,922,687,531
Open timber.....	61,565,472	7	541,472,477,511,826
Meadow.........	16,413,449	4	67,350,327,018,900
	81,373,849		610,743,727,218,257

$$n' = \frac{(81{,}373{,}849)^2}{610{,}743{,}727{,}218{,}257} = \frac{6{,}621{,}703{,}301{,}074{,}801}{610{,}743{,}727{,}218{,}257} = 10.8 \text{ or } 11.$$

The value of t for 11 degrees of freedom for a probability of .95 is 2.201. The confidence interval is 52,065 ± (2.201)(9,020.7) or 52,065 ± 19,855.

$$32{,}210 \leq T \leq 71{,}920$$

To determine sample size for a stratified population it is necessary to specify the type of sampling that will be used as well as the acceptable error and the confidence to be placed in this error.

For the stratified population just discussed the variance of a total is

$$s_{\hat{T}}^2 = \frac{\sum_{h=1}^{m} N_h^2 s_h^2}{n_h}\left[1 - \left(\frac{n_h}{N_h}\right)\right]$$

If the "n_h" are selected by the method called optimum allocation then

$$s_{\hat{T}_o}^2 = \frac{\left(\sum_{h=1}^{m} N_h s_h\right)^2}{n} - \sum_{h=1}^{m} N_h s_h^2 \qquad (32)$$

where

$$n = \sum_{h=1}^{m} n_h$$

If the "n_h" are selected by the method called proportional sampling then

$$s_{\hat{T}_p}^2 = \frac{N\left(\sum_{h=1}^{m} N_h s_h^2\right)}{n} - \left(\sum_{h=1}^{m} N_h s_h^2\right) \qquad (33)$$

where

$$N = \left(\sum_{h=1}^{m} N_h\right) \quad \text{and} \quad n = \left(\sum_{h=1}^{m} n_h\right)$$

With proportional sampling the total sample size can be obtained from the equation

$$n = \frac{t^2(N)\left(\sum_{h=1}^{m} N_h s_h^2\right)}{(\hat{T} - T)^2 + t^2\left(\sum_{h=1}^{m} N_h s_h^2\right)} \qquad (34)$$

With $(\hat{T} - T) = 2000$ and $t = 1.96$ and the estimate of N_h and s_h^2 as used in the last examples, an estimate of total sample size is obtained as shown in table 13.

TABLE 13. Calculations for estimating the total sample size with proportional sampling among the three strata of vegetation cover

Stratum	N_h	s_h	$N_h s_h^2$	$N_h s_h$
Dense timber	246	20.1	99,386.46	4,944.6
Open timber	322	69.8	1,568,796.88	22,475.6
Meadow	72	130.4	1,224,299.52	9,388.8
Total	640		2,892,482.86	36,809.0

Substituting into equation (34) gives

$$n = \frac{(1.96)^2\,(640)\,(2{,}892{,}483)}{(2000)^2 + (1.96)^2\,(2{,}892{,}483)} = \frac{7{,}111{,}528{,}123}{15{,}111{,}763} = 471$$

The distribution among strata will be in proportion to N_h in the strata. Thus for the dense timber stratum the number of samples to take is $(471)\frac{(246\ )}{(640)} = 181$, for the open timber stratum $(471)\frac{(322)}{(640)} = 237$, for the meadow stratum $(471)\frac{(72)}{(640)} = 53$.

If optimum allocation were used the sample size would be obtained from equation (35)

$$n = t^2 \frac{\left(\sum_{h=1}^{m} N_h s_h\right)^2}{(\hat{T} - T)^2 + t^2 \sum_{h=1}^{m} N_h s_h^2} \qquad (35)$$

$$= \frac{(1.96)^2\,(36{,}809)^2}{(2{,}000)^2 + (1.96)^2\,(2{,}892{,}483)} = \frac{5{,}204{,}993{,}371}{15{,}111{,}763} = 344$$

The distribution of these 344 among the strata will be in proportion to $N_h s_h$ Thus for the dense timber stratum $n_h = \frac{(344)(4{,}944.6)}{36{,}809} = 46$, for the open timber stratum $n_h = \frac{(344)(22{,}475.6)}{36{,}809} = 210$, and for the meadow stratum $= n_h \frac{(344)(9{,}388.8)}{36{,}809} = 88$.

In the example of sample size under proportional and optimum allocation it will be noted that as expected fewer samples are needed when optimum allocation is used.

On examining the optimum allocation results, it will be noted that the number of samples computed for the meadow stratum, 88, is larger than the total number in that stratum. This is not a computational error and when this occurs it means that all observations in the stratum should be taken. Then the number to take in the other strata must be reestimated, assuming optimum allocation in the remaining strata. All of the error is thus associated with the remaining strata.

Using equation (35) and noting that now

$$N = 568 \qquad \sum_{h=1}^{m} N_h s_h = 27{,}420$$

$$\sum_{h=1}^{m} N_h s_h^2 = 1{,}668{,}183$$

$$n = \frac{(1.96)^2\,(27{,}420)^2}{(2{,}000)^2 + (1.96)^2\,(1{,}668{,}183)} = \frac{2{,}888{,}331{,}546}{10{,}408{,}492} = 277$$

The number of observations to be assigned to the dense timber stratum is

$$\frac{(227)(4{,}944.6)}{27{,}420} = 50$$

The number assigned to the open timber stratum is

$$\frac{(277)(22{,}475.6)}{27{,}420} = 227$$

The total sample size under optimum allocation is thus 72 + 227 + 50 = 349.

It will be noted that the total sample size 349 is a little larger than the original optimum allocation sample size of 344. The reason for this can best be seen by studying the equation for the variance of the total. Thus

$$s_T^2 = \frac{N_1^2 s_1^2}{n_1}\left(1 - \frac{n_1}{N_1}\right) + \frac{N_2^2 s_2^2}{n_2}\left(1 - \frac{n_2}{N_2}\right) + \frac{N_3^2 s_3^2}{n_3}\left(1 - \frac{n_3}{N_3}\right)$$

Whenever $n_i > N_i$ the contribution of that term to the total variance is negative, thus permitting the other terms to make a larger contribution to the variance of the total, and since those contributions are larger the sample size is smaller. It is not logical for any term to be less than zero; therefore, the sample size for that stratum is set equal to the stratum total. The sample size in the other strata must be increased to offset the contribution of the negative term because $n_i > N_i$.

To show what is gained by stratification, it is necessary to estimate the standard deviation of individuals if no stratification were used. This is found to be 87.70. The estimated sample size to obtain the same accuracy as stated for the stratified sample is found to be 528. Thus stratification has enabled the sample size to be reduced from 528 to either 349 or 471, depending on whether the observations are assigned to strata by optimum allocation methods or are assigned in proportion to stratum size.

It is interesting to note that if the confidence limit were set at 5,000 instead of 2,000, the sample size under proportional allocation would be $n = 197$, and under optimum allocation $n = 144$. The latter sample sizes would give a sampling error of less than 10 per cent at the .95 confidence level.

To show what is accomplished by stratification some additional calculations have been made using different stratum means and variances. The stratum means are such that the estimate of the total is unchanged. Three sets of data were used.

(a) Original stratum means but smaller variances.
(b) Original stratum variances but means closer together.
(c) Means used in (b) with variances used in (a).

The data actually used are shown in table 14.

TABLE 14. (a) Original means for the three strata in table 9 with variances smaller, (b) original variances for the three strata with means closer, and (c) means closer and variances smaller

	(a)		*(b)*		*(c)*	
N	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*
246	18.1	16	70	20.1	70	16
322	105.2	50	80	69.8	80	50
72	190.8	100	125	130.4	125	100

Using these data the sample size has been calculated to give the same error assuming stratification with optimum allocation and also assuming no stratification. The sample sizes for the original data and the three examples are shown in table 15.

TABLE 15. Sample size for stratification with optimum allocation of samples and unstratified vegetation cover for the original data from the three strata presented in table 9 and the three examples presented in table 14

	Sample size		
Set of data	*No stratification*	*With stratification*	*Ratio of stratified to unstratified sample size*
Example 1	528	349	.66
Example a	497	282	.57
Example b	478	349	.73
Example c	402	282	.70

For stratified sampling the sample size depends only on the variation within strata. However, the gain through stratification depends a great deal on the differences among stratum means. For examples b and c where the stratum means are close together the size for an unstratified sample is less than for examples 1 and a. However, by stratification a smaller sample of about 70 to 73 per cent of the unstratified sample is needed to give the same error. When the stratum means are further apart, as in examples 1 and a, the sample size for a stratified sample is only 57 to 66 percent of the unstratified sample.

It should be recognized that optimum allocation is not necessarily more desirable than proportional, or other allocation. In many surveys a number of measurements are taken on a single plot or individual, and in many it is planned to remeasure the plot at intervals. It will usually be the case that the optimum allocation for one of the variables measured may be far from optimum for another, or for measuring changes between remeasurement periods—for example, optimum allocation for studying the use pattern, the encroachment of noxious plants, or the trend of the range condition. It is thus particularly important in stratified sampling that a thorough evaluation be made since the allocation of sample observations to the strata, and in fact the formation of the strata, should depend upon the various objectives of the survey and their relative importance.

Multiphase sampling: It is frequently possible to increase the efficiency or precision of sample estimates by subdividing the work into two or more phases or steps. This technique is, in a sense, an extension of stratified sampling but generally different in that strata are not mapped or otherwise delineated and stratum areas are not known but are estimated in one or more of the phases or steps in the work. The strata and substrata so created, or recognized, may be classes such as vegetation types or species, or intervals of a continuous variate such as density intervals. A usual feature of such sampling designs is a substantial difference in the unit observation costs of the different steps. In a 2-step sample of the total weight of the forage, or the weight of a single species, the first step might be the classification of a large number of plots into a few (4 to 8) broad weight classes. This could be done rapidly or at a low cost per plot. When sampling a single species, one of the classes might be zero which would give an estimate of the number of plots (or the percentage of the area) from which the species is absent. In range forage sampling, it may require only two minutes to reach and classify a plot into a broad density or weight class whereas it would require thirty minutes of combined field and laboratory time to reach, clip, transport, and weigh the forage on a plot—a ratio of 15:1.

With this sampling method, the estimating equation is

$$\hat{T} = A \sum_{i=1}^{m} p_i \bar{x}_i \qquad (36)$$

where

$\hat{T}$ = total forage in grams.
A = area of pasture in plot units.
p_i = estimated proportion of the pasture in weight class i.
$\bar{x}_i$ = average weight per plot in weight class i.
m = number of classes.

If the p_i were known population values as in ordinary stratified sampling, the variance of $\hat{T}$ would be

$$s_{\hat{T}}^2 = A^2 \sum_{i=1}^{m} p_i^2 s_{\bar{x}_i}^2 \tag{37}$$

This assumes that p_i is known without error or is small; otherwise, a more elaborate calculation is involved.

In this case, however, the p_i are sample estimates even though based on many (perhaps 1000) random determinations. The estimate $\hat{T}$ is now the sum of a series of products of two variables, both subject to sampling error. In addition, the errors of the products are not independent since evidently the sum of the sample estimates of the proportions in the m classes must be one (unity).

Assume there are D (say 1000) determinations of weight class, and that there are n_i clipped and weighed plots in class i. Assume further that the samples of both weight class and clipped weight are so small in proportion to the total number of possible observations in the population that the effect of the sample size in the variance of $\hat{T}$ can be ignored. We now have

$$\hat{T} = A \sum_{i=1}^{m} p_i \bar{x}_i = A\bar{x} \tag{38}$$

where

$$\bar{x} = \sum_{i=1}^{m} p_i \bar{x}_i$$

$$s_{\hat{T}}^2 = A^2 s_{\bar{x}}^2$$

Thus the variance of $\hat{T}$ becomes

$$s_{\hat{T}}^2 = A^2 \left\{ \sum_{i=1}^{m} p_i^2 \frac{s_{x_i}^2}{n_i} + \sum_{i=1}^{m} \bar{x}_i^2 \frac{p_i(1-p_i)}{D} - \sum_{i \neq j=1}^{m} \bar{x}_i \bar{x}_j \quad \frac{p_i p_j}{D} \right\}^* \tag{39}$$

which can be written as

$$s_{\hat{T}}^2 = A^2 \left\{ \sum_{i=1}^{m} p_i^2 \frac{s_{x_i}^2}{n_i} + \frac{1}{D} \left[\sum_{i=1}^{m} p_i \bar{x}_i^2 - \left(\sum_{i=1}^{m} p_i \bar{x}_i \right)^2 \right] \right\} \tag{40}$$

Note that the second term in the square brackets is simply the square of the weighted mean.

As with ordinary stratified sampling, the gain in precision from employing this sampling method is that the variance of measured weights of forage

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* The term $\sum_{i \neq j=1}^{m} \bar{x}_i \bar{x}_j p_j p_i$ is twice the sum of all products of $p_i \bar{x}_i$ of two weight classes.

within a stratum or weight class is normally much smaller than that of plots taken at random without regard to weight class.

In the Forest Survey, aerial photographs are used to stratify the area into various strata or classes, such as nonforest, nonstocked forest land, seedling and sapling, pole stands, and sawtimber stands. After classifying a large number of points on aerial photographs, a sample of each class is selected for examination in the field, and for determination of volume. The basic data obtained from such a survey are shown in columns 1 to 5 in table 16. While these data are not from range work, the procedure could be used to estimate forage yield. The points classified on photos could be classed as to (1) meadow, (2) open timber, (3) dense timber; and the field plots could be actual or estimated forage yields on small plots.

The computation of the mean volume and its variance using equations (38) and (41) is shown in columns 6 to 9 of table 16.

TABLE 16. Calculations for estimating the mean volume and its variance from six strata identified from aerial photographs in a forest survey

Class	N_i	p_i	$\bar{x}_i$	s_i	n_i	$p_i\bar{x}_i^2$	$p_i\bar{x}_i$	p_is_i	$\frac{p_i^2s_i^2}{n_i}$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Nonforest	2642	.5403	6	45.4	252	3.24	19.45	24.53	2.39
Large sawtimber	121	.0248	2046	1079.2	16	50.74	103,815.68	26.76	44.76
Small sawtimber	762	.1558	1394	836.5	80	217.19	302,756.17	130.33	212.32
Poles	802	.1640	1025	748.2	65	168.10	172,302.50	122.70	231.62
Seedling-sapling	359	.0734	423	383.8	21	31.05	13,133.39	28.17	37.79
Understocked	204	.0417	77	140.7	15	3.21	247.24	5.87	2.30
Totals	4890	1.0000				473.53	592,274.43	338.36	531.18

Correction term $(CT) = (473.53)^2$ therefore $592{,}274.43 - 224{,}230.66 = 368{,}043.77$

The mean volume is 473.53. Its variance is

$$s_{\bar{x}}^2 = 531.18 + \frac{368{,}043.77}{4890} = 531.18 + 75.26 = 606.44$$

and its error is

$$s_{\bar{x}} = \sqrt{606.44} = 24.63$$

The confidence interval for a probability of .95 is obtained by using $t = 1.96$. Thus confidence band or interval is $\pm\ (1.96)(24.63) = 48.27$.

$$473.53 \pm (1.96)(24.63) \text{ or}$$
$$473.53 - 48.27 \leq \mu \leq 473.53 + 48.27$$
$$425.26 \leq \mu \leq 521.80$$

The equation for the variance of $\bar{x}$ is

$$s_{\bar{x}}^2 = \sum_{i=1}^{m} \frac{p_i^2 s_i^2}{n_i} + \frac{1}{D}\left[\sum_{i=1}^{m} p_i \bar{x}_i^2 - \left(\sum_{i=1}^{m} p_i \bar{x}_i\right)^2\right] \quad (41)$$

If the estimates of p_i, s_i, and $\bar{x}_i$ are available then, as for other types of sampling problems, the number of observations needed to give a specified error can be determined. To determine the sample size one must first decide on the type of sampling to be used to obtain the volume plots. Will the number of plots "n_i" per class be allocated in proportion to "p_i" or will they be obtained by optimum allocation procedures? If the optimum allocation procedures are used then the equation for the variance of $\bar{x}$ becomes

$$s_{\bar{x}}^2 = \frac{\left(\sum_{i=1}^{m} p_i s_i\right)^2}{n} + \frac{1}{D}\left[\sum_{i=1}^{m} p_i \bar{x}_i^2 - \left(\sum_{i=1}^{m} p_i \bar{x}_i\right)^2\right]$$

For a given $s_{\bar{x}}^2$, if the value of "n" or of "D" is specified the equation can then be solved to determine the other value. Such a procedure may not be too efficient as far as the cost of the survey is concerned. If cost is considered then the relation of D to n is given by the equation

$$D = \frac{\sqrt{\sum_{i=1}^{m} p_i \bar{x}_i^2 - \left(\sum_{i=1}^{m} p_i \bar{x}_i\right)^2}}{\sum_{i=1}^{m} p_i s_i} \left(\frac{\sqrt{C_n}}{\sqrt{C_D}}\right)(n)$$

where

C_n is equal to the cost of a field plot.

C_D is the cost to classify a point on the photos as to an area.

To determine "n" the equation is

$$s_{\bar{x}}^2 = \left[\left(\sum_{i=1}^{m} p_i s_i\right)^2 + \sqrt{\sum_{i=1}^{m} p_i \bar{x}_i^2 - \left(\sum_{i=1}^{m} p_i \bar{x}_i\right)^2}\left(\sum_{i=1}^{m} p_i s_i\right)\frac{\sqrt{C_D}}{\sqrt{C_n}}\right]\frac{1}{n}$$

Thus if $s_{\bar{x}}^2$ is specified and estimates of p_i,x_i,s_i C_D and C_n are available the value of "n" can be estimated. Knowing "n," the value of D can be determined. If the volume plots are assigned to the various strata by proportional allocation then the only change in these equations is to substitute

$$\sqrt{\sum_{i=1}^{m} p_i s_i^2} \quad \text{for} \quad \sum_{i=1}^{m} p_i s_i$$

Using the data from the example, the sample size will be computed to give a confidence interval of ± 20 for a probability of .95. With this probability, the estimate of the variance of $\bar{x}$ would be the square of the ratio of the confidence interval divided by a $t = 1.96$. Thus $s_{\bar{x}}^2 = \frac{(20:0)^2}{(1.96)} = (10.2)^2 = 104.04$.

To obtain an estimate of "n" it is necessary to solve the equation

$$104.04 = \left[(338.36)^2 + \sqrt{368,043.77}\,(338.36)\left(\frac{\sqrt{C_D}}{\sqrt{C_n}}\right)\right]\frac{1}{n}$$

The cost of a field plot C_n for the given locality is about $18 and the cost of a photo determination is about 20 cents, thus

$$104.04 = \left[114,487 + (606.67)(338.36)\left(\frac{.4472}{4.2427}\right)\right]\frac{1}{n}$$

$$= \left[114,487 + (205,273)(.1054)\right]\frac{1}{n}$$

$$= (114,487 + 21,636)\frac{1}{n} = \frac{136,123}{n}$$

or

$$n = \frac{136,123}{104.04} = 1,308 \quad \text{and}$$

$$D = \frac{606.67}{338.36}\,\frac{(4.2427)}{.4472}\,(n)$$

$$= \frac{2,573.9}{151.3}\,(n) = 17.01\,(n)$$

$$= 17.01\,(1,308) = 22,249.$$

With proportional sampling $n = 2633$ and $D = 30,780$.
The allocation of "n" to strata is as shown in table 17.

TABLE 17. Calculated number of samples (n) per strata shown in table 16 with optimum and proportional allocation

	Optimum	*Proportional*
Nonforest	95	1423
Large sawtimber	103	65
Small sawtimber	504	410
Poles	474	432
Seedling-sapling	109	193
Understocked	23	110
	1308	2633

"Double" or regression sampling: In many studies it is found that the variable which is to be sampled is difficult or expensive to measure whereas another variable is easy or cheap to measure, and that the values of the two variables for the same individual or plot are related in a signficant manner.

Range sampling is no exception. Range workers have long recognized the ability of trained range specialists to make occular estimates of forage density, weight, species composition percentages, and other important variables. These estimates can, of course, be made in a small fraction of the time required to make instrumental measurements of the same variable. The contrast is especially great when measurement requires clipping, bagging, and weighing of the species separately, or the tedious charting and later planimetering of the charts for species density measurement.

Double sampling requires two separate operations. The first is to obtain observations of the independent and dependent variable (for example, the ocularly estimated and clipped weight of the forage) on a sample of plots. The individuals on which both observations are obtained need not be completely random, that is, the number of observations allotted to ranges of values of the independent variable may be selected arbitrarily but plots must be selected completely at random within these ranges of the independent variable. These related observations are used to determine the line of regression relating the two variables as will be described. The plots for these observations may be selected completely at random and it may be desirable administratively to do so. The second operation (although not necessarily later in time) is to procure a large sample, which must be representative of the whole population and therefore preferably random, of the independent variable.

From the first step, the equation of the line of regression of the dependent variable (clipped weight) on the independent variable (ocularly estimated weight) is computed by least squares.

$$\hat{Y} = \bar{y}_r + b(X - \bar{x}_r) \tag{42}$$

where

$\hat{Y}$ = regression estimated clipped weight of plot.

$\bar{y}_r$ = average clipped weight of plots in the regression sample.

$$b = \text{coefficient of regression of } Y \text{ on } X \text{ or } \frac{\sum_{i=1}^{n} (X_i - \bar{x}_r)(Y_i - \bar{y}_r)}{\sum_{i=1}^{n} (X_i - \bar{x}_r)^2}$$

X = ocularly estimated weight of plot.

$\bar{x}_r$ = average of ocularly estimated weights of plots in the regression sample.

To estimate the population mean of the plots if all had been clipped and weighed, it is necessary simply to insert the large sample mean value of the

ocularly estimated weights for X in equation (42).
Thus:

$$\hat{y}_e = \bar{y}_r + b(\bar{x}_e - \bar{x}_r) \tag{43}$$

where

$\hat{y}_e$ = estimated mean plot weight of the population.

$\bar{x}_e$ = sample mean of the ocular estimates, based on "m" values.

