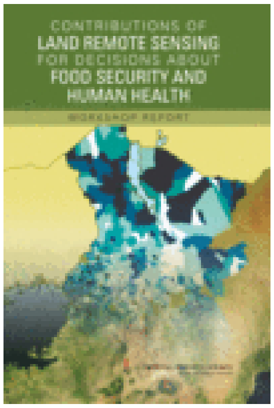

Contributions of Land Remote Sensing for Decisions About Food Security and Human Health: Workshop Report

Committee on the Earth System Science for Decisions About Human Welfare: Contributions of Remote Sensing, Geographical Sciences Committee, National Research Council

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CONTRIBUTIONS OF LAND REMOTE SENSING FOR DECISIONS ABOUT FOOD SECURITY AND HUMAN HEALTH

WORKSHOP REPORT

Committee on the Earth System Science for Decisions About Human Welfare:
Contributions of Remote Sensing

Geographical Sciences Committee

Board on Earth Sciences and Resources

Division on Earth and Life Studies

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Cover: A choropleth map showing levels of poverty in northern and western Kenya fades into a satellite image showing the color of the Earth's surface in northern Tanzania. Kenya poverty gap index map courtesy of the Center for International Earth Science Information Network (CIESIN), Columbia University. Satellite imagery courtesy of NASA.

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Preface

The National Research Council (NRC) Committee on Geographical Sciences first considered a study on remote sensing for human welfare several years ago. Since then, the world has witnessed the tsunami of 2004, Hurricane Katrina of 2005, wildfires in the western United States damaging human lives and property, emergence of diseases such as severe acute respiratory syndrome (SARS) and avian influenza, and entrenched chronic poverty and hunger in many parts of the world. These occurrences add to an already long list of human welfare concerns that intricately link land use, environmental conditions, and vulnerabilities of human populations. Effective decisions about human welfare—how to foresee changing environmental conditions on the land surface with negative outcomes for human welfare, where and when to respond, how to foster land use and development policies that enhance human welfare—inevitably depend on understanding and communicating these complex linkages.

Coming decades will see major changes in the numbers, distribution, and lifestyles of human populations; climate and other environmental conditions; and land use in response to both economic demands and altered environments. These vast transformations challenge the scientific community to understand complex linkages between environmental conditions and human access to food, water, healthy living conditions, and other aspects of human welfare—and to transfer this understanding into usable information. Remote sensing data offer one piece in this multifaceted puzzle. Combined with other data, remote sensing reveals interactions over space and time that simply cannot be observed from the ground.

This report offers examples that illustrate the possibilities of addressing agency objectives to apply remote sensing for societal benefit. Beyond these illustrative examples, the report summarizes workshop discussions on the opportunities and challenges in moving toward the long-term goal of integrating land remote sensing into decision making on a range of human welfare decisions. The committee organized this workshop to consider the potential, recognizing that the scientific community has only begun to address the opportunities. The workshop was one of many stepping stones to bring together multiple perspectives from different disciplines to transfer this potential into reality.

The workshop and this report would not have been possible without the hard and dedicated work of the organizing committee and the workshop participants. In addition, NRC staff provided the logistical support as well as substantive contributions. Hedy J. Rossmeissl helped in developing the agenda and all aspects of organization. Sammantha Magsino and Peggy Tsai contributed immensely in drafting the report. Amanda Roberts assisted at the workshop and behind the scenes. This report is the product of the combined talents of all of these individuals. We hope that it serves as a launching point for many scientific endeavors, interactions with decision makers, and applications that harness the capabilities of land remote sensing to advance human welfare.

Ruth S. DeFries
Chair

Acknowledgments

This report was greatly enhanced by input from the presenters and participants at the workshop (see Appendix E). These presentations and discussions helped set the stage for the committee's fruitful discussions in the sessions that followed. Robert Pool prepared an initial summary of the workshop, which was useful to the committee in writing this report.