It is assumed here that the regression sample is not a random sample of Y values but was selected so as to provide a better (i.e., smaller variance) estimate of the population regression coefficient β of which b is an unbiased estimate. The estimate of the population total weight is

$$\hat{T} = N\bar{y}_e$$

where N is the number of plots in the population. Its sampling variance is

$$s_{\hat{T}}^2 = N^2\left\{s_{y.x}^2\left[\frac{1}{n} + \frac{(\bar{x}_e - \bar{x}_r)^2}{\sum_{i=1}^{n}(X_i - \bar{x}_r)^2}\right] + b^2\frac{s_x^2}{m}\left(1 - \frac{m}{N}\right)\right\} \tag{44}$$

$$s_{y.x}^2 = \frac{\sum_{i=1}^{n}(Y_i - \bar{y}_r)^2 - b^2\sum_{i=1}^{n}(X_i - \bar{x}_r)^2}{n - 2} \tag{45}$$

is the sample estimate, based on $n - 2$ degrees of freedom, of the variance of Y for plots having the same X value. (It is assumed that this variance is constant).

n = the number of paired regression observations.

Y_i and X_i = the Y and X values for observation i ($i = 1, 2, \cdots, n$)

$$s_x^2 = \frac{\sum_{j=1}^{m}(X_j - \bar{x}_e)^2}{m - 1} \tag{46}$$

is the estimated variance of X based on the large independent sample of m values of X.

If, even though m is large relative to n, it is insignficant relative to N, the term $(1 - \frac{m}{N})$ can be ignored. This will normally be true in unimproved pasture or range allotment sampling.

The variance $s_{\hat{T}}^2$ can be reduced by making either n or m or both larger. The most profitable distribution of the sampling effort between the regression sample and the sample of the independent variable depends upon the relative cost of Y and X observations and on the ratio of the variance of Y for a specific value of X and the variance of a random sample of Y, ignoring X. The procedure for computing the appropriate allocation of effort is somewhat cumbersome and will not be outlined here. It is suggested, particularly in new fields of application, that equation (44) be solved, for a selected value of $s^2_{\hat{T}}$, for a series of values of n and the corresponding values of m, using guessed values for the costs, variances, and correlation of Y and X. These computations will lead rapidly to efficient combinations. If the specifications of linearity of regression and uniformity of variance are not met, small biases will be introduced but these usually will not be serious. If the correlation of Y and X is high and the cost of a Y observation is high relative to that of an X observation, substantial economies can result.

The concept of double sampling can be extended readily to stratified sampling. Here, separate regression estimates are made for the total weight $\hat{T}_h$ of each stratum. If there are m strata, the estimate becomes

$$\hat{T} = \sum_{h=1}^{m} \hat{T}_h \tag{47}$$

and its variance is

$$s^2_{\hat{T}} = \sum_{h=1}^{m} s^2_{\hat{T}_h}$$

where $s^2_{\hat{T}}$ is the variance of the regression estimate of the total weight of forage in stratum h.

Ratio estimates: If the regression of Y on X can be expected to pass through the point $Y = 0$, $X = 0$, the ratio estimate is available. This method finds its greatest advantage in situations where the population value is known for independent variable X. In many cases the value of X is the value of the variable being estimated but measured at a previous date as found in a recent estimate of the volume of records in National Forest files based on a complete canvass in a base year and a random sample of forest records in the current year. More often the independent variable is a different but related variable.

If we designate by Y the variable to be estimated and by X the related variable for which the population value, say T_x, is known, the ratio, or regression, estimate is

$$T_y = rT_x$$

where r is the sample estimate of the ratio $R = \dfrac{T_y}{T_x}$.

If a random sample of n observations is taken from the N available in the population, then r is computed as

$$r = \frac{\sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} X_i}$$

It can be shown that if the regression of Y on X passes through $Y = 0$, $X = 0$, and if the variance of Y values for constant values of X is proportional to X, then r is an unbiased estimate of R. In fact, it is the value of the regression coefficient when a line is fitted by the method of least squares taking into account that the weights of Y observations are inversely proportional to their variance, in this case to $1/X$. When these conditions are not met r is a biased estimate of R, the population ratio. The bias decreases as n increases and as the correlation of Y with X for individual sample observations increases. In general, in cases where the ratio estimate would be profitable, the bias is small in relation to the sampling error of r and can be neglected.

The variance of T_y' is

$$s^2_{T'y} = T^2_x s^2_r ,$$

however, the variance of the estimate of T'_y is best expressed as the relative error squared, in which case

$$\frac{s^2_{T'y}}{(T_y')^2} = \frac{s^2_r}{r^2} = \left(\frac{N-n}{N}\right)\frac{1}{n}\left[\frac{s^2_y}{\bar{y}^2} + \frac{s^2_x}{\bar{x}^2} - 2r_{xy}\frac{s_x}{\bar{x}}\frac{s_y}{\bar{y}}\right]$$

In this equation r_{xy} is the coefficient of correlation of Y and X i.e.,

$$r_{xy} = \frac{\Sigma(X-\bar{x})(Y-\bar{y})}{\sqrt{\Sigma(X-\bar{x})^2\,\Sigma(Y-\bar{y})^2}}$$

The factor $\frac{N-n}{N}$ is the finite population sampling factor and may be omitted if n is small relative to N.

A useful alternative form of the variance is

$$s^2_{T'y} = N^2\bar{x}^2r^2\left(\frac{N-n}{N}\right)\frac{1}{n}\left[\frac{s^2_y}{\bar{y}^2} + \frac{s^2_x}{\bar{x}^2} - 2r_{xy}\frac{s_x}{\bar{x}}\frac{s_y}{\bar{y}}\right]$$

which may be expanded readily to accommodate ratio sampling of stratified populations.

Systematic sampling: By systematic sampling is usually meant a plan of selecting sample observations such that a description of the system of selection plus the selection, at random or otherwise, of the initial observation predetermines the selection of all other observations in the sample. If n observations are to be taken, the population is divided into k equal parts of size n and one observation is selected at random, usually in the end or corner segment. With this as a starting point, every k^{th} successive observation is selected.

Systematic sampling is easily planned and controlled and in some tests with areally dispersed natural populations has been found to be efficient.

If the systematic sample has a random starting point as described above, the entire sample can be recognized to be a single random observation and as such provides an unbiased estimate of the population mean or total. Since, however, it is but a single observation it has in it no measure of the dispersion to which such observations are subject. Examples in which the variance among randomly selected systematic grids or clusters could be evaluated have shown that the application of random sampling error formulas to systematically selected values may lead to estimates of precision that are far divergent from those measured.

The advantages of convenience, control, and efficiency are so great that attempts have been made to assess the accuracy of a single systematic sample through a study of relationships among the observations making up the cluster or grid. These have generally approached the problem through fitting a curve or surface to the specially related observations and use of the variation around the curve or surface as the basis of estimating the precision of the observation grid as a whole (DeLury 1950, Osborne 1942). Generally, it cannot be said categorically that systematic samples lead to more, or less, accurate estimates than random samples of the same intensity or cost. This depends upon the specific system adopted and the distribution in space or time of the variable measured as well as on the knowledge of strata, trends, and other factors available before the sampling is begun.

It should be kept in mind that controversies regarding systematic and random sampling arise almost only in those instances when the computation of a sampling error is required. In sampling a pasture, for instance, the sample may consist of 50 randomly selected 1/10-acre plots. On the plots, the forage measurement may consist of three mechanically spaced transects 50 feet long on each of which are located three 1 × 2½-foot plots which are clipped and weighed. In this case, the variance of the pasture estimate is based upon the variation among the 50 1/10-acre values. The variance is inflated by an unassessable amount from that which would have been obtained if the 1/10-acre plots had been completely clipped and weighed because the results from the clipped 2½-square-foot plot, when expanded to the 1/10 acre plots, do not equal exactly the 1/10-acre values. Variation among the 2½ square foot plot values does not enter the computation of the variance of the pasture mean or total explicitly.

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Chapter 10
Experimental Designs

THE PRIMARY reason for experimental design is to provide accurate estimates of treatment effects and the variation associated with treatments, and likewise the variation associated with experimental error. Design provides an effective and simple method of obtaining valid estimates of means and isolating and testing variation in the process of making statistical inferences. Otherwise, laborious sampling procedure, complicated mathematical formulae, and elaborate calculating machines might be required for arriving at the same conclusions.

Steps in Designing

There are three important steps to be followed in designing an experimental study.

First, the objectives of the study must be clearly stated, and each objective must be given an appropriate priority. This will lead to statements of the hypothesis to be tested. A hypothesis is a statement about the parameters of the populations being studied. A null hypothesis states that there is no difference between the parameters involved. In biological research the population being studied usually does not exist, but the experiment is designed to establish something about a population if it did exist.

The second step involves a description of the experimental material, an outline of the treatments to be made, and conditions under which the treatments will be compared. The experimental material may be homogeneous or highly variable, and the proposed treatments must be selected on the basis of the contribution they will make to the objectives. Likewise, the conditions under which the treatments are to be applied and measured will influence the choice of design. Such factors as soil fertility variation, climatic conditions, season of the year, harvesting procedures, and method of treatment application are examples of conditions that may affect type of design.

The third step in selecting a design should be a description of the measurements to be made, the precision desired, and the type of conclusions to be drawn. All of these are informative and contribute to the ultimate selection of the design. To a large degree, the application of results is determined by the design of the experiment.

These steps should be well outlined so that the experimental design can be carefully planned in advance. Too often the objectives of the study and interpretations and application of the data are conjured after the study has been made.

Systematic and Randomized Designs

All designs fall into two general categories: (1) the systematic design, and (2) the randomized design. In the systematic design the treatments within the study area are assigned according to a predetermined pattern so that generally the position of each treatment is decided upon in advance and not left to chance. For instance, the experimenter may restrict his treatments within each of three replications in any number of combinations, such as:

Replication I			Replication II			Replication III		
A	B	C	A	B	C	A	B	C

Replication I			Replication II			Replication III		
A	C	B	B	C	A	C	A	B

Replication I	A	B	C
Replication II	C	A	B
Replication III	B	C	A

Systematic designing is valuable in a demonstrational area as well as experimental, and it may permit intelligent placement of treatments so that each treatment is represented in each variable sub-area within the experimental area. However, in systematic sampling, there is said to be no valid error for testing differences and the adjacent effect of treatments may be accentuated since the same individual treatments may always appear together. Also there is danger of confounding treatment effect with soil and environmental variation differences within the experimental area. This might be the case if the systematic design placed all three replications in one segment of the experimental area.

A	A	A	B	B	B	C	C	C

The randomized design may be completely randomized whereby the treatments and replications are randomly located over the entire experimental area or randomization restricted so that each treatment occurs once in each of several blocks (randomized block).

Efficiency in Experimental Design

If it is desired to compare two designs, one with mean square per unit of s_1^2, and the other with the mean square per unit of s_2^2, the relative efficiency of one to the other is a simple ratio of s_1^2/s_2^2. However, if the degrees of freedom are different for the two designs, the relative efficiency is measured by the formula (Goulden 1952):

$$\frac{(n_2 + 1)(n_1 + 3)\, s_1^2}{(n_1 + 1)(n_2 + 3)\, s_2^2} = \text{Relative efficiency}$$

where n_1 represents the degrees of freedom for design 1 and n_2 represents the degree of freedom for design 2.

In many cases the researcher in the selection of the experimental design will need to consider costs as well as the ratio of the comparative magnitude of the mean squares per unit. In this case, the formula (Federer 1955)

$$\frac{(r_2c_2)}{(s_1^2)}\frac{(df_1 + 1)}{(df_1 + 3)} \Big/ \frac{(r_1c_1)}{(s_2^2)}\frac{(df_2 + 1)}{(df_2 + 3)} = \text{Relative efficiency,}$$

where s^2 is error variance per unit, r the number of replications, c the cost per replicate, df error degrees of freedom, and the subscripts the first and second design.

Methods for Reducing Errors in Research

When one or more treatments are applied to experimental material, the results are affected not only by the nature of the treatments, but also by extraneous variation or by variations that cannot be explained. Carefully planned research attempts to measure these two kinds of variation accurately. Inferences can then be made concerning the real treatment effects expected under the conditions observed. The magnitude of treatment effects may be influenced by a bias inherent in the method of measurement of the results. This can only be removed by a refinement of technique. The decision as to how far one should go in this direction must be based upon the cost involved and consideration of the magnitude of the bias removed related to the size of the extraneous variation. If one is interested primarily in treatment difference, a bias may not be serious since, presumably, it affects all treatments alike.

Failure to standardize the application of treatments and measurement of results will affect both the treatment effects and the extraneous variation. The effort and resources expended in this direction must be consistent with the result achieved, as measured by the reduction in this source of variation. One frequently finds that the small reduction achieved by refining experimental technique is not worth the cost involved when the magnitude of other sources of extraneous variation is considered.

Regardless of the source or cause of experimental error, its effect may be reduced to any desired point by increasing the size of the experiment in terms of increased replications, more treatments, or a combination of both. This is based on the assumption that increased size will not require the use of more variable material. Increased replication of a simple design should always be considered in terms of costs and results to be achieved when compared with fewer replications of a more complicated design. Often a limited amount of experimental material may make this choice impossible.

It is also possible to reduce the magnitude of experimental error by various methods of handling the experimental material. In the first place, one might select or develop more uniform experimental material upon which to apply the treatment. This is often effective, but is fraught with danger since it may seriously limit the breadth of application of the results. Often it is possible to reduce the effect of extraneous variation by making additional measurements on the experimental material, using the statistical technique known as the "analysis of covariance" to reduce the magnitude of the experimental errors involved in testing differences between treatments. There are some disadvantages to this method since the summary, presentation, and interpretation of results become more complicated. Frequently, however, precision can be increased considerably at small cost when additional measurements can be easily made, and when a high degree of correlation exists between them and the extraneous variation of the experimental units.

Great advances have been made in controlling the effect of undesirable variation in experiments by careful grouping of the experimental units to which the treatments are applied. There are a great many arrangements from which one may choose. Before deciding on a given design, one should be familiar with the methods of randomization to be used and the analysis of the results. If an analysis of variance is to be made, the degrees of freedom should be broken down and the appropriate formulae for arriving at the standard error of a mean difference should be available. It is also worthwhile to become familiar with the advantages and disadvantages of various designs.

In comparatively new fields of research it is desirable to test the relative efficiency of simple designs compared to more complicated ones, so that the benefits of each will be known for future planning.

SIZE AND SCOPE OF EXPERIMENT

One of the first questions encountered in designing an experiment concerns its size or the number of replications required for attaining a given degree of precision. In order to answer this question the research worker must specify the degree of precision required, have an estimate of the standard error per experimental unit, and decide the risk he is willing to run of being wrong. The precision desired may be specified as the size of the true difference the experiment is to detect by a test of significance or by stating the width of the confidence interval desired for the true difference. For routine applications of this method the reader is referred to "Experimental Designs," Cochran and Cox, 2nd Edition, pages 17 to 22. It is important to consider this problem in designing every experiment to make sure that the limitations of the results will be known before the experiment is started.

INTERPRETATION OF RESULTS

Experimental results are frequently variable and the drawing of conclusions is extremely difficult. For this reason, experimental design, statistical estimation, and hypothesis testing are used to make definite statements which have a specified probability of being correct. From these statements accurate application of the results can be made.

Statements from experimental results are frequently made with reference to confidence limits with certain probabilities. For instance, it is possible to calculate an upper and lower limit within which the true value or the true difference will lie with a given probability of being correct.

After an experiment is completed it is the responsibility of the research worker to summarize and present the results in a concise form and to give his interpretation of their meaning. This is usually done by computing a test of significance of the treatment variation compared with the appropriate experimental error. If the treatment variation is not significant, the conclusion is that any real treatment effects were too small to be detected by the experiment conducted. If, however, the test is significant, further analysis is necessary to separate the significant treatment differences.

It is frequently desirable and necessary to divide the treatments into as many sub-groups as they naturally fall, making a test of significance for the treatments within each group. When significance is found at the probability level chosen, the research worker should use appropriate methods for making comparisons among the individual means. In the past the least significant difference has been incorrectly used for differentiating a group of means.

The reader is referred to Chapter II of *Experimental Design* by Federer (1955) for a full discussion of this problem and the use of more appropriate methods for testing significance among means.

A routine analysis of variance in all of its aspects, including tests of significance and the use of confidence limits, is based upon three assumptions which may or may not be true in actual practice. First, it is assumed that all treatment and block effects are additive. This is to say that each treatment or block has the constant effect of increasing or decreasing the response of any experimental unit by a constant amount. Second, the residual or extraneous variations are assumed to be independent from one unit to another, and third, to be normally distributed with the same variance. When these basic assumptions are not met, it may be desirable to transform the scale of measurement to bring the data into agreement with any one of the assumptions. If deviation exists in more than one of the assumptions it is difficult to find a transformation which will correct all of them. For a detailed description of this subject see assumptions made in model, pages 47 and 91, Cochran and Cox (1957), or transformation of data, Federer (1955).

COMPLETE BLOCK DESIGNS

Completely Randomized Design

This type of design is flexible and simple and is frequently applied to conditions in which all treatments and replications are allocated to plots within one large area entirely by chance or, in a similar manner, a group of animals are allocated to various treatments at random. In the completely randomized design, randomization is not restricted to insure treatment application to similar or uniform units or plots within a separate block or replication. The replications or repeated treatments are completely randomized within the experiment. Therefore, the entire variation among plots enters into the experimental error term and increases the experimental error variance. In this sense, precision is improved by other designs.

By the use of completely randomized designs the degrees of freedom are increased for error compared to other designs. In this way such designs are considered more sensitive. An illustration using three species and four replications for a completely randomized design follows:

Completely Randomized Design

Spec. A	Spec. A	Spec. C	Spec. A	Spec. B	Spec. C	Spec. C	Spec. B	Spec. A	Spec. C	Spec. B	Spec. B
10	12	18	8	6	16	18	6	14	10	5	4

TABLE 1. Analysis of variance for the completely randomized design using three species and four replications

Source	*D.F.*	*Sum of squares*	*Mean square*
Species	2	211	105.5
Error (among plots within species)	9	66	7.3
Total	11	277	

Randomized Blocks

In field research, the randomized block generally is more efficient and is more widely used than the completely randomized design since the reduction in experimental error variance more than compensates for the increased error degree of freedom obtained by the completely randomized design. The design consists of the application of treatments randomly within several blocks. The use of several blocks is referred to as replication of the experiment. The use of blocks increases the precision of comparing treatment means because the differences between blocks are kept free from sources of experimental error. Normally, uncontrolled variation is kept to a minimum within blocks, but is allowed to vary among blocks. In fact, variation among blocks is introduced frequently to test the responses of the treatments to highly variable conditions. Actually, the data have application only to the variability included among replications. For this reason, replications are sometimes widely separated and include distinct contrasts. If topography, fertility, or other variability is present, the blocks should be placed to separate such differences among them and yet retain as much uniformity within blocks as possible.

It must be remembered in selecting locations for replications, differences between blocks can become so great that it would be better to set up separate experiments in each of the different site expressions or strata. If the yield of the best block exceeds the yield in the poorest by more than 5 to 10 times, the effects may be nonadditive and the mean squares non-poolable. Therefore there is no way of obtaining suitable error terms for testing treatment differences statistically.

In randomized block experiments, uncontrolled variation or normal variation to be included is kept to a maximum among replications and to a minimum within replication. Plots within blocks should be made as nearly alike as possible.

Randomized Block Experiment

Block I			Block II			Block III			Block IV		
Spec. A 10	Spec. C 16	Spec. B 5	Spec. C 18	Spec. A 12	Spec. B 6	Spec. A 14	Spec. B 6	Spec. C 18	Spec. B 4	Spec. A 8	Spec. C 10

TABLE 2. Analysis of variance for the randomized block experiment using three species and four replications

Source	D.F.	Sum of squares	Mean square
Species	2	211	105.5
Blocks	3	51	17.0
Error (spec. x blks.)	6	15	2.5
Total	11	277	

The randomized block experiment can be used with any number of treatments and replications. At least two replications are required to establish an experimental error for testing significance among treatments. However, unless differences among treatments are comparatively large, two replications are generally insufficient. When differences between treatment means are expected to be small, it is advantageous to add replications in order to provide an experimental error to test relatively small differences. If, for instance, the standard error among treatments is 15 per cent of the mean for all treatments in four replications, the estimate of standard error of a treatment mean percentage-wise is then $15/\sqrt{4}$ or 7.5 per cent and the standard error of a mean difference is $\sqrt{2s^2/n}$ or $\sqrt{(2)(15)^2/4} = 10.61$. The previous example for a randomized block experiment dealing with three species and four replications yielded a standard error of $\sqrt{2.5}$ or 1.58 and a mean value of 10.58 for the experiment. The standard error (1.58) divided by the mean of all treatments (10.58) equals 15 per cent. Thus, the $t_{.05}$ value (2.45) at 6 degrees of freedom multiplied by the standard error of a mean difference or 10.61 per cent would yield a difference of about 26.0 per cent which would be the approximated difference necessary between treatment means to be significant at the 5 per cent level or about 39.3 per cent (3.7 $\times$ 10.61) at the 1 per cent level. If the required difference appears too great, the replications might be increased to 6, whereby the estimate of standard error of a treatment mean percentage-wise would be $15/\sqrt{6}$ or 6.12 per cent. In this case a difference of about 19.05 per cent between treatment means would be significant at the 5 per cent level. The calculation follows $t_{.05}$ at 10 D/F ($\sqrt{2s^2/n}$) or $2.2\sqrt{(2)(15)^2/6} = 19.05$. By the same calculation using $t_{.01}$ value 3.1 a difference of about 26.85 per cent at the 1 per cent level would be required for significance. The degrees of freedom for error mean square is now 10 because there are now six replications and three species. The number of replications to be used will depend largely upon the probable size of mean differences to be measured, and the desired accuracy of testing the mean differences. Since the randomized block design is popular, almost any textbook on experimental design or research methods presents many and varied examples of its use.

Latin Squares

This design is well adapted where relatively few treatments are involved and the experiment is to be carried out in the laboratory or in the field where heterogeneity is suspected but is not evident from physical observations. The number of replications must be the same as the treatments in the Latin square; therefore, it is less flexible than the randomized block. In the field the Latin square is usually laid out in an area with four equal sides. The square is divided into rectangular strips called rows, and subdivided into strips perpendicular or at right angles to the rows. These latter strips are referred to as columns. There are an equal number of columns and rows and as many of each as there are treatments. The Latin square design is usually used so that field variability is controlled in both directions; however, the field design may be laid out with all plots in one continuous line instead of a square if desired.

Random assignment of the treatments is made to the plots with the restriction that each treatment must occur only once in each row and each column. An illustration using five treatments, A, B, C, D, and E, in a square area and a rectangular area appears as follows:

Columns

Rows

B	E	A	C	D
D	A	E	B	C
E	B	C	D	A
A	C	D	E	B
C	D	B	A	E

or

Columns

Rows

I	II	III	IV	V
B 12	E 8	A 10	C 14	D 6
D 14	A 12	E 4	B 16	C 30
E 6	B 12	C 20	D 10	A 18
A 10	C 30	D 10	E 6	B 16
C 20	D 16	B 14	A 14	E 10

TABLE 3. Analysis of variance for the Latin square using 5 treatments

Source	D.F.	Sum of squares	Mean squares
Rows	4	88.6	22.2
Columns	4	88.6	22.2
Treatments	4	687.0	171.8
Error	12	162.0	13.5
Total	24	1026.2	

TABLE 4. Analysis of variance as a randomized block for data shown in Table 3

Source	D.F.	Sum of squares	Mean squares
Reps. (columns)	4	88.6	22.2
Treatments	4	687.0	171.7
Error (reps. x treat.)	16	250.6	15.7
Total	24	1026.2	

The Latin square offers greater accuracy generally than the randomized block since it eliminates field variation in two ways.

The error has increased from a mean square of 13.5 for the Latin square (table 3) to 15.7 for the randomized block (table 4). However, the additional degrees of freedom for the randomized blocks must be considered. To make allowances for this advantage of increased degrees of freedom from 12 for the Latin square to 16 for the randomized block, we use the formula $(N_1 + 1)\ (N_2 + 3)/(N_2 + 1)\ (N_1 + 3) = M$, where M is a multiplier to correct the mean square $[(12 + 1)\ (16 + 3)/(16 + 1)\ (12 + 3) = 0.969]$ (Cochran & Cox 1957, page 112). Therefore, the comparable mean square for randomized blocks would be 0.969×15.7 or 15.2. Thus, in this case there was an increased efficiency of about 12.6 per cent $[(15.2 - 13.5)/13.5]$ by use of the Latin square. If the field variation is slight or it can be controlled by blocks in one direction, there would be no advantage of the Latin square over the randomized block.

Graeco-Latin and Hyper-Graeco-Latin Squares

Graeco-Latin square and Hyper-Graeco-Latin square designs are seldom used because units cannot conveniently be balanced into the appropriate number of groupings. However, when there are more than two sources of extraneous variation to control, the use of these designs may prove advantageous. For details of the designs and analysis of data see Federer (1955), Cochran and Cox (1957), and Fisher (1951).

Simple Factorial Experiments

The factorial experiment, for example, is one in which different treatment levels may be applied to different varieties or to a given variety at different times. Then each combination of variety and treatment is included in the test. Such a factorial experiment could be placed in a randomized block design, in which case each such combination would be represented in each block.

The effect of such treatment-variety combination consists of the sum of varietal effect plus treatment effect plus interaction of variety and treatment. Treatment might refer to the amount of fertilizer, different combinations of fertilizer, different amounts of poison in killing undesirable plants, different intensity of seeding as it might concern different species. The interaction measures the degree to which treatment effects vary with species. The interaction term is the important term in these tests, since the object is to find the optimum treatment combination.

Should it happen in a factorial experiment that the interaction is not significant, no information is lost because each treatment and species is replicated and effects can be tested over a wider range of situations than would be the case without the factorial.

In the factorial experiment the effects of a number of factors are tested in all combinations. For example, we might want to test the effect of four intensities of seeding (1, 2, 3, and 4,) four drill-row spacings (I, II, III, and IV,) with four species of grass (A, B, C, and D) at two seasons (fall and spring) with three replications.

		Fall		
Species A				
Spacing	I	III	II	IV
Intensity	1, 3, 2, 4	2, 4, 3, 1	3, 4, 2, 1	1, 4, 3, 2
Species C				
Spacing	I	IV	III	II
Intensity	4, 3, 2, 1	1, 3, 2, 4	1, 2, 3, 4	2, 3, 1, 4
Species D				
Spacing	II	III	IV	I
Intensity	1, 3, 2, 4	4, 3, 1, 2	3, 1, 4, 2	2, 3, 4, 1
Species B				
Spacing	IV	II	I	III
Intensity	2, 3, 4, 1	2, 1, 3, 4	1, 4, 3, 2	1, 3, 4, 2
		Spring		
Species B				
Spacing	IV	II	III	I
Intensity	4, 3, 1, 2	1, 4, 3, 2	2, 1, 3, 4	2, 3, 4, 1

Continued on following page

Species A				
Spacing	I	III	II	IV
Intensity	3, 2, 1, 4	1, 2, 3, 4	1, 4, 2, 3	1, 4, 3, 2
Species C				
Spacing	III	II	I	IV
Intensity	4, 1, 2, 3	2, 3, 4, 1	1, 4, 3, 2	1, 4, 3, 2
Species D				
Spacing	II	IV	I	III
Intensity	3, 2, 4, 1	2, 4, 3, 1	2, 4, 1, 3	4, 1, 2, 3

TABLE 5. Treatments and degrees of freedom for a factorial experiment using four species, four drill row spacings, and four seeding intensities during the fall and spring

Source	*D.F.*
Species	3
Spacings	3
Intensity	3
Season	1
Replication	2
Spec. x spa.	9
Spec. x int.	9
Spec. x sea.	3
Spa. x int.	9
Spa. x sea.	3
Int. x sea.	3
Spe. x spa. x int.	27
Spe. x spa. x sea.	9
Spe. x int. x sea.	9
Spa. x int. x sea.	9
Spe. x spa. x int. x sea.	27
Error	254
Total	383

In the factorial the effect of each factor can be compared separately and in all combinations with the other factors. For example, the effect of intensity (3 degrees of freedom) can be evaluated and also the effect of intensity with season, intensity with spacing, intensity with species, intensity with season and spacing, intensity with spacing and species, intensity with season and species, and intensity with all three factors (table 5). In this way each factor can be separated into its various effects singly or in combination with other factors.

In analyzing factorial experiments it is often useful to segregate the SS for individual D/F. In cases where successive levels of treatment are applied, it is then possible to determine whether the effect is linear, quadratic, or cubic.

The procedures for doing this are described by Cochran and Cox (1957), Yates (1937), and most other modern statistical texts.

In a factorial, the factors frequently are applied at various levels or in increasing increments of equal value. For example, intensity of seeding could be made at two pounds, four pounds, six pounds, and eight pounds, and spacing at seven inches, fourteen inches, twenty-one inches, and twenty-eight inches. The effects of levels or increasing increments are important in the interpretation of data and should not be overlooked in the analyses. In many factorials various levels or increasing increments of the factors make up the entire treatment effects and are, therefore, designed to determine the effects of increasing levels. Such an examination of effects of increased intensity would consider each degree of freedom as shown in table 6.

TABLE 6. A separation of degrees of freedom to determine the linear, quadratic, and cubic relationship in a factorial experiment dealing with increasing increments as treatments

Source	*D.F.*
Intensity	(3)
Int. linear	1
Int. quadratic	1
Int. cubic	1
Int. x species	(9)
Int. L spe. L	1
Int. L spe. Q	1
Int. L spe. C	1
Int. Q spe. L	1
Int. Q spe. Q	1
Int. Q spe. C	1
Int. C spe. L	1
Int. C spe. Q	1
Int. C spe. C	1
Int. x season	(3)
Int. L x S. L.	1
Int. Q x S. L.	1
Int. C x S. L.	1
etc.	
Error	254
Total	383

The measure of intensity, 3 degrees of freedom, is a measure of intensity as a main effect as compared with the experimental error with 254 degrees of freedom. If intensity is significant, then it is of interest to know whether the effect is linear, cubic, or quadratic, or a combination of these effects.

If the factors being tested are independent, a factorial experiment measures the main effects with the same precision as when the whole experiment is devoted to each of the factors individually. However, it does not measure the specific effect of each factor acting entirely alone unless such comparisons are incorporated in the experiment.

Another use of the factorial experiment is in range feeding trials dealing with supplemental feeding of livestock with various nutrients at different levels. For example, 10 animals in each of 27 groups could be used as follows:

$Protein_0$			$Protein_1$			$Protein_2$		
$Phos._0$	$Phos._1$	$Phos._2$	$Phos._0$	$Phos._1$	$Phos._2$	$Phos._0$	$Phos._1$	$Phos._2$
$E_0E_1E_2$	$E_0E_1E_2$	$E_0E_1E_2$	$E_0E_1E_2$	$E_0E_1E_2$	$E_0E_1E_2$	$E_0E_1E_2$	$E_0E_1E_2$	$E_0E_1E_2$

TABLE 7. Source of variation and degrees of freedom for a factorial experiment using three nutrients with three levels of feeding in each and ten animals in each of twenty-seven treatment groups

Source	*D.F.*
Treatment	(26)
Protein (Pr)	2
Phosphorus (P)	2
Energy (E)	2
Pr x P	4
Pr x E	4
P x E	4
Pr x P x E	8
Error	243
Total	269

The measure of interaction is a measure of independence. A significant interaction indicates dependence; thus, the factors are interdependent and function together in some way to cause a significant effect upon the responses being measured.

The objective in a factorial experiment is to obtain a broad picture of the effects of the various factors being studied, their main effects, and their effects in combination with other factors.

If the effects of the various factors are independent, then each factor could have been studied in separate experiments just as effectively. However, unless they are studied in a factorial experiment, their interdependence and relative effects cannot be determined. For example, suppose wool yield is to be maximized from supplements including three variables such as protein, phosphorus, and energy. The research worker desires the optimum combination of these three constituents in order to obtain the maximum wool yield. In like manner, it might be desirable to determine the optimum level for each constituent to obtain maximum yield consistent with cost per unit of the various constituents. These can be determined from an experiment such as the example of supplemental feeding. However, to accomplish this, special formulae are required depending upon the results and manipulation of cost and return relationships (Cochran and Cox 1957).

The factorial experiment is ideally suited to determine the effects of each of a number of factors over a specified range of increased or decreased magnitudes. The factorial lends itself to testing many factors suspected of being interdependent that could not be determined under individual studies dealing only with individual factors. In addition, results lead to recommendations that have broad scope and apply over a wide range of conditions.

It should be remembered that all main effects and interactions are really measurements of the additive effect of these factors on all others and, therefore, are not actual measurements of the specific effects of the various factors operating alone. In the supplementary feeding example, there are 27 treatments, and to measure the specific effect of any one level of protein alone, without the superimposed effect of other factors, there would be only 10 animals in each group from which to base the results. This small number may be woefully inadequate to predict the expected returns from feeding any one supplemental factor alone. However, when measuring the additive effect of the various levels of protein on all other treatments, there are 90 animals in each of the three levels (protein, two degrees of freedom.)

If specific returns in saleable produce from individual supplemental factors are important evaluations, the factorial design is frequently inadequate and must be followed or preceded with designs to measure the individual factors separately without additive effects from other factors.

When several factors at several levels are used, the factorial design may become unwieldy. In field trials the inclusion of several factors at several levels makes the blocks so large that experimental error cannot be efficiently controlled, since it is desired to maintain uniformity within blocks and let the variability occur among the blocks.

Confounding in Experimental Design

Confounding is usually described by referring to non-orthogonality among treatments with replication. Orthogonality in designing is the most direct and simple method whereby each block or replication contains the same kind and number of treatments and is referred to as a balanced design; whereas, when non-orthogonality or confounding is introduced, each block does not contain all of the treatments. In this case special methods of calculation are required to separate the treatment and block effects because treatment effects are confounded with block effects.

The purpose of confounding is to increase the accuracy of measuring the more important effects by sacrificing accuracy of comparisons of less important effects. Other advantages may include the reduction of plots or animals required for treatment combinations and a reduction in time interval required of a technician.

The method of confounding can be illustrated by use of a simple design involving three fertilizers (nitrogen, phosphorus, and sulfur) at two levels along with a control. This presents a total of eight treatments, (check), N, P. S, NP, NS, PS, and NPS. If we choose to use eight replications, confounding could be used in a 8 × 8 Latin square. However, if we choose fewer replications, it would ordinarily be arranged into a randomized block design. A field plan with three replications in a randomized block design without confounding would be as follows:

Replication I		Replication II		Replication III	
N 7	NS 7	S 5	NSP 14	P 4	NP 7
NP 5	(1) 2	(1) 2	P 3	PS 6	(1) 1
P 5	PS 5	NP 6	PS 5	NPS 16	N 6
S 6	NPS 15	N 6	NS 10	S 5	NS 8

Actual signs and methods of calculating sum of squares are shown in table 8.

TABLE 8. Calculations of sum of squares for a simple randomized block experiment using three fertilizers singly and in combination

	Treatment combinations									
Factorial effect	*(1) 5*	*N 19*	*P 12*	*S 16*	*NP 18*	*NS 25*	*PS 16*	*NPS 45*	*Comparisons*	*Sum of squares*
N	−	+	−	−	+	+	−	+	$(58)^2/24$	140.17
P	−	−	+	−	+	−	+	+	$(26)^2/24$	28.17
S	−	−	−	+	−	+	+	+	$(48)^2/24$	96.00
NP	+	−	−	+	+	−	−	+	$(12)^2/24$	6.00
NS	+	−	+	−	−	+	−	+	$(18)^2/24$	13.50
PS	+	+	−	−	−	−	+	+	$(14)^2/24$	8.17
NPS	−	+	+	+	−	−	−	+	$(28)^2/24$	32.67

In a simple experiment of this kind the second order interaction NPS would generally be considered of least importance; therefore, it may be confounded with blocks.

This interaction effect is estimated by data comparison (NPS) + (N) + (P) + (S) — (NP) — (NS) — (PS) — (check). Therefore, if three replications are used and NPS is confounded with block, each replication would be split into two blocks making a total of six with the (+) effects in one block of each replication and the (—) effects in the other block as follows:

Replication I		Replication II		Replication III	
1	2	3	4	5	6
NPS 15	NP 5	NPS 14	NS 10	(1) 1	P 4
N 7	NS 7	P 3	NP 6	NP 7	N 6
P 5	PS 5	N 6	PS 5	NS 8	S 5
S 6	(1) 2	S 5	(1) 2	PS 6	NPS 16

The total from blocks 1, 3, and 6 subtracted from blocks 2, 4, and 5 represents the NPS interaction total. This NPS effect is also a block effect and is said to be completely confounded with blocks. However, the remaining effects are not confounded and are orthogonal with blocks. In each of the 6 blocks there are 2 treatments containing each of the fertilizers and 2 that do not.

The analysis of variance for both the confounded design and the ordinary randomized block for this simple illustration is shown in tables 9 and 10.

TABLE 9. Analysis of variance for a randomized block with the treatment (NPS) confounded

Source	*D.F.*	*Sum of squares*	*Mean square*
Main effects (N, P, S)	3	264.34	88.11
1st order interaction (NP, NS, PS)	3	27.67	9.22
Blocks	5	38.00	7.60
Error	12	7.99	0.67
Total	23	338.00	

TABLE 10. Analysis of variance for the same treatments shown in table 9 without confounding in an ordinary randomized block design

Source	*D.F.*	*Sum of squares*	*Mean square*
Main effects (N, P, S)	3	264.34	88.11
1st order interaction (NP, NS, PS)	3	27.67	9.22
2nd order interaction (NPS)	1	32.67	32.67
Replications	2	0.25	.12
Error	14	13.07	0.93
Total	23	338.00	

In the confounded randomized block, 5 degrees of freedom among blocks have been used for error control among blocks, compared to only 2 degrees of freedom in the ordinary randomized block design. Thus, by isolating heterogeneity among blocks by increasing the degrees of freedom from 2 to 5, the error for 12 degrees of freedom by confounding is proportionally smaller and gives a more precise estimate of the remaining effects than the error for 14 degrees of freedom by ordinary randomized blocks. If the variation within blocks is slight or it is difficult to group the confounded effects in order to control extraneous variation, little can be gained by confounding.

In the illustration the confounded randomized block had a mean square of 0.67 and the ordinary randomized block had a mean square of 0.93. However, the additional degrees of freedom for the mean square value of 0.93 must be considered in evaluating increased efficiency by confounding. This can be accomplished by the formula $(N_1 + 1)\ (N_2 + 3)/(N_2 + 1)\ (N_1 + 3)$ = the multiplier for reducing the mean square to allow for the additional 2 degrees of freedom. Thus, $(12 + 1)\ (14 + 3)/(14 + 1)\ (12 + 3) = 0.982$ or a mean square adjusted to 0.91 (0.93×0.982) instead of 0.93 for randomized blocks. Thus, this illustration shows that the efficiency was increased about 35.8 per cent $[(0.91 - 0.67)/0.67]$ by confounding, compared to the ordinary randomized block experiment. The illustration is somewhat exaggerated to demonstrate the gain in efficiency when extreme variability within replications exists compared to only slight variability among replications. In this situation actual experiments of this size would seldom be encountered.

This example of confounding was of the simplest type; however, any of many factorial effects may be confounded in this manner. Frequently, the more complicated and meaningless interactions are confounded so that more accurate evaluations of the remaining effects can be obtained.

In complete confounding all information on the confounded effect is lost. Therefore, designs frequently employ partial confounding with only a partial loss of information for the confounded effects.

In partial confounding different effects are confounded only in a part of the replications. In this manner it is possible to obtain a part of the information from the confounded effects.

Suppose NPS, NP, and SP are partially confounded. As before, NP is estimated by the comparisons (check) + (NP) + (S) + (NPS) — (N) — (P) — (NS) — (PS) and PS by the comparisons (check) + (PS) + (N) + (NPS) — (P) — (S) — (NP) — (NS). The design would be in the following form:

Replication I		Replication II		Replication III	
1	2	3	4	5	6
NPS 15	NP 5	(1) 2	N 6	(1) 1	P 4
N 7	NS 7	NP 6	P 3	PS 6	S 5
P 5	PS 5	S 5	NS 10	N 6	NP 7
S 6	(1) 2	NPS 14	PS 5	NPS 16	NS 8

In replication I the interaction effect NPS is confounded, but in the other two replications this effect is orthogonal with blocks. Thus, the NPS effect within replications II and III can be determined. Similarly, NP effect is confounded with blocks in replication II but estimates of the effects can be made from replications I and III and, in like manner, PS effect which is confounded with blocks in replication III can be estimated from replications I and III (table 11).

TABLE 11. Calculations of sum of squares for partially confounded effects NPS, NP and PS

	Totals from Treatment Combinations in Replications II and III									
	(1) *3*	*N* *12*	*P* *7*	*S* *10*	*NP* *13*	*NS* *18*	*PS* *11*	*NPS* *30*	*Comparisons*	*Sum of squares*
NPS	−	+	+	+	−	−	−	+	$(14)^2/16$	12.25
	Totals from Treatment Combinations in Replications I and III									
	(1) *3*	*N* *13*	*P* *9*	*S* *11*	*NP* *12*	*NS* *15*	*PS* *11*	*NPS* *31*	*Comparisons*	*Sum of squares*
NP	+	−	−	+	+	−	−	+	$(9)^2/16$	5.06
	Totals from Treatment Combinations in Replications I and II									
	(1) *4*	*N* *13*	*P* *8*	*S* *11*	*NP* *11*	*NS* *17*	*PS* *10*	*NPS* *29*	*Comparison*	*Sum of squares*
PS	+	+	−	−	−	−	+	+	$(9)^2/16$	5.06

The factorial effects in an analysis of variance for the partially confounded experiment is shown in table 12.

TABLE 12. Analysis of variance for a randomized block where NP, PS, and NPS are partially confounded

Source	*D.F.*	*Sum of squares*	*Mean square*
Main effects N, P, S	3	264.34	88.11
NS	1	13.50	13.50
NP_{pc} (partially confounded)	1_{pc}	5.06	5.06
PS_{pc}	1_{pc}	5.06	5.06
NPS_{pc}	1_{pc}	12.25	12.25
Replications	5	29.00	5.80
Error	11	8.79	0.80
Total	23	338.00	

Since information on each confounded effect was recovered from 2 of the 3 replications, the ratio of ⅔ is a measure of the extent of confounding and, likewise, an index to the percent of recovery of information.

In the analysis of variance the sum of squares for blocks and for unconfounded effects is found in the usual way.

Thus, in partial confounding only part of the information was lost and, as with complete confounding, the accuracy of determining the effects of the more important factors was increased.

Treatments in a Latin square, as in the randomized block, can be confounded. Such designs are sometimes referred to as quasi-Latin square, half-plaid Latin square, plaid-Latin square, and the magic-Latin square. If the variation within rows and columns is small there is little to be gained from confounding the effects in a Latin square.

Split Plot Designs

The split plot normally described in literature refers to an additional factor or factors that are applied to a portion of each plot in each of the blocks. Occasionally this technique is used for a treatment that has been added after the original experiment has been under way for some time. An illustration might be the application of a herbicide to one half of each plot in a block that was seeded to grass at 5 intensities in 3 replications to determine the effects of released annual weed competition on grass establishment (see example 1).

Split Plot Design, Example 1

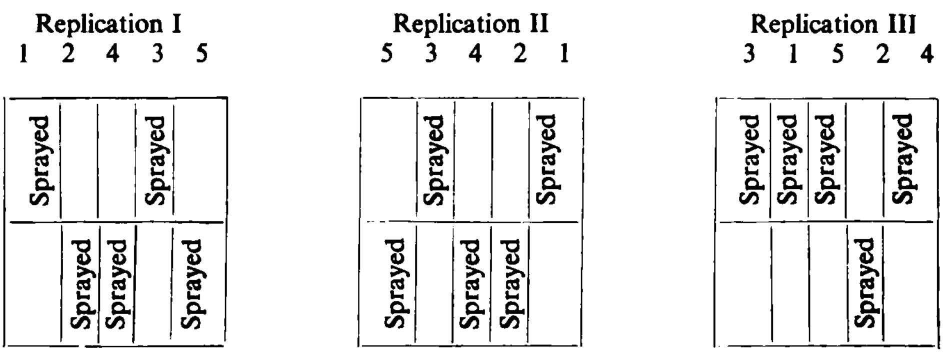

TABLE 13. Source of variation and degrees of freedom for a split plot design using five intensities of seeding in three replications with an herbicide applied on one half of each plot

Source	*D.F.*
Intensity	4
Replication	2
Rep. x int. (Error a)	8
Spray vs. unsprayed	1
Int. x spray	4
Error b	10
Total	29

The split-plot or subplot treatments and interactions are measured more precisely than the main plot treatments (table 13).

This same experiment could have included spraying at the outset of the experiment and arranged in a randomized block. This, of course, implies that the application of the herbicide was anticipated at the time the design was laid out in the field. In this case there would be 3 blocks with 10 treatments and the analysis of variance would be as shown in table 14.