This workshop summary report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

George H. Born, University of Colorado
Michael Emch, University of North Carolina, Chapel Hill
Gregory Glass, Johns Hopkins University
Michael F. Goodchild, University of California, Santa Barbara
Marshall A. Martin, Purdue University
Billie L. Turner II, Clark University

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the workshop summary report before its release. The review of this report was overseen by Daniel G. Brown, University of Michigan, Ann Arbor. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

Analyses of remotely sensed observations from aircraft and satellite provide information regarding changes in the Earth's surface and atmosphere, including changes in land cover, sea surfaces, temperatures, and many other terrestrial, marine, and atmospheric variables. Remotely sensed data can provide spatial and temporal information necessary to address some of the most challenging issues related to society's health and well-being. Although remotely sensed data are combined with other data types for purposes such as weather forecasting, remotely sensed observations of the land surface are not routinely applied to decisions about human welfare.

This report summarizes a two-day workshop on the contributions of land remote sensing to human welfare decisions. The National Research Council, at the request of the National Aeronautics and Space Administration (NASA), the U.S. Department of Agriculture, the Centers for Disease Control and Prevention, and the U.S. Environmental Protection Agency, organized an ad hoc committee to plan the workshop. The committee's charge was to conduct a workshop on the contributions of remotely sensed data to land use and land cover change analyses and on ways to use the physical, biological, temporal, and social characteristics of particular locations to support decisions about human welfare. Topics covered were to include (1) how to effectively use remote sensing, in combination with other types of data to forecast ecological and social repercussions of changes in land use and land cover; (2) usefulness of land remote sensing for improving human welfare; (3) technical issues of integrating disparate data (e.g., different remote sensing platforms at different temporal and spatial scales, ground-based scientific data, and socioeconomic data) into decision support systems that address human welfare; and (4) trends in research and data availability that enable decision support systems and processes to use remotely sensed land data.

As focal points for the workshop, the committee selected two aspects of human welfare in which remotely sensed environmental conditions play a key role: human health and food security. These two aspects were selected to represent a range of existing experience within the scientific and policy communities on the applications of remote sensing. The application of remote sensing to food insecurity is relatively mature. Application to human health has received less attention and research efforts are beginning to emerge. The ability of land remote sensing to identify variables such as land cover, responses of vegetation to climate variability, and locations of human infrastructure provides critical information in forecasting and determining appropriate responses to disease outbreaks, food shortages, and other consequences for vulnerable populations. Applications of land remote sensing to monitor crop yields, enable precision agriculture, and identify impending food shortages in developing countries offer successful examples. The use of remote sensing data for human health is not as advanced as for food security beyond a few case studies, although workshop participants believe the potential is great.

Workshop participants identified three themes that, if fostered, would help realize the potential for the application of land remote sensing to decisions about human welfare.

1. *Integration of spatial data on environmental conditions derived from remote sensing with socioeconomic data.* The success of using land remote sensing in human welfare decisions rests on the ability to integrate remote sensing data with socioeconomic information. In the human health domain, for example, the integration of socioeconomic information, such as locations and vulnerabilities of human populations and access to infrastructure, with environmental conditions, such as habitats for disease vectors and potential disease outbreaks, is key to providing information that is effective in generating response strategies. The research community is only at the beginning stages of achieving this integration. Integration involves communication across disciplines to consider the full range of ecological and socioeconomic factors affecting human welfare, data collection that facilitates merging multiple types of data, and tools such as geographic information systems (GIS) to combine data sets.

2. *Communication between remote sensing scientists and decision makers to determine the effective use of land remote sensing data for human welfare issues.* Successful application of remotely sensed data to human welfare issues depends on several factors, including cooperation between remote sens-

ing, natural, and social scientists and decision makers. From the remote sensing side, successful application depends on correctly identifying what variables on the Earth's surface require measurement for human welfare applications. Perspectives on the information needs from officials who ultimately use the information are equally important to the perspectives of remote sensing scientists in generating the information. Communication that allows multiple perspectives in determining information needs is critical to the effective use of remote sensing.

3. *Acquisition, archiving, and access to long-term environmental data (both past data and data to be collected) and development of capacity to interpret these data.* Workshop participants agreed that maintenance of the continuity of current satellite coverage monitoring environmental conditions over extended time frames is most important to the realization of any potential in applying land remote sensing to human welfare. Access to affordable data is a key constraint for the underlying research to develop applications and the applications themselves. Capacity in interpreting data has advanced considerably but remains a key constraint.