TABLE 14. Source of variation and degrees of freedom for five intensities of seeding with and without herbicide in three replications as a randomized block experiment

Source	*D.F.*
Replications	2
Treatments	(9)
Spray	1
Intensity	4
Spray x intensity	4
Error	18
Rep. x spray	(2)
Rep. x intensity	(8)
Rep. x spray x intensity	(8)
Total	29

In the randomized block all treatment effects are measured with the same degree of precision. However, in a design where plots are split the subtreatment is measured more effectively than the main plot treatments.

Sometimes in field work it is necessary to use a split plot design or modification of it in order to make use of big machinery or treatments not suited to small plots, such as drilling, use of fire, and plowing. In this case, the blocks are divided in two parts with all the treatments applied systematically in strips crosswise to the divisions or within each division. The divisions are not necessarily limited to two, but can be any number. An illustration consisting of fertilized and unfertilized strips, seeded to grass, legumes, and a mixture in four replications follows (example 2):

Split Plot Design, Example 2

Replication 1		Replication 2		Replication 3		Replication 4	
Fert.	Unfert.	Fert.	Unfert.	Unfert.	Fert.	Fert.	Unfert.
gr	ass	mix	ture	leg	ume	gr	ass
leg	ume	leg	ume	gr	ass	leg	ume
mix	ture	gr	ass	mix	ture	mix	ture

TABLE 15. Source of variation and degrees of freedom for a modified split plot design where fertilizer was applied throughout the blocks where a grass, a legume and a mixture was previously seeded

Source	*D.F.*
Fertilizer	1
Replications	3
Fert. x rep. (error a)	3
Seeding	2
Reps. x seeding (error b)	6
Fert. x seeding	2
Reps. x seeding x fert. (error c)	6
Total	23

Where the blocks are split (example 2) and the treatments applied in strips, the fertilizer treatment of 1 degree of freedom is tested with error a, 3 degrees of freedom. Whereas, seeding, 2 degrees of freedom, is tested with error b, 6 degrees of freedom, and the interaction between fertilizer treatment and seeding is tested with error c, 6 degrees of freedom (table 15).

If in the foregoing example the seeding treatments had been randomized within the 6 plots in each block in a randomized split plot design instead of seeded across the entire block, the seeding 2 degrees of freedom would be tested with error 12 degrees of freedom (example 3) (table 16).

Split Plot Design, Example 3

Replication 1		Replication 2		Replication 3		Replication 4	
Fert.	Unfert.	Fert.	Unfert.	Unfert.	Fert.	Unfert.	Fert.
grass	legume	mixture	grass	legume	mixture	mixture	grass
mixture	grass	mixture	legume	grass	mixture	legume	legume
legume	mixture	legume	grass	legume	grass	grass	mixture

If application of treatments can be adapted to the design, the randomized block experiment could be used. In this case fertilizer, 1 degree of freedom, and seeding, 2 degrees of freedom, are both tested with error, 15 degrees of freedom as shown by the following example:

Replication 1		Replication 2		Replication 3		Replication 4	
grass fert.	legume unfert.						
mixture unfert.	grass unfert.						
legume fert.	mixture fert.						

TABLE 16. Source of variation and degrees of freedom for a modified split plot where the fertilizer was applied to one half of each of four replications but the seeded grass, legume and mixture was randomized within each of the fertilized and unfertilized plots

Source	*D.F.*
Fertilizer	1
Replications	3
Fert. x reps. (error a)	3
Seeding	2
Fert. x seeding	2
Error b	12
Reps. x seeding	(6)
Reps. x seeding x fert.	(6)
Total	23

TABLE 17. Source of variation and degrees of freedom for a randomized block where both fertilized and unfertilized grass, legume and mixture were placed at random in each of four replications

Source	*D.F.*
Treatments	5
Fertilizer	(1)
Seeding	(2)
Fertilizer x seeding	(2)
Replication	3
Replication x treatment (error)	15
Total	23

Sometimes the split plot is applied to the Latin square when equipment and treatments require relatively large plots. An illustration testing the effects of a herbicide under dry and moist conditions on eradication of six noxious plants, applied in strips and at random in split plots in a Latin square design appears:

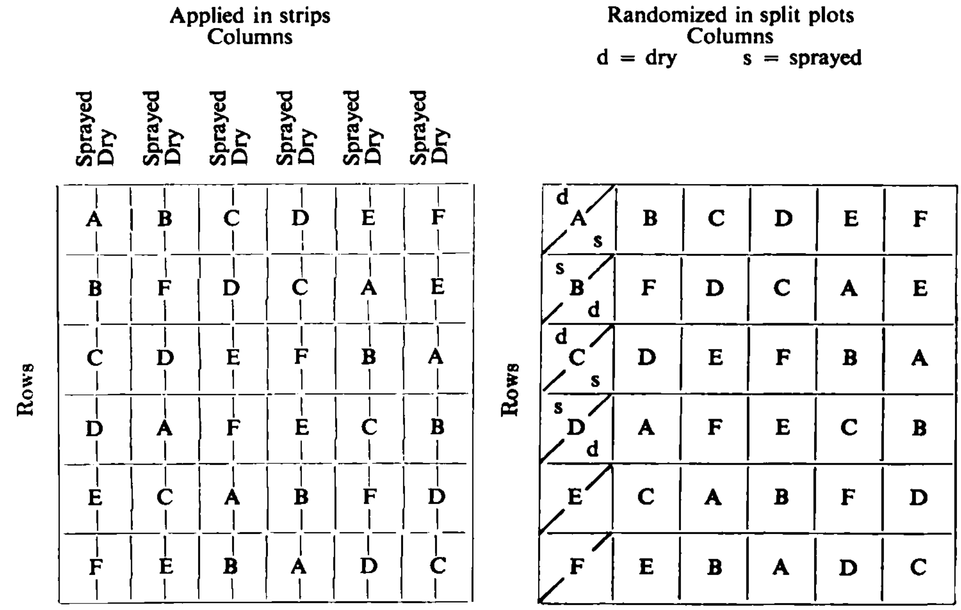

TABLE 18. Source of variation and degrees of freedom for a modified split plot where herbicide was applied wet and dry in strips on six noxious plants previously planted in a Latin square and for a standard split plot where each half of each plot was treated separately with the wet or dry application of the herbicide

Analysis when applied in strips		*Analysis when applied at random in each plot*	
Source	*D.F.*	*Source*	*D.F.*
Plants	5	Plants	5
Rows	5	Rows	5
Columns	5	Columns	5
Error (a)	20	Error (a)	20
Application (dry and moist)	1	Application (dry and moist)	1
Error (b)	10	Plants x application	5
Row x application	(5)	Row x application	5
Column x application	(5)	Column x application	5
Plants x application	5	Error (b)	20
Error (c)	20	Total	71
Total	71		

The systematic application of a factor in strips in a modified split-plot design is convenient when some treatments require large plots or an additional factor is to be applied after the plots have been laid out and the whole plot treatments have been initiated. The split-plot Latin square has the same advantages over the split-plot randomized block design as the Latin square had over randomized blocks.

Incomplete Block Designs

An increase in the number of treatments in a randomized block design is usually accompanied by an increase in the experimental error since it becomes more difficult to get uniformity within large groups of experimental material required for one complete replication. This effect is frequently alleviated by reducing the block size through confounding unimportant degrees of freedom as previously shown in a factorial experiment. When the treatments are not factorial in nature the same effect can be gained by using one of a great many incomplete block designs which have been investigated and described in recent years.

For example, one might wish to evaluate the adaptability of a large number (25 or more) of species or varieties of forage plants. In this case one of the many incomplete block designs might be used to control environmental variations within replications.

An incomplete block design is one where the blocks contain only part of the treatments. The variation between blocks is removed in a similar but more complicated way than the error control automatically afforded by the complete blocks in a randomized block design. If a large number of varieties or treatments are to be compared and all comparisons are of equal importance, then balanced incomplete blocks can be formed which provide for every variety or treatment to occur with every other variety or treatment the same number of times in a block. Balanced designs are greatly restricted as to number of units per block and number of replications. In some designs the blocks may be arranged to form complete replications. This is desirable whenever possible because the design cannot then be appreciably less efficient than a randomized block experiment.

Only a few of the more popular incomplete block designs most likely to be useful to the range technician will be reviewed here. The reader is referred to any recent book on experimental design for a complete review of the subject. If this type of design is to be used it is suggested that the basic layout, the method of randomization, and method of analysis be obtained from one of the texts listed in the references.

One group of incomplete block designs which have been widely used in agricultural experiments is known as lattice designs. With the exception of the rectangular and cubic lattices to be described later, these designs are limited to a number of treatments which form a perfect square, e.g. 16, 25, or 49. The number of units in a block is the square root of the number of treatments. For purposes of illustration a 3×3 lattice design with nine treatments will be used. In practice an experiment of this size would usually not be considered large enough to warrant the use of a lattice design.

Simple Lattice

If the key numbers for the treatment are written in the form of a square, then for a simple lattice the treatments in the rows form one set of blocks and those in columns the second set. A minimum of two replications is required and these may be repeated to provide any even number of replicates. This may be illustrated as follows:

Basic square

1	2	3
4	5	6
7	8	9

Rep.	*Block*	*Treatments*	*Rep.*	*Block*	*Treatments*
1	1	1, 2, 3	2	4	1, 4, 7
	2	4, 5, 6		5	2, 5, 8
	3	7, 8, 9		6	3, 6, 9

Triple Lattice

For a triple lattice there are three groups of different incomplete blocks. The first two are identical with those of the simple lattice and the third is obtained from the diagonals of the square as follows:

Rep.	*Block*	*Treatments*
3	7	1, 5, 9
	8	2, 6, 7
	9	3, 4, 8

A minimum of three replications is required and these may be repeated to provide any multiple of three replications.

Quadruple and Other Partially Balanced Lattice Designs

The required grouping of treatments into incomplete blocks can be obtained for any square to form simple and triple lattices. One group takes the rows of treatments, a second the columns, and the third the diagonals as indicated previously. As one considers quadruple or higher lattice designs, obtaining the groupings of incomplete blocks becomes more difficult. The problem has been studied extensively by a number of statisticians and rules can be given for writing the blocks, but they vary from square to square. For example, for all squares where p, the square root of the number of treatments, is prime or a power of a prime number, it is possible to write out $p + 1$ different groups of blocks, the last one completing a balanced set of replicates giving a balanced lattice design. A balanced set does not exist for the 6×6 square and the 10×10 has not been carried beyond 3 groups, nor the 12×12 beyond 4. The most useful arrangements that exist have been given by Cochran and Cox (1957). Where the groups exist any number of replicates for a partially balanced lattice may be used for the balanced design with $p + 1$ replicates. As a rule it is best to use the most nearly balanced design where a choice exists. For example, a quadruple lattice design is generally superior to a simple lattice with 4 replications where the 2 groups are repeated.

Balanced Lattice Designs

If sufficient replications can be employed to balance a lattice design it has several advantages over the partially balanced design, the most important of which are greater ease in summarizing the results and every treatment comparison is made with the same degree of precision. The most serious limitation is the requirement of $p + 1$ replication which for the larger squares may be excessive.

For a balanced 3×3 lattice the fourth group to be added to the 3 for the triple lattice design outlined previously is as follows:

Rep.	*Block*	*Treatments*
4	10	3, 5, 7
	11	2, 4, 9
	12	1, 6, 8

If one reviews the 4 replications $(p + 1)$ of the 3×3 square used to illustrate the principle of lattice designs, he will find that treatment 1 occurs with 2 in block 1, 3 in block 1, 4 in block 4, 5 in block 7, 6 in block 12, 7 in block 4, 8 in block 12, and finally with treatment 9 in block 7. It never occurs with any treatment more than once in the same block. This is an important property of all balanced incomplete blocks, namely, that every treatment occurs an equal number of times with every other treatment in a block. In the example given each treatment occurred once with every other treatment. With other balanced incomplete block designs the integer might be 2, or 3, etc., although the number of replications is likely to be excessive.

Rectangular Lattice Designs

Another group of designs which adds to the assortment of designs available for testing large number of treatments is the rectangular lattice. With the ordinary lattice designs discussed previously the number of treatments must form a perfect square, whereas with the rectangular lattice the number of treatments must be the product of 2 adjacent integers $p(p + 1)$, e.g. 5×6, 6×7, 7×8. A simple rectangular lattice may be used with 2 replications or a triple rectangular lattice with 3 replications. Each of the basic designs may be repeated for greater replication.

The rectangular lattices are handled in about the same way as other lattice designs. The summary of results is somewhat more complicated. The reader is referred to Cochran and Cox (1957) for a complete description on methods of anlysis for these designs.

Cubic Lattice Designs

When the number of treatments, varieties, or species to be evaluated becomes extremely large, or where blocks of uniform experimental material are small, a cubic lattice may prove advantageous. In this design the number of treatments must form a perfect cube and the size of the incomplete block is the cube root of the total number of treatments. Suppose that one wishes to compare the effect of 27 chemical compounds on the leaves of a plant and that only 3 comparable leaves are available on each plant. In this case one might use a cubic lattice with 9 plants of 3 leaves each to evaluate the 27 compounds. The cubic lattices must have 3 or some multiple of 3 replications. For a description and method of analysis of these designs see Cochran and Cox (1957).

Other Designs

The incomplete block designs reviewed here are comparable to randomized complete block designs in that they control variation in one direction or from one source only. There are a great many incomplete block designs which, like the Latin square, will control two sources of variation. These are known as lattice squares and incomplete Latin squares. The reader is referred to Cochran and Cox (1957) for a review of these designs.

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Chapter 11

Problems Involved in the Application of Research Techniques in Range Management

Introduction

THIS CHAPTER discusses some of the problems and variables the investigator encounters in conducting each of several phases of range research: range seeding, fertilization, brush and weed control, experimental grazing, management of big game ranges, and use of fire as a range improvement measure. Of the many methods, statistical techniques, and concepts described in the preceding chapters, some are more suited to certain problems than are others. Also, there are variables not readily apparent to one unfamiliar with some of the problems encountered when conducting research. Proper evaluation of these at the start is essential to the research program.

Range Seeding Research

Research in range seeding is intended to solve problems encountered when revegetating the range on a large scale by seeding to grass, legumes, or other plants. Such seeding may be for the purpose of reestablishing a vegetation on depleted range that cannot be improved through management alone, of reestablishing certain kinds of plants on the range, or of introducing some new species to fill a certain need. Increasing quantity or quality of forage, increasing browse on game ranges, and erosion control are examples of reasons for seeding.

Techniques used in range seeding research include those used in both ecological and agronomic research. However, variability of stand and yield resulting from geologic, climatic, and biotic influences on rangelands usually exceeds that encountered on irrigated land. Remnants of original cover are usually present. These make necessary the use of larger plots or more replications than are generally employed in agronomic research.

The main biological problems of range seeding are (1) evaluating range sites as to quality for and need of seeding; (2) finding species and varieties that establish readily and yield a satisfactory volume and quality of herbage on available sites over a long period and are adapted to needed uses; (3) preparing the land for seeding; (4) assuring good quality seed; (5) planting proper amounts of seed and at the optimum season; (6) establishing uniform stands of optimum density; and (7) managing seeded stands for maximum, dependable production (Plummer *et al.* 1955, Hull and Johnson 1955, Cornelius and Talbot 1955, Lavin and Springfield 1955).

Adaptation to Site and Use

The species alone is no longer an adequate basis for seeking better adapted plants for range seeding. As more ecotypes are recognized and tested and as plant breeders develop new strains and varieties, continuing work on adaptation to site and use is needed. Strain selections within a species or variety often differ as much in their relative adaptability to differences in sites and productiveness as do many species and varieties.

The researcher will find innumerable species, varieties, and strains to

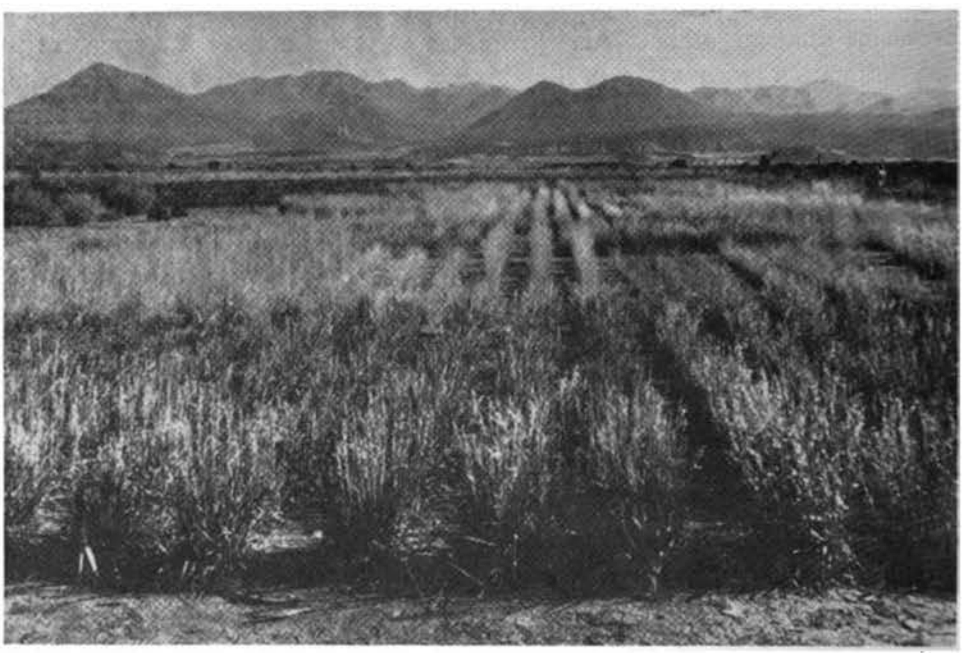

FIGURE 1. Row trials to determine adaptability of grass and legume plants to climatic zone. In these trials each species was planted in 3 rows and on different sites. The center of the 3 rows is the only one observed since the 2 outside rows are subjected to interspecies competition. *(U.S. Forest Service photo)*

test under any set of growth conditions of interest. Many new accessions can be eliminated by field trials, simply on the basis of genetic makeup or source. Others that appear worth field testing may be eliminated quickly as a result of screening tests conducted in clean cultivated nurseries (figure 1). Caution must be used in screening tests because slow-starting plants rejected in the first or second year might have just begun to show their worth after several years when quicker starting kinds are beginning to decline (Hull 1954).

Plant vigor as measured by seed or forage yield may be a better indicator of adaptation than number of plants established in a given trial. Poor stands may reflect faulty planting methods or other correctable factors. However, ease of establishment is an important consideration. After preliminary testing, relative yields from a smaller group of plants may be desirable. Replicated plots of rows 12 to 20 feet long are useful for this purpose.

Once the plant demonstrates satisfactory site relationships, ability to maintain itself and nourish livestock under various seasons and intensities of utilization should be tested. An important trait is competitiveness or ability to prevent the return of the original unwanted species or invasion by new ones under moderate to heavy grazing (figure 2).

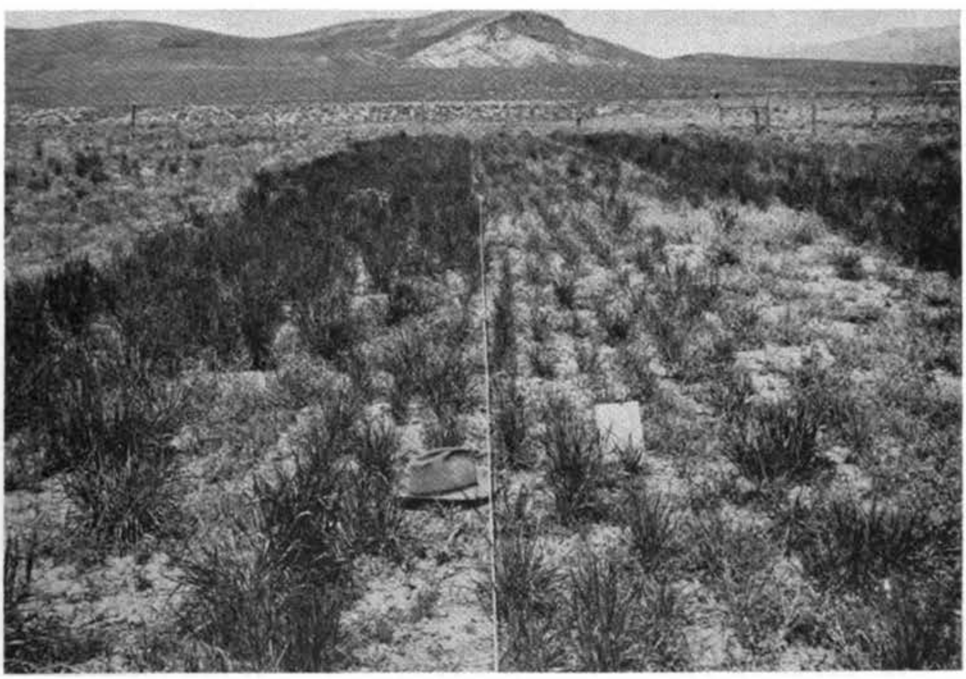

FIGURE 2. Field trials where several species can be tested, using project scale equipment, and allowed to compete with native vegetation. On this site each species was planted in 2 plots each 12 feet wide (width of the drill) and 60 feet long. *(U.S. Forest Service photo)*

FIGURE 3. Four kinds of equipment commonly used on rough rangelands: *A*, heavy offset disc; *B*, brushland plow especially adapted to brushy and rocky terrain; *C*, beater used for reducing short stiff brush; and *D*, rail used to remove sagebrush. *(A, B. and D, U.S. Forest Service photos, and C, courtesy of the Caterpillar Tractor Company)*


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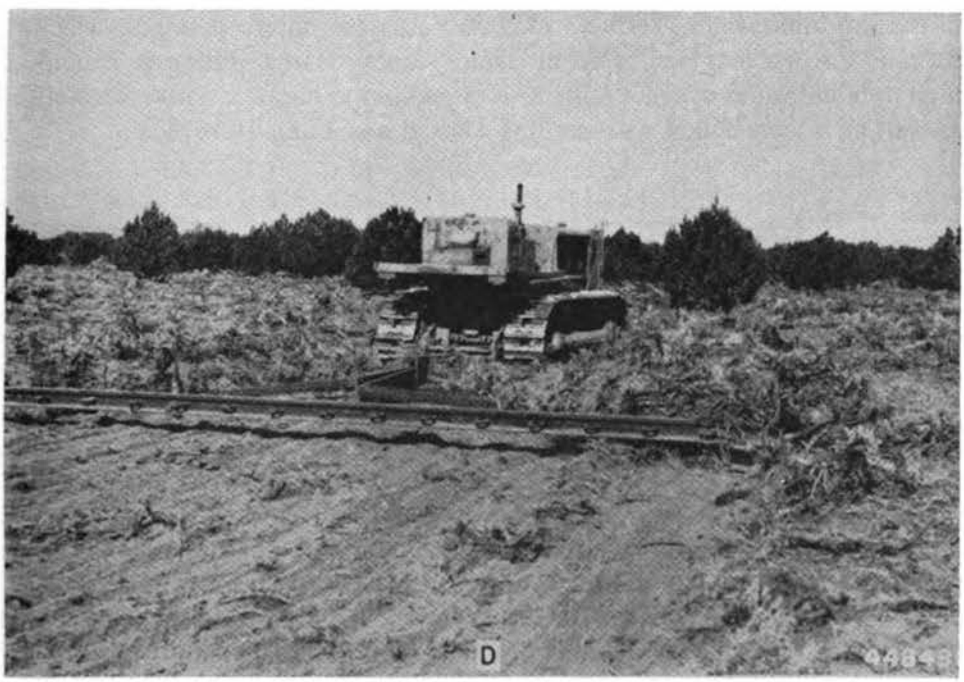
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Land Preparation

Land preparation is usually for the purpose of preparing a suitable seedbed and to reduce existing plants that may compete with the seeded species. Characteristics of the soil and plant cover will govern the choice of tools for land preparation. Soils may be rough or rocky, precluding use of ordinary farm tillage equipment. Specialized equipment adapted to range conditions has been developed (U.S. Forest Service 1957) (figure 3). Unwanted species such as big sagebrush *(Artemisia tridentata* Nutt.), rabbitbrush *(Chrysothamnus* spp.), or tarweed *(Madia* spp.) may be present and must be killed to remove competition before seeding (Pechanec *et al.* 1954). Sandy soils should not be exposed to wind erosion, nor steep slopes to erosion by runoff water. Control burning, treatment with herbicides, beating, dragging, or various methods of tillage may be used. For example, beating, dragging, and fire are usually ineffective against crown-sprouting species of rabbitbrush and horsebrush *(Tetradymia* spp.). On the other hand, such methods may serve well to reduce nonsprouting species and provide excellent land preparation under certain conditions. Many annual forbs may be reduced by early spring tillage (Stevenson 1950). The first step in many situations will involve experiments dealing with methods of eliminating these undesirable plants. Information on designing such experiments is presented in this chapter under "Control of Brush and Weeds."

Land preparation for erosion control is aimed at retaining water and increasing infiltration. Terraces may be necessary on steep slopes, whereas contour furrows may suffice on moderate slopes. Range pitting is a method used to retain water where it falls. It is often used to improve native vegetation as well as in connection with seeding (Rauzi and Lang 1956).

Seed Quality

An adequate, uniform stand quickly established with the minimum rate of seeding is desirable. Seeds of native shrubs, weeds, and some of the grasses present troublesome peculiarities in seeding such as size, dormancy, and appendages. Certain species that germinate well in the spring after fall planting will not germinate for a full year after spring planting. Others with high viability soon after harvest are known to lose viability rapidly in dry storage. Still others are unable to germinate when fresh but improve gradually over a period of 10 years or more. Seeds of native plants which neither germinate nor mold after several days in the germinator probably require some type of stratification to induce germination, such as temperature treatment, chemical or mechanical scarification, or leaching (U.S. Production and Marketing Administration 1952 and U.S. Forest Service 1948).

Seeds of species known to have none of these peculiarities should germinate well when fresh. Should it be necessary to use older seed with low viability, the percentage germination should be determined shortly before planting and used to calculate the adjusted rate of sowing to seed the desired amount of viable seed (table 1).

Seeds of many species deteriorate gradually in the soil from time of planting until conditions of temperature and moisture are right for germination. The time and rate of such decline in viability may be studied by placing seed in porous bags in the soil at usual seeding depths. Pairs of bags are removed at intervals for examination and germination tests.

In research it is important to know the source and genetics of the seed. Mounted specimens should be deposited in a permanent collection to provide identification reference.

The need for treating seed to prevent damping-off or other diseases and for inoculating legumes should not be overlooked.

TABLE 1. Conversion factors for determining number of pounds of sack-run seed to sow per acre*

Purity per cent	*Per cent germination* 50	55	60	65	70	75	80	85	90	95	100
50	4.00	3.64	3.33	3.07	2.86	2.66	2.50	2.35	2.22	2.10	2.00
55	3.64	3.30	3.03	2.80	2.59	2.43	2.27	2.14	2.02	1.92	1.82
60	3.33	3.03	2.78	2.56	2.38	2.22	2.08	1.96	1.85	1.76	1.67
65	3.07	2.80	2.56	2.37	2.20	2.05	1.93	1.81	1.71	1.63	1.54
70	2.86	2.59	2.38	2.20	2.04	1.90	1.79	1.68	1.59	1.50	1.43
75	2.66	2.43	2.22	2.05	1.90	1.78	1.67	1.57	1.49	1.40	1.33
80	2.50	2.27	2.08	1.93	1.79	1.67	1.56	1.47	1.39	1.32	1.25
85	2.35	2.14	1.96	1.81	1.68	1.57	1.47	1.38	1.31	1.24	1.18
90	2.22	2.02	1.85	1.71	1.59	1.49	1.39	1.31	1.23	1.17	1.11
95	2.10	1.92	1.76	1.63	1.50	1.40	1.32	1.24	1.17	1.11	1.05
100	2.00	1.82	1.67	1.54	1.43	1.33	1.25	1.18	1.11	1.05	1.00

* Source: Figure 1 from Converting standard seeding rates for grasses to actual seeding rates per acre, by Joseph F. Pechanec. U.S. Forest Service. Pacific Northwest Forest and Range Experiment Station. Research note 67. 1950. Portland, Oregon.

Evaluation of Stand Establishment

Measurement of stand establishment of perennial plants seeded on semiarid range is best commenced toward the end of the second growing season. In some cases where annual plants are thick it may be desirable to evaluate the stand early in the growing season. Only tentative data can be obtained the first season because the seedlings have not been subjected to the stresses of winter. Grass seedlings sometimes go into drought dormancy during the first summer after planting, and appear to be dead.

Relative establishment on different sites, or by different species or strains, or at different fertility levels, planting dates, planting depths, or seed treatments may be studied individually, or together in a larger experiment. Where information on the combined influence of several factors upon establishment is needed, a factorial design is more desirable than two or three simpler experiments dealing with the principal factors separately. However, physical limitations inherent in certain methods may restrict the free assignment of treatments. For example, the relation of normal rodent or insect populations to stand establishment may require study. Methods of rodent exclusion or use of insecticides are not as applicable to subplots as are planting dates or fertility levels.

Establishment on row plots is often expressed as number of plants per foot of row. Survival as a percentage of emerged seedlings, and emergence as a percentage of live seed planted are useful expressions. However, these percentages should be accompanied by information on causes of mortality. Seedlings, as they emerge, may be marked to show the period of appearance. Painted wire stakes have been used, a different color for each emergence date. Subsequent weekly observations until the dormant period will help reveal the relative importance of insects, erosion, birds, and drought, or other causes of mortality.

Stand evaluation on large areas may be done by temporary plots. Results are expressible in either plants per square foot or percentage frequency. Either will provide comparative data if the same size plot is used on all areas. Belt transects 1 foot wide and long enough across the drill rows to include 100 plants can be read rapidly because one can count the plants, then pace back to the starting point. With reasonable care in counting and pacing, the number of plants per square foot can be estimated reliably.

Two difficulties arise in use of the plant count method in studying bunchgrasses. Plants in drilled rows tend to merge by the second or third year, making the identification of individual plants difficult. When bunchgrasses eventually pass their prime, the crowns break into small remnants and plant counts have little meaning. The stem count method is best for erect sodgrasses which have begun to propagate vegetatively. Mat-forming grasses may be measured as number of tufts or as percentage cover. Cover becomes more useful as a measure as the percentage increases.

Estimates of relative success can be used to compare seeded stands of different grasses. Such estimates are unavoidably subjective but are guided by consideration of (1) plant numbers per unit area, (2) distribution of individuals, (3) knowledge of potential requirements or demands upon the habitat by each species, and (4) apparent vigor (Hull 1954). The success ratings may be made on a 5- or 10-point scale and are less reliable for rating seedlings than for older stands. A maximum rating should indicate that the seeded species is fully monopolizing the immediate habitat to the exclusion of other plants, or that it shows every promise of doing so.

Site Evaluation

Much has yet to be learned about classifying range sites with respect to their potential for seeding.

Owing to the relatively small number of weather stations in the West, site classification sometimes must proceed without the benefit of complete climatic data, i.e., on the basis of geologic and biotic measurements. These measurements may be applied in either of two ways in approaching the problems of site evaluation.

An approach is to find numerous good stands of the seeded species throughout a certain environmental range. Such a range might correspond to that of a major dominant or indicator species. Average yields of the seeded species at each location would be correlated with soil and cover measurements. Soil depth, organic matter content of the topsoil, elevation, latitude, cover density, height of plants, and the presence of certain species are examples of site characteristics whose variability may be found by correlation analysis to be associated with variations in yield of the seeded species (Miller 1956). The magnitudes of the standard partial regression coefficients will indicate the relative importance of each site characteristic in estimating the capabilities of ranges (Major 1951 and Snedecor 1956).

A more general approach is to prepare a range site-type classification based upon expression of soil and native vegetation. The same geologic and biotic features are described, but not necessarily quantitatively. These features are used as key characters in distinguishing site-types. Average yields of good stands of seeded species on the various classified site-types are determined. Similar yields of the same seeded species may be expected on the same site-types wherever they occur. Likewise, success of establishment should be similar.

In problem areas seeding experiments should be accompanied by tests of fertilizers, soil conditioners, mulches, rock dams, and other mechanical treatments until the best combination of practices is found for the particular site.

Range Fertilization

Techniques and designs for determining the effects of applying fertilizers on rangelands are similar in many respects to agronomic principles applicable for evaluating crop responses to fertilization, particularly of nonirrigated perennial forages. Studies on rangeland usually must be of longer duration because of frequently greater variation in precipitation and other environmental factors.

In range studies the addition of fertilizers might be expected to increase total herbage yield, nutrient yield, forage quality, palatability, and vigor of the species inhabiting the area. Floral compositions also may be altered. Ultimate effects might be expected to influence the grazing capacity, yield of animal products, the capacity of the plant cover to resist erosion, and the profitableness of a ranching enterprise.

Artificial rehabilitation of ranges may include fertilization along with seeding. In this case it would be desirable to determine the influence of various fertilizer treatments—kinds, rates, dates of application and placement—upon the establishment of seeded species compared to the increase of resident plants on the same area.

In all fertilization trials it is important to evaluate the effects of various levels of an applied nutrient as fertilizer. Therefore, it is necessary to use a rather wide range of application rates to determine optimum or maximum responses consistent with expected or determined economic returns.

Most fertilizer investigations commence with the suspicion or recognition of a need for the addition of fertilizers or soil amendments. A knowledge of soils or geological formations may point up inherent deficiencies. Cropping experience on particular soil types may suggest a need for fertilizers. Nutrient deficiency symptoms in livestock may also be suggestive of certain needs.

Before expensive field trials are undertaken, greenhouse pot tests may be conducted to determine what fertilizer constituents might produce plant responses on a particular soil. Such tests may indicate the various levels of the fertilizers which would be most appropriate in the field trials. Many soils can be tested with several fertilizers in the greenhouse in a relatively short period of time, thereby pointing out the fertilizers which should be tested in the field.

A combination of greenhouse pot tests followed by field plot trials is a suggested approach when little is known about the expected plant responses from various fertilizers.

Pilot trials may also be employed to explore the need for testing certain fertilizers in more intensive field plot investigations. Such trials may first be made using single fertilizers at various levels. It is advisable to choose fertilizers which will supply a single fertilizer nutrient to avoid complementary or other effects which might be incorrectly interpreted in planning more intensive future studies.

Since some fertilizer constituents are complementary to others when added in certain proportions, it is essential to determine the proper combination of constituents and the appropriate level of each. Therefore, a factorial design is generally used.

If, for example, it were suspected that application of nitrogen and phosphorous would increase the yields and quality of forage and it was desired to study these influences and determine the proper levels of each when applied together, a simple factorial design would be appropriate. In this case three levels of each nutrient might be used such as: phosphorus at 0, 40, and 80 pounds per acre, and nitrogen at 0, 30, and 60 pounds per acre. If these were to be applied in a factorial design, we would have a total of nine treatments as follows:

P_0	P_{40}	P_{80}
N_0, N_{30}, N_{60}	N_0, N_{30}, N_{60}	N_0, N_{30}, N_{60}

These nine treatments could be applied in a randomized block including any number of replications on any number of sites or locations.

This particular example is comparatively simple but could be expanded to include more levels and more fertilizer nutrients.

Season, soil type, soil moisture, and carryover effects of the fertilizer treatment from year to year are as important as the fertilizers. They must be included in the study as main effects, or evaluated in a suitable manner properly to determine their influence upon range fertilization responses and economics. In semiarid rangelands the residual effects of an initial fertilization may last 2 or 3 years and the cost of application may be so great that it may be feasible only to apply fertilizers every third year instead of annually. Methods of applying fertilizers and the placement of nutrients where they may be readily available are problems deserving more critical study.

The simpler experimental plot designs, such as the randomized complete block, split-plot, or Latin square, are suggested for initial field plot testing. As space becomes more critical with more intensive testing, incomplete block and lattice designs may prove to be more efficient. On all areas, but especially on slopes, care must be taken to leave an adequate untreated buffer strip between plots which receive fertilizer treatments. This is necessary to avoid contaminating effects of runoff water. Protective border ridges or dikes may be essential where plots are irrigated or are subject to flood hazards.

Range fertilization is a relatively new tool for managing and improving rangelands. Consequently, the techniques are not well developed. While agronomic practices developed from investigations in dryland agriculture may serve as a guide for fertilization trials on rangelands, it is to be expected that many adaptations will need to be made by range scientists.

Control of Brush and Weeds

Research on brush and weed control involves many problems common to other types of range research but some quite different. Since the weeds and brush involved in range research are natural stands, the location where they are found and the conditions that prevail impose limitations on the size and design of experiments. Usually the researcher must go where the weeds are and accept the condition he finds. Selection of suitable areas or plant populations to fill the requirements of the experiment is of prime importance but may be difficult. Often the experiment will need to be planned or revised to fit the stand of brush or weeds available and the conditions that exist.

Most studies in brush and weed control involve use of herbicides. This introduces a number of problems in designing experiments, in equipment and techniques to provide controlled rates of application under highly variable conditions, and for minimizing spray drift from treated plots by wind.

In general, the information on statistical methods and experimental designs presented in chapters 8 and 9 applies to experiments on control of brush and range weeds.

Relation of Objectives to Experimental Design

Many different factors affect the size and design of brush and weed control experiments. Usually the variables of species, chemicals, application rates, and dates of application are involved. Others may be carriers, volumes, and spray droplet size. It is easy to include too many variables in one experiment. Since one usually cannot study reasonably the effects of all variables in one experiment, he must clearly define the objectives, pinpointing the variables of primary interest. Experiments designed to answer a multitude of questions usually yield limited information on any specific point.

The researcher must first decide how small a difference he is interested in and how many replications will be necessary to measure this difference. If the study is merely exploratory and the expected differences large, a completely randomized design with two or three repetitions of each treatment usually will be sufficient (Bohmont 1952, Hurd 1955). If several factors such as chemicals, rates, and date of application are studied in all combinations in one experiment, a much larger experiment must be designed and a randomized complete block or an incomplete block design probably would be the most suitable (Hyder 1953, Klingman and McCarty 1958). If a factorial combination is included in the experiment the main effects of each factor can be separated and the interactions studied. Factorial combinations should be included if it is known, suspected, or even questioned that the action of the variables may be interdependent (Hyder and Sneva 1955). However, if it is known that the interaction of two variables is of no importance, an incomplete factorial with respect to these two factors may be considered to reduce the number of treatments (Alley 1956, Robocker *et al.* 1958). Usually it is best not to include more than three variables in one experiment. If more are involved, companion experiments should be used to test them in groups of two or three (Hyder and Sneva 1955). Usually three replications of each treatment are sufficient for an experiment that is analyzed factorially.

When deciding objectives of an experiment, the researcher should consider the type of inference which is to be made from the results or the area where the information will be applied. If the results are to have general applicability, for example, the optimum date for applying 2,4-D on sagebrush in Wyoming, then the different altitudes, moisture situations, seasons, and other aspects must be sampled. These environments may be represented by experiments conducted in different years, experiments conducted at different locations, altitudes, or sites, or a combination of these. For such experiments, two or three replications per experimental site or year would be sufficient.

On the other hand, if it is desired to make a critical evaluation of one or two factors at two or more levels, such as the optimum rates of one or two promising herbicides, extreme care is necessary in designing and locating the experiment. A more uniform stand of brush or weeds, more replications, and more refined techniques are required to measure small differences for treatment effect.

In many instances weed or brush control is only one facet of an overall range study. The effect of various management measures upon revegetation following weed control is of primary importance. Where such a program is planned, it may be possible to compare all variables in a randomized complete block design but often it may be more convenient to use a split-plot design where use of large equipment, differential grazing practices, or some other consideration requires large plots (Alley 1956, Klingman and McCarty 1958). Where possible the main effects of the study should involve the factor on which the most information is known or which is expected to yield the largest differences, while the subplots should involve those factors about which little information is available or upon which a more critical evaluation is needed.

Effect of Plant Factors

The nature and size of the infestation often will limit or dictate the size and design of the experiment. In the study of some herbaceous perennial range weeds such as larkspur, lupine, and death camas, infestations usually are small, spotted, and limited to areas where moisture and soil conditions are most favorable. In such situations, several distant locations may be used as blocks and each block contain all treatments. It may be desirable to include several untreated checks in each block and use an incomplete block design. This is especially desirable where all treatments are to be compared with untreated observations. Small stands are best suited to small plots and hand methods or small-scale chemical or mechanical treatments with motorized equipment rather than airplane or large-scale ground-rig applications.

Infestations of annual range weeds may be on either small or large areas and in either relatively pure stands or interspersed among brush and other perennial range vegetation. Considerable variation may be found from year to year in density of stand, plant vigor, and other characteristics. These factors should be considered in planning experiments and interpreting data on annual weed infestations. Repeated experiments in successive or different years may be necessary to measure the effcts of varying seasonal conditions.

Brush infestations such as sagebrush, mesquite, or oak usually are extensive but frequently are highly variable in density of stand, age, and size of plants. In brush control experiments involving large area treatments by airplane or ground-rig equipment, individual plots should be large enough to provide for efficient operation of the equipment and inclusion of variation in stands. On the other hand, they should be small enough to avoid introducing other undesired variables such as other species of brush and differences in topography or soil. The number of variables that can be compared and the number of replications that can be included without exceeding the area of uniform plant population and growth conditions available are limited (Hyder and Sneva 1955). In large plots the variations in size, density of stand, and age of plant can be controlled by basing the measurements on individual plants within each plot selected for uniformity in the desired characteristics or by stratifying the population.

When working with brush or tree species such as mesquite and oak, in exploratory experiments, or in critical experiments involving a large number of treatments, it may be best to treat individual plants over an area with conditions as uniform as possible (Cable 1957, Leonard 1957, Tschirley 1956). This may be true of either basal or foliage chemical applications, if the individual plants are sufficiently far apart to prevent the treated plants or untreated check plants from being affected by another treatment. It is best to consider each plant as a treatment replication and select the plants for each treatment at random within each of the replicate areas or blocks. For exploratory studies 5 to 10 individual plants or replications of each treatment may be sufficient but for critical studies intended to measure small differences 30 or more plants in 10 or more replicated plots may be necessary.

Effect of Site Factors

The high degree of variation in soils and topography of rangeland has a definite influence on brush and weed control experiments. Two approaches may be adopted. One would be to limit the size and scope of the experiment to include only one environment such as a south slope or a shallow soil. Another would be to sample a large number of environments so that a generalized conclusion might be drawn.

Effect of Size of the Experiment on the Design

The researcher should choose the simplest design which will efficiently control variability and yield the information desired. If only two treatments are involved, such as two rates of one herbicide, a simple comparison of paired plots may suffice (Offord 1931). In experiments that have only 3 to 6 treatments involving several levels of only 1 factor, a Latin square design may be best if a 2-way classification of variability is present such that a significant reduction in the magnitude of experimental error can be attributed to both the row and column restrictions. However, the Latin square design should not be used if a simple randomized block design will adequately control the variability. Where an experiment includes 7 to 25 treatments and a study of 1 to 3 variables at several levels, a randomized complete block design usually is best. Where a large number of treatments or large plots make it impossible to maintain suitable homogeneity of stand and age of weeds, soil type, slope, or topography within each replicate block, an incomplete block design will give better control of variability (Hyder *et al.* 1958).

When studying 2 or more variables at 2 or more levels in an experiment, for example, 3 different chemicals, each at 3 rates, in 3 different volumes of spray, the selection of treatments based on the factorial principle yields highly desirable information since it is possible to separate the effects of the variables and to study the interactions between the variables. However, the number of treatments and amount of land required for a complete factorial are often prohibitive in experiments on range weeds, especially brush species. Where this situation prevails, a simpler experiment should be designed in which each factor is varied at an optimum level of the remaining factors. For example, the factorial experiment referred to above could be reduced from 27 treatments to 15 by omitting the volume comparison at 2 of the rates of all 3 chemicals or at all rates for 2 chemicals. These possibilities are shown in the following 3 designs:

Rate pounds per acre	*2,4-D ester*			*2,4,5-T ester*			*2,4-D amine*		
	Volume of spray, gallons per acre			*Volume of spray, gallons per acre*			*Volume of spray, gallons per acre*		
	3	*5*	*7*	*3*	*5*	*7*	*3*	*5*	*7*
A. *Complete factorial—permitting study of factors and interactions*									
1	3	5	7	3	5	7	3	5	7
2	3	5	7	3	5	7	3	5	7
3	3	5	7	3	5	7	3	5	7
B. *Nonfactorial—permitting study of factors only*									
1		5			5			5	
2	3	5	7	3	5	7	3	5	7
3		5			5			5	
C. *Nonfactorial—permitting study of factors only*									
1	3	5	7		5			5	
2	3	5	7		5			5	
3	3	5	7		5			5	

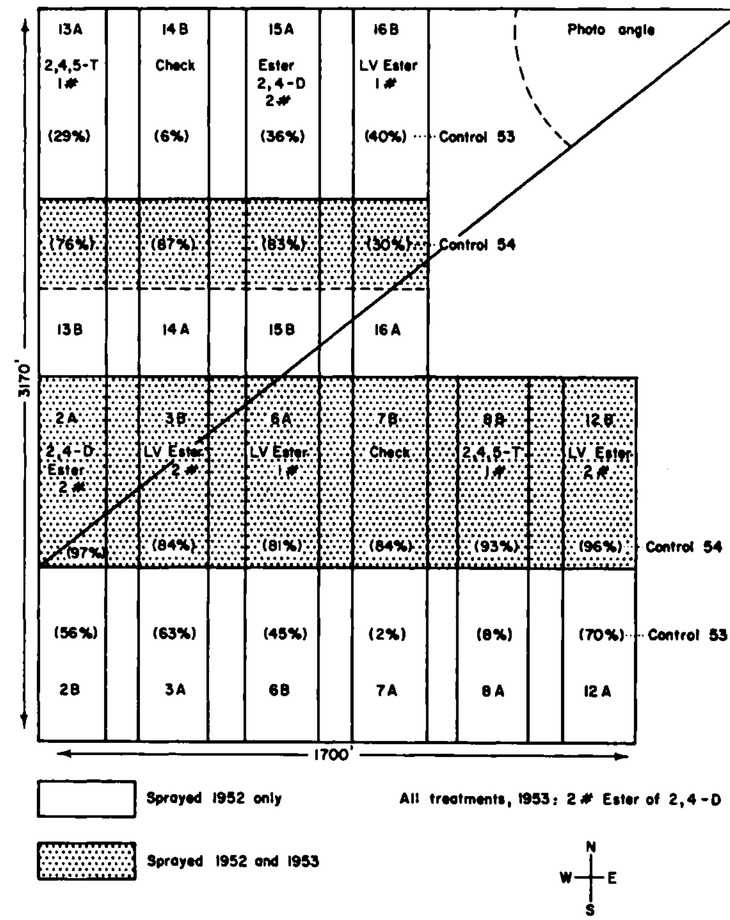


FIGURE 4. A sketch of an airplane spraying experiment on sagebrush in Wyoming which was reduced in number of treatments and size due to boundary fences on the west and south sides and a mountain on the northeast corner. A split plot design was used. The main plots (2, 3, . . . to 16) were 785 feet by 200 feet with 100-foot unsprayed buffer strips. All main plots (both parts A and B) except checks were sprayed in 1952 with different treatments as indicated while part of each main plot (A or B) including checks and buffer strips was sprayed across all plots in 1953 using the ester of 2,4-D at 2 pounds per acre. The percent control observed in 1953 after only one spray application (none on the check) in 1952 and the percent control observed in 1954 after the second application in 1953 (first on check plots) are shown enclosed in parentheses.

An example of a reduction in number of treatments and size of an experiment from the tentative plan to the treatments of greatest interest due to unsuitable topography and the restricted area of suitable sagebrush available is shown in figure 4 (Alley 1956). Both the size and layout of the experiment were adjusted to fit the range conditions which prevailed. In

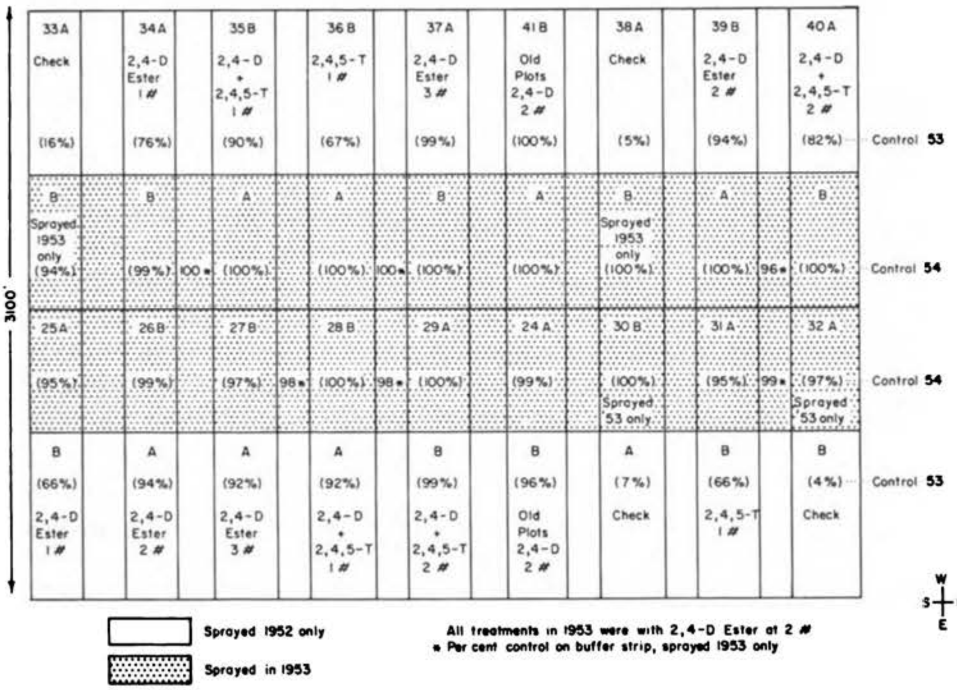


FIGURE 5. A sketch of an experiment on airplane applications of herbicides on sagebrush showing a split plot design. The main plots (Nos. 25, 26, . . . 40) were 775 feet by 200 feet with 100-foot buffer strips between plots. All main plots (both parts A and B) except the checks and old plots were sprayed with different treatments in 1952 as indicated while the subplot of each main plot (A or B) including checks and buffer strips, was sprayed across all plots in 1953 using the 2,4-D ester at 2 pounds per acre. No observations of results were made closer than 100 feet from the ends of the main plots in order to avoid the areas where spray applications may have lacked uniformity.

figure 5 the area was limited which required the omission of some treatments but no topographical difficulties were encountered.

Plot Size and Shape

For a given experiment the size and shape of plots will necessarily be controlled by (1) the size of the overall infestation where the experiment will be located, and (2) the size of the machinery or equipment used.

For Hand Spraying

The compressed air sprayer is commonly used in weed control research (Bohmont 1952, Cable 1957, and Hurd 1955). The size of the plots treated should be relatively small and usually conveniently measured as square rods.

For screening of materials it is suggested that 4 by 8 feet be a minimum size for a trial involving a rather uniform stand of weeds. If the stand is sparse, a rod-square plot or multiple thereof may be used for preliminary trials.

For Motorized Ground-Rig Spraying

In extending the evaluation trials and other treatments to a more practical field basis, sprayers mounted on jeeps, tractors, or trucks are used (figure 6). Under such conditions it is suggested that a convenient plot size would be 16½ feet wide by 100 feet long. The inherent difficulty of starting at the starting point and stopping immediately at the termination point should be recognized. Therefore, measurements of treatment effects should exclude a portion on both ends of the treated plot (Hyder *et al.* 1958). The plots should be long enough to permit excluding 0.5 to 1 rod on each end and still provide sufficient area for measuring results. An area of 1/40 acre should be adequate for studying poisonous plants, sagebrush, and similar low-growing species with uniform stands.

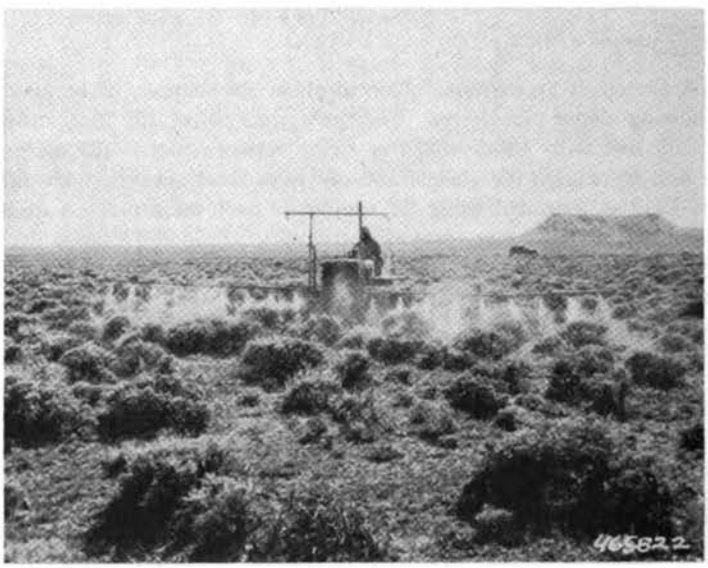


FIGURE 6. A tractor-mounted ground sprayer that is suitable for large-scale experiments on annual, perennial, and low-growing brush species. (*U.S. Forest Service photo*)

For Mechanical Methods

Mechanical methods of control are also used in experiments on control of range brush and weeds. Plots for treatments involving mowers or tillage machinery probably should not be smaller than 0.5 to 1.0 acre in size (Klingman and McCarty 1958). The width of the equipment will determine the size of the plot, but a suggested size is 100 feet wide by 435 feet long. A buffer strip of 12 to 20 feet should be left around the experiment to allow for access roads and maneuvering of machinery.

For Airplane Spraying

The airplane is especially suitable for the control of brush (figure 7). For experiments using airplane spraying the area should be readily accessible by air with no serious obstructions for the pilot in maneuvering over the experimental area. Level terrain is best. The width of the treatment plot will depend upon the equipment and the kind of plant (figure 8). Most planes currently used for experimental applications have a swath of 25 to 50 feet. A 50-foot swath is the extreme limit which should be considered for a single engine airplane in research work. A 33-foot swath is most common.

Air currents will affect the distribution of spray; therefore, an untreated buffer strip 50 to 100 feet wide should be included on both sides of each plot (Alley 1956, Kissinger *et al.* 1952, Robocker *et al.* 1958). The wider strip should be used when spray drift is expected to be greater due to greater height of spraying or to higher velocity crosswinds. Increasing the width of sprayed plots does not correct for lack of uniformity of application due to spray drift. Airplane spraying on experiments should be done when there is no wind, if possible, and should be avoided when wind velocity exceeds 5 miles per hour.

The length of the plot should be sufficient to allow the pilot to apply the material under field conditions the same as for nonexperimental spraying. A minimum length should be 500 to 750 feet. The maximum should not be over 1,000 to 1,500 feet. Longer plots make flagging difficult and increase the expense. The best width of plot is from 2 to 5 swaths wide, or 50 feet wide as a minimum for herbaceous weeds and low brush to 250 feet as a maximum treatment for tall brush such as mesquite.

In applying the chemical, two flagmen should be employed for each replicate block, one at the beginning of the plot and the other at the end. Each should carry a bamboo pole with 3 colored (yellow, white, and red) flags on the end. This combination will allow the pilot good visibility in lining up, regardless of the background.

Methods of Sampling to Measure Results

The methods of studying vegetation discussed in chapter 3 may be applied in a general way to measuring the results of brush- and weed-control experiments. The choice of sampling techniques may depend upon (1) the nature of weed involved, (2) the number of species being studied in one experiment, (3) the density of stand, (4) the size of plot, and (5) the degree

FIGURE 7. An experimental airplane application of an herbicide spray in early morning when there was no wind. Note the uniform spray pattern and absence of spray drift. Both are essential in experimental applications. *(U.S. Forest Service photo)*

FIGURE 8. A portion of the experiment shown in figure 5. The strips of living sagebrush in the area sprayed are due to lack of complete spray coverage. The spray swath width of 50 feet should have been reduced to about 33 feet for the small plane used. *(Wyoming Agricultural Experiment Station photo)*

of refinement in the experiment and the necessity for reducing sampling error within each plot. Other considerations are where to locate the samples within each plot and when, following the treatments, the data should be obtained.

Visual Estimates

The most rapid and simple method of measuring experimental results is by visual estimates of percent defoliation, percent topkill, percent plant kill, and/or amount of regrowth (Hurd 1955, Offord 1931). When properly used, this method is sufficiently accurate to measure large differences from experiments where the control of only one species is being studied. This method is subject to errors from personal bias and inexperience of the investigator. Such errors can be reduced by having three or more experienced men make independent estimates in each plot. An average of all estimates gives the evaluation of each plot. Since visual estimates are based on size and vigor as well as the number of surviving plants, the estimates should be made before recovery and excessive growth of surviving plants begin to mask the actual number of plants that survived. When estimates of effects of treatments on perennial species are made in successive years, the estimates should be made at the same stage of growth.

Plant Counts

Counts of living plants before and after treatment give a more accurate measurement than visual estimates and should be used in critical experiments where small differences are important or when the effects on more than one species are being studied (Alley 1956, Cable 1957, Hyder 1953). Usually it is desirable to make plant counts in untreated plots each time they are made in treated plots, in order to measure the effect of factors other than treatments. The sample areas may consist of quadrats or belt transects located permanently or selected at random within each plot each time the results are evaluated. The size of quadrats may vary from 1-foot square for small plants with dense stands such as halogeton, 1-yard square or 1-meter square for somewhat larger plants with less dense stands such as larkspur, to 1-rod square or larger for brush species such as sagebrush with sparse stands in larger treated plots (Bohmont 1952, Kissinger *et al.* 1952, Klingman and McCarty 1958). For spotted stands of medium to sparse density, belt transects a few inches to a foot or more wide and 10 to 25 or more feet long may give more efficient measurement of plant survival than square quadrats. The number of quadrat or belt transect samples within each plot should be 3 to 5 or more, depending upon the density and uniformity of stand, the size of plot, and the accuracy desired.

A variation of the plant-count technique is to count as dead or alive individual plants nearest the right foot every so many steps (5 for example) in a straight line or zigzag course across the treated plot until 100 plants or other desired number have been counted (Kissinger *et al.* 1952). Care must be used to avoid personal bias in selecting the course. Another variation which is suitable for large brush or tree species is to select and mark a certain number (50 for example) within each plot before the treatments and use these trees for determining defoliation, plant kill, and resprouting. The individual trees should be selected at random and should be representative of sizes and ages of plants as well as locations.

Point Transects

When the effects of herbicide treatments or plant competition on several low-growing weed species or one weed and several associated forage species are being studied, the point transect method of sampling is frequently the most accurate and convenient. One common way of using this method is to locate 10 points 2 inches apart through holes in a 2-inch by 4-inch board 2 feet long (Levy and Madden 1933) and take samples at random through the middle of or diagonally across each plot and record the strikes and misses on the species being studied. Another excellent way is to stretch a steel tape the desired distance (e.g. 100 feet) between two stakes in a line perpendicular to or diagonal to the sides of the plot (Robocker *et al.* 1958). Strikes and misses of the various species under study at selected intervals along the tape (e.g. 1 foot) are determined with a metal rod with a 2-inch diameter ring welded at one end and are recorded independently for each species. This method is well suited for airplane or large-scale ground-rig chemical spraying experiments on low-growing weeds with dense stands and associated forage where it is planned to measure the treatment effects. It is particularly useful for measuring the variability of results that may be due to lack of uniformity in applying the spray. The method is one of the more precise for measuring small differences and is recommended for experiments on control of annual weeds where the difference between 100 per cent control (prevention of seed maturity) and 95 per cent, or even 99 per cent, control is important. Disadvantages of the method are that it is tedious and time-consuming.

Location of Samples in Plots

Experimental plots on chemical control of brush and weeds are more subject to border effects from adjacent plots and lack of uniformity of treatment at the ends of plots than are the plots in most other range experiments. This is particularly true of plots sprayed by airplane because of the likelihood of spray drift and the difficulty in beginning and shutting off the spray exactly at the ends of plots. The important thing is to take measurements at a distance from the borders or ends of plots to avoid spray drift or other border effects and uneven spray application at the ends of plots. Sampling should not be done closer than 3 feet from the borders of hand-sprayed plots, or from the sides of larger plots sprayed with a power sprayer and 15 feet from the sides of plots sprayed by airplane. The distances should be greater if the treatments are applied when the wind is blowing. Samples should not be taken closer than 10 feet from the ends of plots sprayed by a ground-rig power sprayer or 100 feet from the ends of plots sprayed by airplane. End margins twice that wide are safer.

In plots sprayed by airplane, a perpendicular gradient in amount of spray applied is nearly always present. Often a second gradient or pattern of variation parallel to the line of flight is also present. Where it is known that only the perpendicular gradient exists, the sampling should be done along lines perpendicular to the line of flight (Robocker *et al.* 1958). However, when it is suspected that due to vertical movement of the plane, uneven topography, vertical air currents or other factors, there is also a tendency for variability parallel to the line of flight, the sampling should be done along lines at a 45-degree angle from the direction of flight.

Time of Sampling

Estimates of percent plant kill or defoliation should be delayed until the treatments have had the maximum visible effect, but should be made before regrowth, refoliation, or new seedling growth has developed enough to mask the top kill. Usually the best time for such measurements is toward the end of the growing season in which the treatments are made.

Estimates of percent kill or counts of dead or living perennials should be delayed until about 1 year after the treatments (Bohmont 1952, Hurd 1955). With certain woody species, final readings on kill and resprouting should be delayed until the second growing season following the treatments, or later (Cable 1957, Leonard 1957). Estimates of kill or regrowth of perennial species should be made only when soil moisture, temperature, and other growth factors favor growth from living plants.

Greenhouse Experiments with Range Weeds

Greenhouse experiments with range weed species ordinarily do not involve unique procedures or techniques which are much different from those with other weed or crop plants. Some range species that are adapted to dry soil, high pH, and low humidity may be difficult to propagate and grow under greenhouse conditions. However, after successful methods for propagation and growth in the greenhouse are developed, the usual greenhouse procedures and techniques apply. Greenhouse experiments with woody species of range weeds, such as mesquite, usually must be conducted with seedling plants.

Many types of studies with range weeds can be conducted advantageously in the greenhouse (figure 9) to supplement those in the natural habitat (Hull 1954, Offord *et al.* 1952, Alley *et al.* 1956, Weldon *et al.* 1958). These include preliminary evaluation of new herbicides, relation of age of species to herbicide susceptibility, absorption and translocation of herbicides by different species, and other studies that can be conducted more economically or critically where various factors such as humidity, temperature, light, soil moisture, and pH can be controlled accurately. The purpose of this discussion is not to suggest specific procedures and techniques for greenhouse studies but to encourage such studies where they will prove valuable as preliminary or supplementary to those on the range.

EXPERIMENTAL GRAZING

Experimental grazing involves the use of animals under control, either through herding or in fenced enclosures. The experiments are made to ascertain animal and vegetation response to selected methods of grazing. They may additionally correlate these measurements with timber production, water

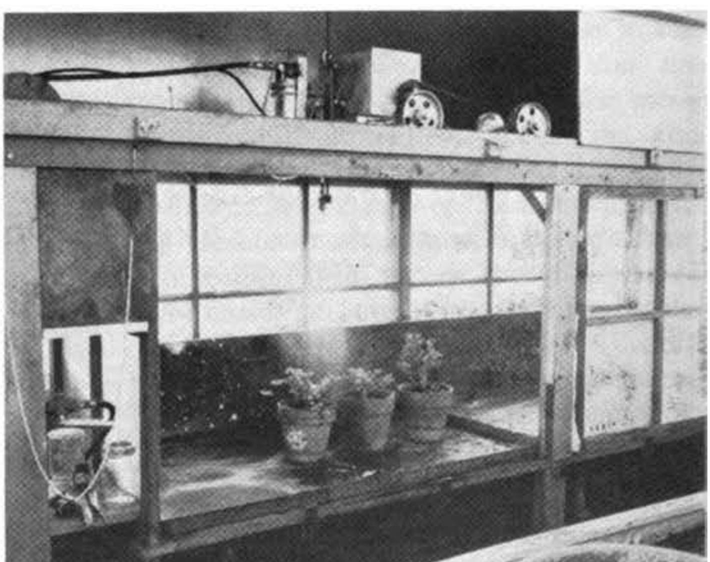


FIGURE 9. Experimental spraying of potted sagebrush plants in a special spraying compartment for a greenhouse experiment. The overhead spraying equipment is regulated to pass over the sprayed plants at the required speed for applying the test herbicide at the desired rate. The spraying compartment equipped with an exhaust fan and deactivating chamber is designed to prevent spray particles or volatilized fumes from escaping the greenhouse and damaging sensitive plants. *(Wyoming Agricultural Experiment Station photo)*

yield, or other natural resource values. Many techniques exist for measuring both plant and animal reactions. Standardization in experimental grazing studies is undesirable (Amer. Soc. Agron. *et al.* Joint Committee Report, 1952), since vegetation, climate, soil, and practices worthy of test vary from one locality to another. The best available procedures and facilities, however, should be adopted and used to meet the objective of each experimental study.

The objectives of grazing experiments include one or more of the following: determination of effects of various stocking rates, best period of use, comparisons of different systems of grazing, and isolation of factors that affect both vegetation and animals. Criteria frequently studied in management of the range are: range condition and trend; forage utilization; plant succession and determining factors such as weather, competition from game animals, and rodent infestations; plant life histories; growth and reproduction of important plants; grazing management of reseeded ranges; and the general relation of grazing and climate to range maintenance and improvement.

The results of grazing experiments can be measured for animals in such terms as weight gains, condition, reproductive rates, longevity, wool yields, and market values. These factors, in turn, can be related to nutritive quality, yield, seasonal abundance, and other characteristics of forage. Methods of measuring vegetation and selection of animals have been discussed in detail in preceding chapters.

The use of pastures in experimental grazing has advantages over empirical studies in that animal and seasonal control are possible. Desired intensities and qualities of treatments can be limited to specific areas, vegetation or edaphic types, or to watersheds. Permanent installations can permit ecosystem studies of long duration. Statistical control is possible.

Disadvantages of pasture experiments include lack of representativeness of ranch units and animal handling practices in the surrounding community. Pasture vegetation may not be typical of overall conditions in the area of application. Cattle distribution and plant utilization may present a pattern different from that on open range, and sheep habits may not be comparable to those in herded bands. Many of the disadvantages can be overcome by coordinating research with practice and by careful selection of representative experimental areas.

Selection of the Experimental Area

The experimental area should be viewed as an outdoor laboratory where range research is the primary objective. Suitability for secondary studies, including timber and watershed management and game management, will, of course, enhance the study value of the area. General considerations in the choice of a suitable area include: representativeness of soil and vegetation; adequate size for experiments contemplated; accessibility from towns and roads; livability for working personnel; usability for demonstration and inspection visits; and adaptability to cooperation with livestock owners and research agencies (Cooperrider 1939).

Additional criteria to consider are: suitability of the vegetation, whether normal or deteriorated; uniformity of area for comparative studies; erosion or other factors that could mask treatment effects; and capability of supporting a variety of studies related to the major problems of the locality (Stewart 1939). Adaptability to experimental designs and intensive plot systems is important. Additional important items include: feasibility of administration with regard to included and adjacent land ownerships, water and mineral rights; community attitudes; and possibility of support from federal, state, and local agencies. A final question: Will range research on the area adequately serve the stockmen, the community, and the region?

Physical Layout of Experimental Area

The Informal Observational Study

Where control of animals can be planned and executed through herding, successful grazing experiments can be made on unfenced areas. A study of sheep grazing on orange sneezeweed-infested range by Doran and Cassady (1944) has furnished a good example. On-the-ground observations of two bands of sheep using adjacent allotments were made during 3 summer seasons. Herders cooperated in directing the band movements so that good and poor management was alternated between allotments in the first 2 years, and improved for both bands in the third year. Utilization of forage plants was determined by clipping and weighing ahead of each band before grazing and behind each band soon after grazing (Cassady 1941). Records were maintained for each band, including routes of travel, methods of herding, use of bedgrounds, use of sneezeweed, symptoms of poisoning, death losses, average weights, and gross income from sale of lambs after the animals were marketed each fall.

The principal physical layout of the area consisted of a series of flags and markers which enabled the observers to determine at all times the band locations and the spots where the various observations were made.

The Formal Pasture Experiment

The size, shape, number, and arrangement of pastures into replicates for statistical comparison should be considered when the area is being selected. Adequate acreage should be available to permit installation of all the pastures necessary to the experimental grazing contemplated at the time and visualized for the foreseeable future. Requirements for physical facilities—fences, corrals, water developments, reserve or holding pastures, roads within pastures—should be mapped for tentative study of cost, feasibility in the experimental design, and practicability with regard to routes of animal travel and handling of livestock.

Size: Pasture sizes in grazing experiments have varied from 1 acre to several thousand acres. Ideally, pasture areas approximating those used in grazing by ranch operators should produce the least bias in applying results. Cost, acreage limitations, and sampling considerations usually dictate a choice different from the community average. The selected research procedure may even require different sized pastures.

On the San Joaquin Experimental Range in California, duplicate pastures of 160, 240, and 320 acres for three intensities of grazing were used (Campbell 1940). At the U.S. Range Livestock Experiment Station in Montana, summer and winter areas were each divided into three pairs of pastures radiating from central wells and handling facilities (Hurtt 1951). At the Desert Experimental Range in Utah and the Central Plains Experimental Range in Colorado, pastures of 320 acres each were used. In the latter case, 18 million acres of surveyed range in the Great Plains indicated that the average pasture used by ranchers in the area was approximately 320 acres.

Controversy exists over the practice of varying the size of pasture for different intensities of grazing with the same number of animals in each pasture as compared with pastures of the same size and different numbers of animals. In considering these alternatives, bear in mind that pastures are seldom comparable in the first place. Different sizes and shapes result in different animal habits. Also, grazing capacity varies with seasons and years, and the impact of different degrees of grazing becomes cumulative with use. Thus, to achieve a semblance of uniformity in utilization of forage, numbers of animals have to be varied.

Shape: Rectangular pastures, approximately twice as long as wide, generally are preferred in gentle topography because they are most efficient from a sampling standpoint, and cause the least divergence from normal animal distribution habits. In mountainous areas rectangular pastures seldom are feasible. Pie-shaped and other unusual layouts are liable to influence animal movements and result in concentration areas. Pastures built on watersheds for comparisons of water yield, erosion, soil stabilization, and other studies must necessarily be of different shapes.

Number of pastures in the experimental design: Cost, manpower, and facilities for making vegetation records usually limit the pastures to less than the number that proper statistical procedure would suggest. Numerous studies report the use of only two pastures, with no replications. A few extensive experimental designs have reported the use of 12 or more pastures in a single major study.

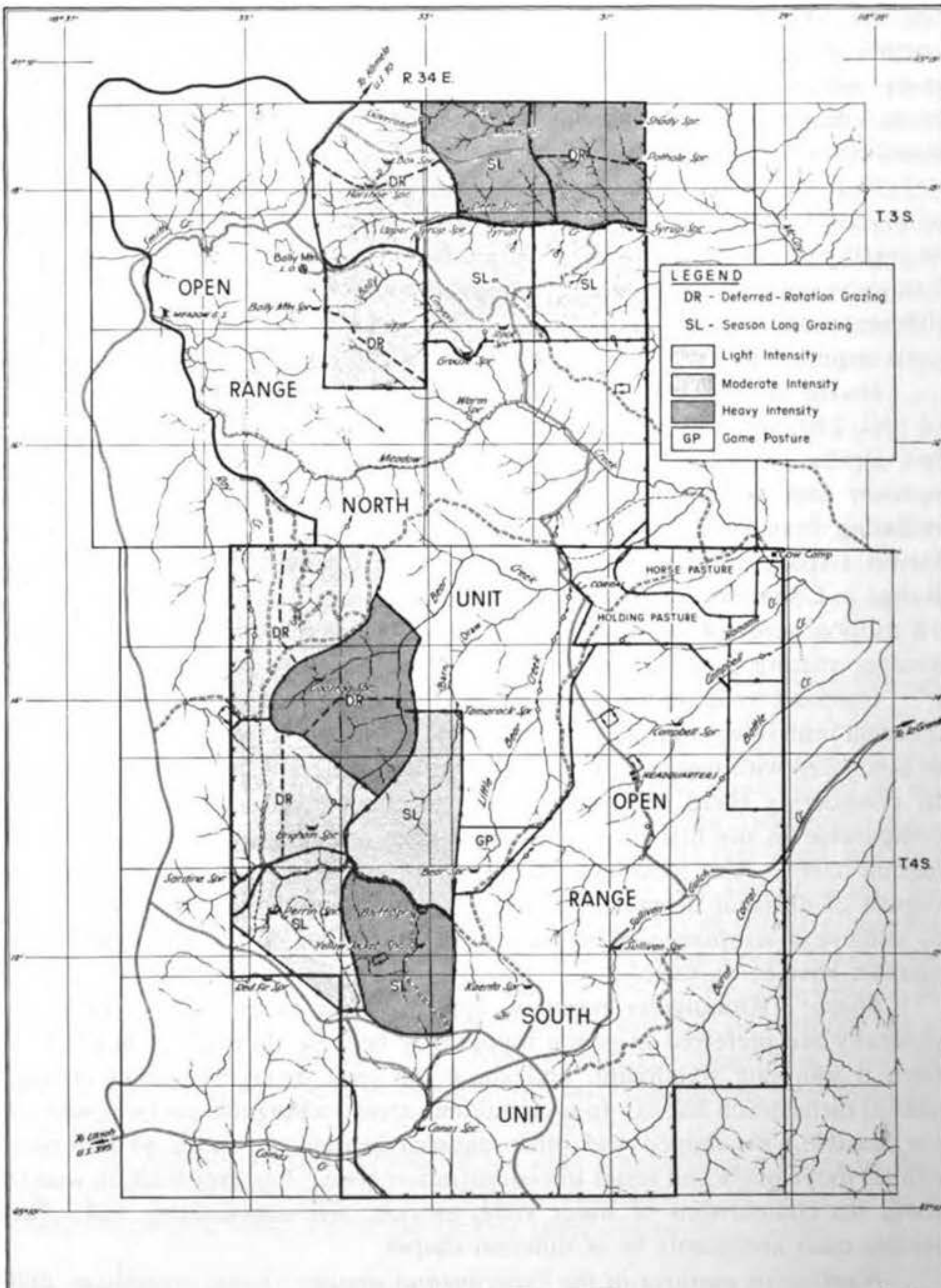


FIGURE 10. Arrangement of treatments in a range grazing experiment on the Starkey Experimental Forest and Range, Wallowa-Whitman National Forest in Oregon. Deferred-rotation vs. season (summer and fall) long grazing are being tested. Because effects of grazing by deer and elk cannot be eliminated from the pastures, special measurements of it are necessary.

On the Central Plains Experimental Range, Colorado, 12 pastures were grouped into 4 blocks, with 3 intensities of grazing each. Cattle numbers were varied each year to approximate 20, 40, and 60 per cent utilization of the major short grass species. On the Desert Experimental Range, Utah, 18 pastures were grazed with sheep at 3 intensities in 3 seasons in a factorial experiment.

Blocks, Latin squares, and other statistical arrangements are desirable in the design of pasture experiments, but true replication of vegetation, animal characteristics, or treatment effects can only be approached, not actually attained. On the Central Plains Experimental Range, for example, more than 10 years of trials achieved not 3 rates of grazing replicated 4 times, but 12 rates of grazing that could be ranked in order from marked overgrazing down to definite undergrazing. The block design, however, was still valid for analytical purposes.

Experimental Animals

The kind and class of animals used in range grazing experiments are important considerations and are usually determined by the purpose of the experiment and the availability of the animals. Discussion of this phase is amply covered in chapter 6.

Pasture Management in the Experimental Program

The management program involves several choices which should be made before the experiment begins. The period of grazing, for example, can be set to correspond with prevailing practices in the locality, to relate to vegetation cycles, or to test animal and plant responses for periods that previously have not been tried. The system of grazing usually is established for comparison of seasonal, alternate, rotation, deferred, or some combination of these methods of grazing, depending on the objectives of the study. Establishment of the basic rate of grazing sometimes must be deferred until a calibration has been made over a period of years by comparing forage yield, utilization, and stocking. If the initial stocking rates are in error, an experiment involving intensity of use, for example, may result in 3 degrees of overgrazing and 3 degrees of undergrazing.

The Basic Rate of Grazing

The desired intensity of grazing is best established by actual trial in the experimental pastures. A 3-year calibration period is usually the minimum, if weather is about average. Constant adjustment of animal numbers or of period of grazing usually is necessary even to approximate a given degree of plant utilization.

Past stocking records are an aid to establishment of basic grazing rates (Pechanec and Stewart 1949), and are most useful when combined with a close examination of range condition and trend. Range surveys also may furnish an index for grazing rates, but subsequent adjustments are almost invariably necessary. Hurtt (1951) used the survey method to determine forage acres available before the experiment started and then adjusted pasture sizes to obtain different rates of grazing with equal numbers of animals in the different pastures. How this worked out in the face of differential cumulative plant response and in drought cycles is not clear. Hutchings and Stewart (1953) varied the number of sheep grazed in each pasture. The desired percentages of use were not attained in actual practice, but they were closely approximated. Variation in animal numbers allows for adjustments for type of growing season, drought and wet cycles, and animal death losses.

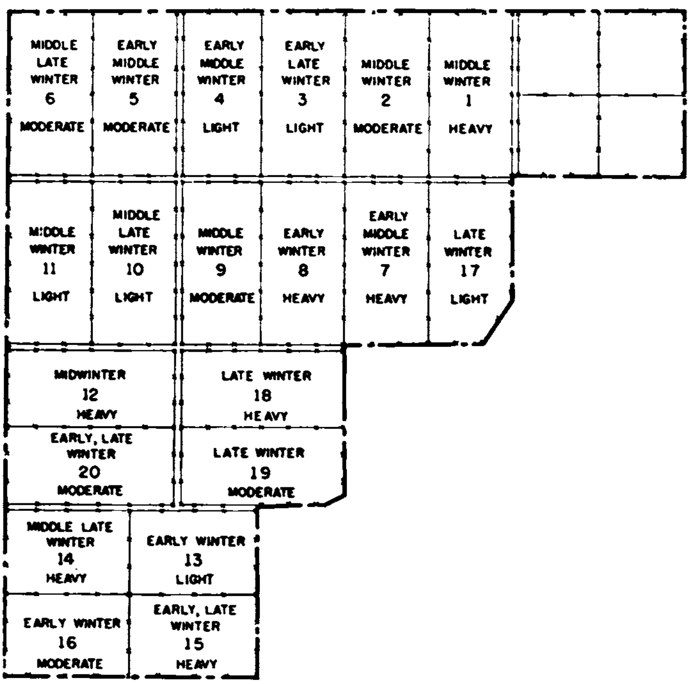


FIGURE 11. Fenced range pastures at the Desert Experimental Range, Utah, used to study effects of time of grazing winter sheep ranges. All combinations of early, middle, and late winter grazing were each grazed to 3 intensities of use. *(From Hutchings and Stewart 1953)*

Systems of Grazing

Numerous systems of grazing have been tested and no general conclusion has been reached as to which is most desirable. Yearlong and seasonal grazing are common practices, dictated in part by climate and ranching facilities. In experimental trials, alternate, rotation, deferred, and deferred-rotation have been studied in many localities (Biswell and Foster 1947, Black *et al.* 1937, Black and Clark 1942, Hodgson *et al.* 1934, and Sarvis 1941). The systems used and their advantages and disadvantages have been discussed by Sampson (1952) and by Stoddart and Smith (1955).

Smith (1895) made one of the first proposals for rotation grazing. Classical studies since then include those of Sampson (1913, 1914), Jardine (1910), Sarvis (1923), Hanson *et al.* (1931). Sampson (1951) in a review of rotation grazing studies in North America found that some trials favored rotation grazing while others proved continuous grazing to be more practical. Recent results reported by Biswell (1951), Fisher and Marion (1951), Hubbard (1951), Hyder and Sawyer (1951), McIlvain and Savage (1951), and Rogler (1951) support the conclusions in Sampson's review.

In the development of deferred and rotation grazing experiments, consideration of seasonal weather patterns and of plant growth cycles is essential. Usually animals should not be rotated or grazed by calendar dates. Great emphasis should be placed on obtaining comparable animal months of impact on the pastures being rotated or deferred. In a system where grazing may occur only once in 4 years, for example, it must be remembered that the grazing impact may hit in a period of poor growth, or in a period of especially good growth, thus adding to the difficulty of interpreting the results of the study. If an area is deferred during the entire season an entirely different response from both animals and plants will be obtained, compared to only partial deferment. In the application of deferred and rotation grazing systems on the range, the expense of fencing and watering, and handling of the animals should be balanced against possible increased favorable animal responses and benefits to the soil and vegetation.

Studying Management of Big-Game Ranges

In many respects, problems of studying big-game range management are similar to those pertaining to domestic livestock ranges. For example, measurements of forage production and of forage utilization are usually desired. Likewise, there is the need for accurate condition and trend evaluations.

On the other hand, some species of game, such as the Rocky Mountain mule deer (*Odocoileus h. hemionus* Rafinesque) derive a high percentage of their forage from browse species, making it necessary to place greater emphasis upon the woody plants. Furthermore, big-game species are more mobile than sheep or cattle. Their natural movements are practically beyond man's control. There is no easy, accurate method of counting, and unless kept in captivity, only an imperfect idea can be obtained of the number of animals being provided forage on a given range.

In the United States game animals belong to the citizens of the state, and possession, dead or alive, is strictly controlled by state game laws. Therefore, necessary authority must be obtained before launching any investigations requiring capture and confinement of wild game animals.

Separating the Effects of Grazing by Animals of Different Species

One problem encountered on range shared by big-game is separating the effects of grazing by different species. It is the exception in the West to find ranges utilized by only one species of grazing animal. It is more common to the East. In most cases, game ranges also serve as domestic livestock ranges. As a result, the researcher must differentiate between effects of use by each species.

A common and inexpensive method, satisfactory for certain types of studies (Julander and Robinette 1950), is to observe the effects of game use in areas, or parts of the range, that are not normally used by other grazing animals. For example, it is possible to obtain an estimate of the intensity of deer browsing on ranges used in common by deer and cattle by examining the browse plants on plots or transects located in steep, rough terrain where forage is not normally utilized by cattle. It should not be assumed, however, that deer browsing on the whole area is comparable to that on the rough terrain. It may be greater or less.

When the problem of separating the effects of use involves game animals and livestock, it may be possible to take advantage of different patterns of seasonal use by different species of animals (Dasmann 1949). For example, a range might be spring-fall for cattle or sheep and winter for deer *(Odocoileus* spp.) or elk *(Cervus* spp.), with little or no overlapping in the period of use. Under such circumstances it would be possible to obtain valid estimates of forage utilization by both domestic livestock and the game animals through two surveys, the first made at the end of the period of cattle or sheep use and before the beginning of game use, the second following at the end of the season of game use.

A more elaborate and frequently more satisfactory method is through the use of fenced plots of such design that certain species are excluded (Julander 1957). Where the game animal is mule deer, this method is useful because of the ease with which these animals hop over or crawl through ordinary livestock fences. A common practice is to construct two fenced plots: one fenced to exclude all large animals and, in some cases, even rodents; the second fenced to exclude livestock, but to allow game animals to enter. This gives the investigator three conditions of use: (1) combined use by all of the animal species, (2) use only by game animals and rodents, and (3) no use by animals.

In planning such a study, consideration should be given to size and location of plots. The location should be as representative as possible of the range being studied; care should be exercised not to block normal routes of travel with the exclosure and thus unduly concentrate the excluded animals around the outside of the plot. The size of the fenced plots should be as large as possible. Cost and land available will usually preclude the fencing of extensive areas. However, the total exclosure should not be smaller than 1 acre and the partial exclosure not smaller than 5 acres. Cost of fencing can be reduced by building the total exclosure within the partial one so that a part of the fence serves both plots. Replicated plots are necessary for most types of investigations using this technique.

Determining Numbers of Game Animals

Another problem which often confronts the investigator is that of determining the number of game animals on a given range. Only under certain circumstances is it possible to count game animals accurately. Partial aerial or ground counts made in successive years under as nearly the same conditions as possible are relied upon to determine trends in herd numbers. Furthermore, the movement of game animals to or from a given area often seems to be dependent more on chance than upon any determinable characteristic of their environment. Under such circumstances, it is difficult to estimate the number of days of usage on a given area.

Pellet-Group Counts

Number of pellet groups (defecations) has been used extensively for studying game populations. Current-year groups are counted on plots or transects. From this sample, an estimate is computed of the total number of pellet-groups on a given area. An estimate of the number of animal days of grazing is obtained by dividing the estimated number of pellet-groups by a factor representing the number of defecations per animal per day. The factor for mule deer and elk is in the neighborhood of 13 defecations per day per animal. Recent studies by Rogers *et al.* (1958) indicate that over-winter defecations rate by mule deer is about 15 groups per day but that on depleted range lacking a variety of forage species a value of 13 pellet-groups per day may be more accurate.

Pellet-groups are counted on a random sample of plots; the sampling unit, whether circular plots or belt transects, should be of such size that all pellet-groups present can be quickly and easily seen in the vegetation on the area. The observer must use care to count only groups of the current year or season. Plots frequently are circular ones of 1/100 acre or belt transects of 0.2 acre, 6 feet wide and 1,452 feet long. Belt transects used by McCain

(1948) in California were spaced at ½- to 1½-mile intervals along a road or trail in the area being studied, and ran at right angles to the road or trail.

Confined Animals

For certain types of basic studies involving food habits, forage utilization measurements, nutrition, and feeding trials, it is desirable and usually necessary to have closer control of the experimental animals than is possible under field conditions. This circumstance dictates some type of confinement for the animals, whether in small pens or cages (Magruder *et al.* 1957 and Smith 1953), in paddocks or in large enclosures approaching normal range conditions.

FIGURE 12. Pens used for feeding trials with deer. *(Michigan Conservation Department photo)*

Game Fences

Experience has shown that fences necessary to confine big-game animals need to be much stronger and higher and constructed to a more rigid standard than fences necessary to hold cattle or sheep (Riordan 1957). They must be free of holes underneath, around gates, and in corners. Such fences are expensive, perhaps averaging five times the cost for livestock fencing.

Obtaining Animals

Obtaining experimental animals of a given species in adequate numbers and at the proper time sometimes presents a problem. Where only a few are required, it may be possible to locate semi-tame ones that have been raised in captivity. Young animals can be captured soon after birth and tamed for use if only a few animals are needed. It is believed that considerable care should be exercised in feeding such young animals to avoid their acquiring an appetite for table scraps which, conceivably, could alter their normal food habits. Pet deer and elk often become regular scavengers, apparently preferring such foods to their normal range diet.

Where considerable numbers of animals are required for pasture experiments, some method of live-trapping wild animals becomes essential. Considerable success has been obtained in catching deer in box-type individual traps, baited with bright alfalfa hay, apples, or similar choice deer feeds when normal food sources are limited by snow in the winter. Deer and possibly elk may be driven into corral-type traps by use of powerful spotlights at night. Such traps are usually constructed near favored feeding sites, such as alfalfa fields. The trap gate is arranged so that it may be closed by remote control, usually by a trip wire-pulley apparatus. A similar system may be used to trap bighorn sheep (*Ovis c. canadensis* Shaw) and elk, except that the animals are baited into the corral with feed (Hunter *et al.* 1946). Antelope (*Antilocapra americana* Ord) are usually trapped by driving them by use of a light airplane into corral-type trap constructed of heavy fish netting.

Another method of capturing wild animals is shooting them with a dart containing a paralyzing or stupefying drug, the effects of which pass off within a few hours. Nicotine derivatives have been successfully used in a 2-year series of experiments on white-tailed deer (*Odocoileus v. virginianus* Boddaert) in Georgia (Crockford *et al.* 1957).

In game range research dealing with controlled numbers of animals for specified periods of time in large enclosures, frequent patrol of enclosure fences is necessary to avoid undetected escape of enclosed animals, or introduction of unwanted animals from the outside. Watering facilities should be provided as for livestock, except that much less water usually is required for game animals. They are able to survive for extended periods without open water where snow is available.

Removing Animals

Removing the animals from the experimental area at the end of the grazing period sometimes can be as difficult as capturing them in the first place. Where the plan of the study calls for capturing new wild stock each

FIGURE 13. Air gun and dart used to capture deer for experiments. On contact the dart injects a paralyzing or stupefying drug. The dart is propelled by compressed carbon dioxide and is effective up to 40 yards. *(Courtesy Lee A. Yeager)*

year, it has been found necessary to remove deer by hunting and shooting the animals (Riordan 1956).

Determining the Effects of Game Use Upon Vegetation

Estimating or measuring effects of big-game grazing or browsing on vegetation is basically the same problem on game ranges as the determination of utilization and its effects on livestock ranges. Browse is often most important, especially on deer range, but other classes of vegetation should not be overlooked. In most game-range studies, estimates of forage production and utilization have been made by ocular methods. Several studies (Julander 1957, Nichols 1957) have been reported wherein weight estimates checked by clipping and weighing were used.

Measurements of the current annual stem or twig length of key browse species have been used as an index to deer forage production and utilization (Aldous 1945). Where fall and winter grazing are to be studied, ungrazed lengths are determined in the fall after growth is completed and before browsing has started; grazed lengths are measured in the spring before beginning of growth and after fall and winter browsing, and percent of length utilized are calculated. This is considered directly related to percent volume removal which may not be true. There is need for adequate sampling in conducting studies of this type and to recognize the desirability of testing by statistical methods the adequacy of the sample used and validity of assumptions made.

FIGURE 14. Measuring twigs to determine utilization of mountainmahogany *(Cercocarpus montanus)* on winter elk range in Colorado. *(Colorado Cooperative Wildlife Research Unit photo)*

Effects of Range Condition Upon Game Animals

There is evidence that the condition of big-game range is reflected in the animals using the range in at least two important respects: body weight and productivity of the species concerned (Jones *et al.* 1956). Body weight from game range can be obtained from checking stations located at convenient points during big-game hunting season. Hog-dressed weights of animals of different age classes are determined for comparison with weights of corresponding age classes from other ranges.

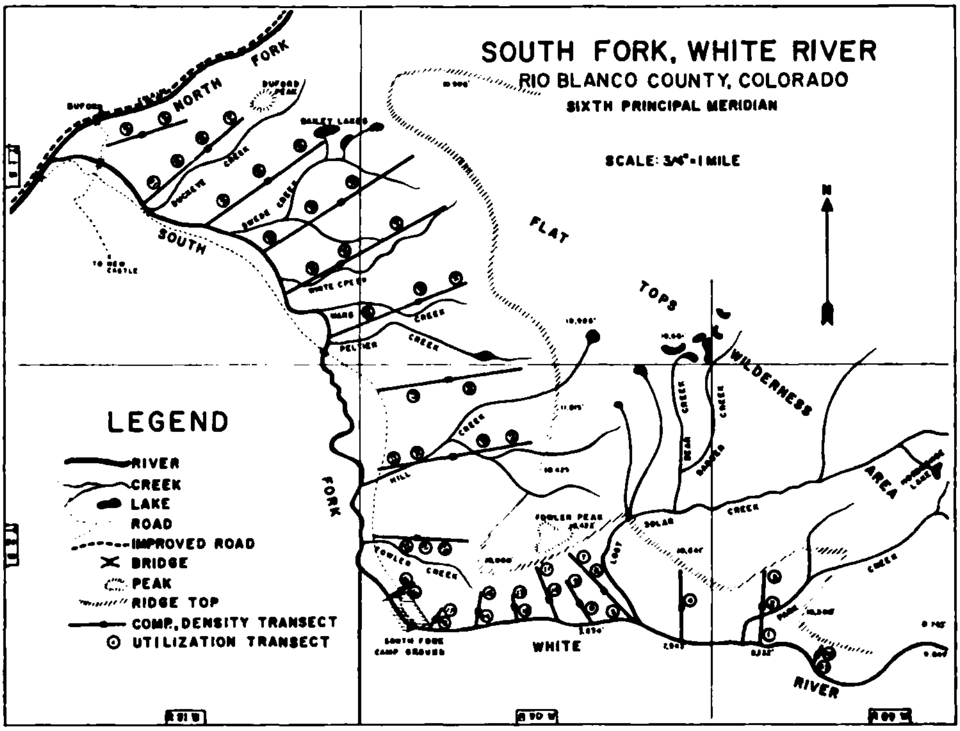


FIGURE 15. Arrangement of transects and plots for studying abundance and utilization of vegetation on winter elk range. *(Courtesy John Harris, Colorado Cooperative Wildlife Research Unit, Colorado State University)*

Variation in manner of dressing game, difficulty of classifying the animals as to age, and the lack of mean weights based upon adequate samples against which to compare weights make use of this method inadvisable except to complement some direct method.

STUDY OF FIRE ON RANGELAND

Fire is used as a tool on certain kinds of rangeland to remove unwanted vegetation and to promote growth of desirable plants. Special problems of field experimentation result from difficulties in (1) obtaining replications of treatments; (2) classifying fire intensity; and (3) determining or classifying factors which determine fire intensity.

Purpose

Fire may be used to remove existing vegetation to prepare an area for seeding. Such a study can be a simple one of determining the best time to obtain a clean burn and prevent reproduction. Fire also may be used to remove one species or class of plants and to preserve others. For example, undesirable shrubs may have a good understory of grasses and forbs that is to be released by burning the shrubs. Under these conditions, burning should be at a time when it will kill the shrubs, but do the least damage to desirable plants. The problem is more complicated when determining how to make a selective burn. Both the heat intensity and the resistance of various plant species to it at different seasons are variables that are difficult to measure.

In the southeastern United States the purpose of burning might be to thin the underbrush under a pine forest to make livestock management easier, or to reduce the accumulation of coarse herbaceous material without controlling any plants. To study burning for such purposes, the effects of season of burning, frequency of burning, and the fire intensities on the tree overstory are important.

Obtaining Replication of Treatments

To obtain reasonably comparable replications of treatment, the researcher should consider site, vegetation, and weather, as well as the application of the burning treatments on the plots themselves.

Variations in Site, Vegetation, and Weather

It is desirable to include all treatments within a replication on relatively homogeneous areas. However, different treatments often must be widely separated so that one treatment will not affect another. This need to place different plots on different areas makes necessary rather detailed classifications of site and vegetation to make certain that all plots within a replication are representative of a single condition. Weather conditions should also be as near constant as possible.

Site: When classifying and defining climatic zones and soil productivity classes, there may be a tendency not to give soil uniformity within an experimental area adequate consideration because of the desire to balance other factors that influence use of fire. This should be avoided because in rangeland experiments all treatment plots should be on a single soil productivity class so that followup measurements of herbage will reflect treatments rather than soil variations.

Slope and exposure must be comparable on all plots because they influence response of vegetation and because differences in terrain greatly affect the spread and intensity of fire. Uniformity in minor relief on all plots is essential, but difficult to achieve.

Vegetation: Standard classifications of vegetation types based on size, canopy density, species composition, and growth stage are useful in study of burning. Further detailed classification by fuel types is essential for selecting experimental areas and treatment plots, and for extension of the results from the experiments.

Fuel classes are defined according to size and volume of woody and herbaceous material, continuity of fuels both horizontally and vertically, and proportion of dry and green fuels in the cover. This usually requires a breakdown by species, density, and age of stand for woody plants and seasonal development for herbaceous plants. A single experiment should include only one fuel type, or the different fuel types should be equally represented in each treatment plot, and effects of fire should be measured separately within each fuel type. Each vegetation-fuel type should contain a characteristic proportion of certain key species so that comparable measurements can be made of removal and kill of brush on the various plots.

Weather: Weather must be classified in two ways: By season of burning, and by fire-weather conditions during burning. Season is classified according to the prevailing weather conditions at definite times of year. For example, in California brushlands an early spring season corresponds to a period of dry weather before initiation of new twig growth on woody vegetation when fine fuels are dry and heavy fuels are still moist and cool. The summer season corresponds with a period of dry, hot weather when heavy dead fuels have dried and all fuels are warm.

Ideally, all plots within a replication should be burned at the same time because this is the best way comparable weather conditions can be assured. Because this often cannot be attained, current weather must be classified exactly according to air temperature, relative humidity, and wind velocity, direction, and gustiness. Each phase of burning must be conducted within a narrow range of these factors so that replications are comparable.

Application of Burning Treatments

Size, shape, orientation, and location of treatment plots within a single experiment usually are dictated by the nature of planned preburning treatments and by the anticipated behavior of fire during the burning treatments.

Preburning treatments usually are aimed at drying or compacting woody fuels or otherwise making green or discontinuous fuels easier to burn. A common objective of experimentation is to compare different methods of pretreatment. For example, complete smashing of brush may be compared with smashing brush on only one-quarter of an area (figures 16 and 17). If heavy equipment is used, the plots must be one to several acres in size to obtain typical effects and to allow maneuverability of the equipment. Where desiccation of fuels with chemical spray, applied by aircraft, is used, the plots must be large and must be separated by wide buffer strips to prevent drift of chemicals onto adjacent plots.

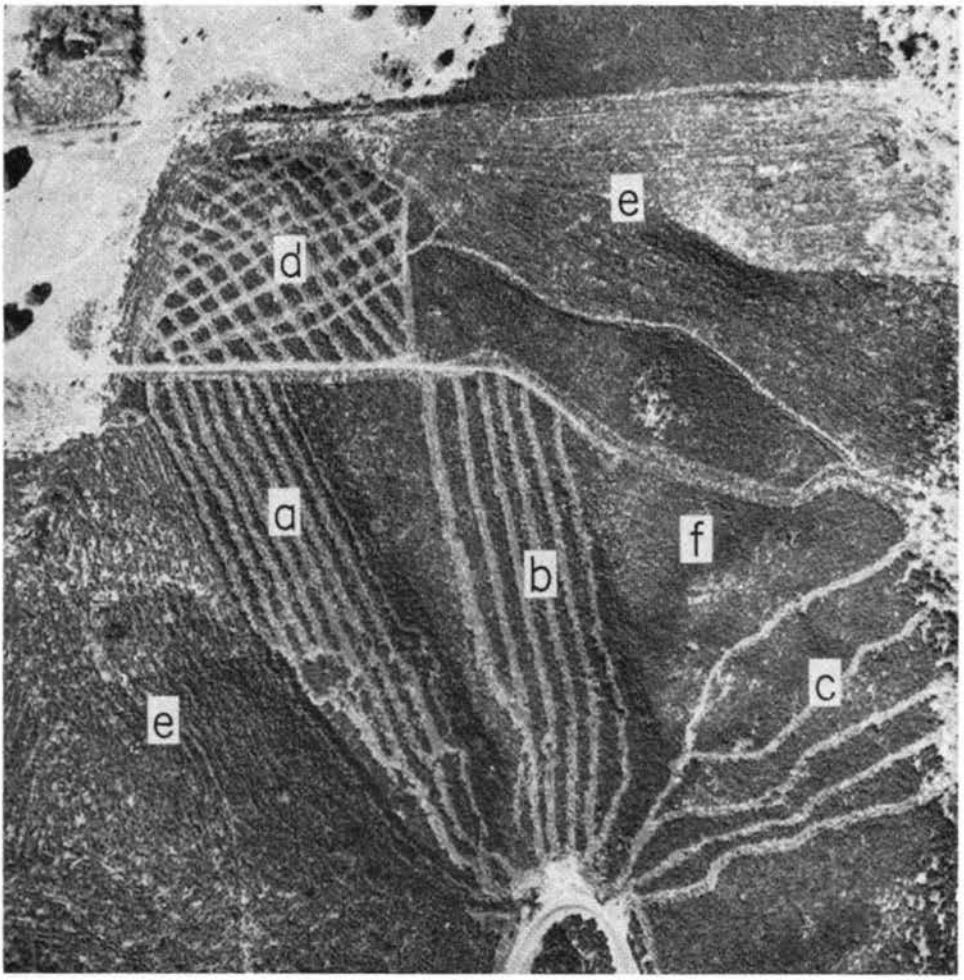


FIGURE 16. Brush smashed with bulldozer for area ignition tests. *A*, 50 per cent of area smashed; *B*, 33 per cent of the area smashed; *C*, 25 per cent of the area smashed; *D*, 50 per cent of area smashed in gridiron pattern; *E*, 100 per cent of area smashed; and *F*, untreated brush. *(From Fenner et al. 1955)*

One problem in experimental design is the fact that fire in ground vegetation tends to follow local air movement caused by wind direction or by upslope drafts. An objective of study may be comparing different techniques for spreading fire. Plots must be oriented so that fire can be spread by prevailing wind or upslope drafts, or carried into the wind or downslope, or spread in other ways. In light fuels on nearly level terrain, spread of fire may not seriously affect the experimental design. In heavy fuels on uneven terrain, the characteristic spread of fire may determine plot shape and orientation, and it will greatly limit experimental design. Sometimes one treatment plot cannot be placed below another on a slope because fire may spread

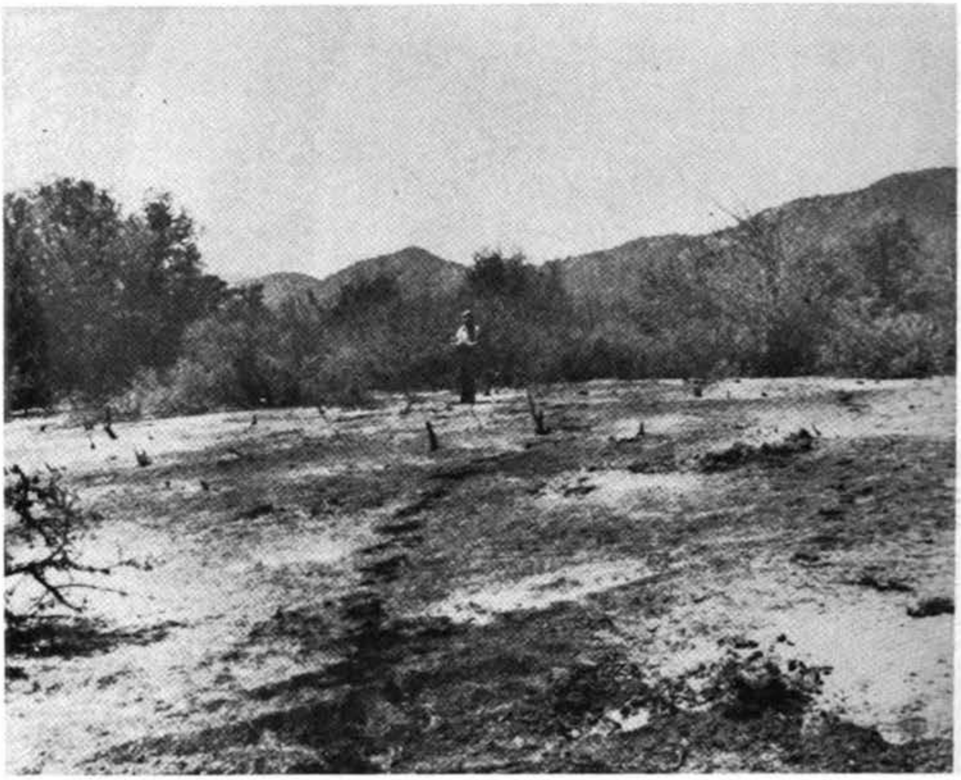


FIGURE 17. Area ignition in the foreground after smashing 40 per cent of the brush. Unmasked brush in background did not burn with conventional line firing. *(From Fenner et al. 1955)*

from the lower to upper plot. In some cases, however, a design can be used that will allow burning all of the upper plots before the lower plots are burned.

Another characteristic of fire that greatly influences plot shape, size, and orientation is the transfer of heat by radiation or convection columns from the burn to vegetation outside of the plot. Plots must be separated by buffer strips of sufficient width so that vegetation on one will not be influenced by the burning treatment on adjacent plots. This may raise no particular problem in slow burning of light fuels on flat terrain. But in burning of heavier taller growing fuels, a wide cleared line is needed. A wide buffer strip also is needed to prevent predrying of vegetation on adjoining plots which are not to be burned or are to be burned by a different treatment. It may be possible to design the experiment so that the plots burned first will serve as control lines for plots burned later. If two or more plots are to be burned separately but at the same time, they must be quite widely spaced so that one fire does not affect another.

In studies of broadcast burning of woody vegetation, it is difficult to duplicate on small plots the energy situation which exists on large burns. On small plots the surrounding vegetation and air have an influence on the release and dissipation of heat so that thermal conditions occurring on the plots are not typical of those inside large burns. This is the common condition where conventional line firing and spread of fire by wind are used to burn unprepared brush. For this treatment, areas of 20 to 100 acres, or more, can be used and measurements made on small plots well within the poorly burned borders of the larger area. Frequently if the brush is prepared by smashing and drying ahead of burning, ignition is easier and faster so that sufficient heat can be generated on smaller areas with only narrow border effects. Recent development of the area-ignition technique (Fenner *et al.* 1955) has made possible the use of hot brush fires on small plots under moderate weather conditions (figure 18).

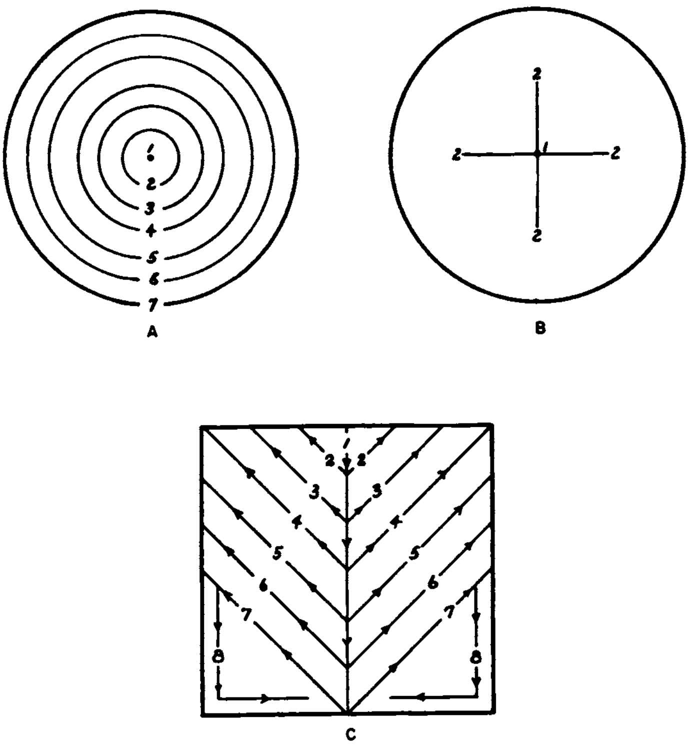
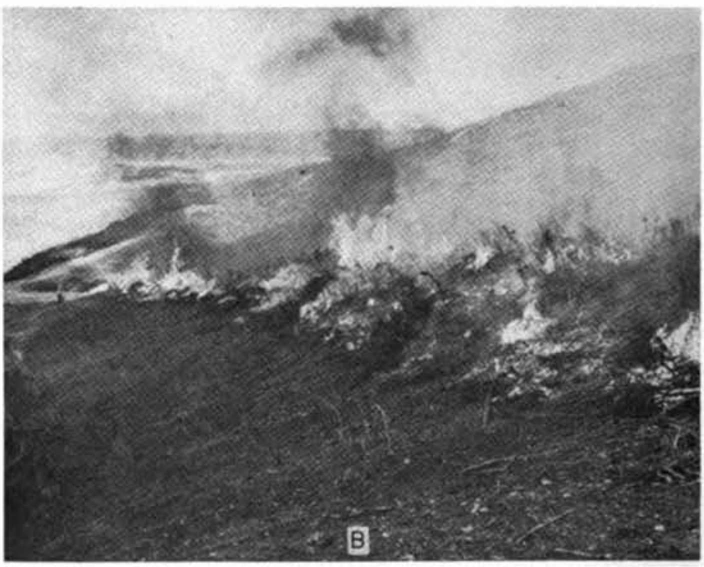


FIGURE 18. Examples of methods of firing for area ignition burns. *A*, (concentric method) and *B*, (radius method) are applicable to flat terrain or areas with a central high point, and *C*, is adapted for steeper even slopes. Numbers indicate the order of firing. In *C*, number one torch continues straight through the center of the area downhill, with a two-man firing team working away from the center after they pass each firing course.

FIGURE 19. Preparing for a control burn in brush in California. *A*, prepared fireline. *B*, burning to the fireline. *(U.S. Forest Service photos)*



The fact that fire is dangerous raises problems in conduct of experiments. An objective of experimentation is to develop methods of using fire effectively at times when danger of escape is at a minimum. Sometimes studies must be conducted at a time when there is danger of fire escaping to adjoining land. This means that adequate crews must be on hand to guard against escape.

Considerable expense in preparation of adequate fire control lines is necessary, unless studies can be tied into other burning operations so that there is no danger of fire escaping.

Classifying Fire Intensity

Classifying fire intensity is difficult so procedures must be well designed.

First, intensity must be defined for every study. It usually embodies four components: (1) heat energy, (2) mass, (3) time, and (4) location. The definition must specifically cover all components. For example, intensity in one study might be the maximum instantaneous temperature reached at the center of a pine needle 6 feet aboveground. But in another it might be the total number of calories released at the surface of the ground during passage of the fire.

Intensity is classified by several procedures, chiefly: (1) observation of the fire while burning, (2) observation of effects on vegetation and soil after the fire has burned (Nelson 1935, McCulley 1950, and Herman 1954), and (3) measurement with devices (Silen 1956 and Lindenmuth and Byram 1948). In classification by observing the fire, such criteria as flame height, flame angle, and time required for the flames to burn past a point are usually estimated. In observing effects after the fire, criteria are: (1) height of scorch line and/or amount of live crown consumed of trees or other plants, (2) amount of fuel consumed, and (3) other evidence of heating, such as discoloration of soil.

Among measuring devices that can be used are thermocouples, thermometers, and alloys or lacquers with specific individual melting or fusing temperatures. Mass is an important consideration in using any of these. Two thermocouples side by side, one large and one small, will give different readings. Likewise, the size of the reservoir in a thermometer affects temperature readings, as does the mass of the shield, if the thermometer is shielded. The thickness of alloy spirals or the weight and thermal characteristics of the base on which lacquers are painted affect the amount of heat required to melt or fuse them.

Methods of heat transfer are also important considerations in using measuring devices. A satisfactory device must be sensitive to both radiation and ambient heat. If the objective is to measure intensity in terms of the heat rise in the bud of a plant, for example, and the measuring device cannot be inserted inside the bud, the measuring device must have the same or consistently similar thermal characteristics as the bud—same reflectiveness, same conductance and so on.

Because of the complexities of measuring fire intensity, observational procedures for classifying intensity are more often chosen, and intensity commonly is expressed qualitatively rather than quantitatively .

Problems in Experimental Design

Complex experimental designs may have some use in study of grass burning on level terrain where all treatments within a block can be applied on a single, relatively homogeneous area. A somewhat different approach seems to be necessary, however, in study of brush burning on rough, broken terrain where a single replication of all treatments cannot be put on a single area. Each study must be kept simple so that a minimum number of areas and conditions of burning will be involved. The possibilities are limited for increased efficiency through use of complex designs.

Sites, vegetation types, fuel types, and weather conditions must be well classified and described in order that the different treatments within a block will be comparable and treatments can be replicated. In each dominant site-vegetation-fuel class at each critical season of the year a series of simple studies can be obtained to determine effects of different methods of fuel preparation or of different ignition methods for initial removal of brush. After information is accumulated for each site-vegetation-fuel class condition, comparisons can be made of the effects of season of burning for any or all combinations of fuel preparation and ignition. Obtaining all of this information from one experiment does not appear feasible.

Studies using split-plot design are sometimes possible where plots involved in the initial brush-removal treatments can be split into subplots for comparison of different followup treatments. These followup treatments, such as reburning, can be applied to smaller individual areas than the initial treatments.

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