Workshop participants developed short- and long-term priorities to determine data needs and develop the ability to implement decision-making strategies. Short-term (five-year) priorities include gaining an understanding of ecological processes and their interactions with disease occurrences or food security issues; fusing cultural data with other types of remotely sensed data into GIS layers; developing risk-based decision-making strategies to enable appropriate action given available data; and enabling data access at reasonable cost. Long-term (10-year) goals include developing an end-to-end system to support human welfare applications, including collection, analyses, and application of data in decision making. Such a system could include a global environmental database containing multi-scale, multi-temporal data, accessible to all for surveillance, monitoring, and prediction. Algorithms to process data, produce relevant GIS layers, and provide robust predictive models for biodiversity, agriculture, health, poverty, and environmental changes through time could be developed as part of the end-to-end system. Finally, a means to link model outputs to the formulation of policies that improve human welfare needs specific attention.

Because of the nature of the workshop charge to consider specific technical issues of integrating disparate data types into decision support systems that address human welfare, the committee thought that providing a compilation of the relevant technical literature would be more appropriate than a detailed discussion at the workshop. Workshop participants agreed this topic is vital for improving the effectiveness of decision support systems, although discussion did not address data formats, software, sensor platforms, and other highly technical issues. A bibliography of resources on this topic is included as Appendix B.

The workshop underscored the large, unrealized potential of the use of land remotely sensed data to a range of human welfare issues that, if developed, could parallel the significant advances in the use of remotely sensed data in the Earth sciences and global climate research in the past several decades.

1

Introduction

Remotely sensed observations from aircraft and satellites record images of the Earth's surface and atmosphere. Analyses of these data reveal changes in the Earth's land cover, sea surfaces, temperature, and many other terrestrial, marine, and atmospheric variables. Remotely sensed data have the potential to provide spatial information crucial for addressing some of the most challenging issues related to society's health and well-being. Today, remotely sensed data, combined with other types of data, are routinely applied to address some of these challenges based on decades of scientific development and operational experience. Weather forecasting is an excellent example of such application. In contrast, remotely sensed observations of the land surface are not routinely applied to decisions about human welfare, although the potential for usefulness is great.

Human welfare is defined in this report as the health and well-being of all humans. Factors affecting human welfare include human and ecosystem health, resource availability, and social and economic stability. Understanding the linkages between human welfare and land cover is progressing at a rapid pace. For example, the relation between land surface characteristics, habitat, and disease vectors at multiple spatial scales has advanced over the last decade. Responses of land productivity to land use and climate variability are revealing insights into the vulnerabilities of human populations to food insecurity. As scientific understanding progresses, so does the potential for applying land remote sensing in operational systems to support decision making about human welfare. Considerable scientific and institutional obstacles must first be addressed, however. Integration of remote sensing with other environmental and socioeconomic data is one such obstacle.

WORKSHOP OBJECTIVES

The National Research Council (NRC) formed an ad hoc committee to organize and conduct a two-day workshop on the contributions of land remote sensing to human welfare decisions. The workshop featured presentations and discussions on the contributions of remotely sensed data to land use and land cover change analyses and on ways to use physical, biological, and social characteristics of particular locations to support decisions about human welfare. The topics covered at the workshop included (1) considerations of the effective use of remote sensing, in combination with other types of data, to forecast the ecological and social repercussions of changes in land use and land cover; (2) usefulness of land remote sensing for improving human welfare; (3) technical issues that arise from the integration of disparate data (e.g., data collected from ground, aircraft, and satellite platforms at different temporal and spatial scales and socioeconomic data obtained through administrative and other sources) into decision support systems that address human welfare; and (4) trends in research and data availability that enable decision support systems and processes to use remotely sensed land data.

As an initial step, the workshop focused on two aspects of human welfare to which land use and land cover remotely sensed data could make major contributions: (1) human health and (2) the vulnerability of human populations to food insecurity due to climate change, land degradation, and other ecological factors. These two aspects were selected to represent a range of existing experience within the scientific and policy communities on the applications of remote sensing. The application of remote sensing to food insecurity is relatively mature. Application to human health has received less attention and research efforts are beginning to emerge. Other human welfare issues—such as disaster management, conservation, and national security—are no less important but were not directly addressed.

The committee posed the following questions to workshop participants to stimulate discussion of the challenges and opportunities for applying remote sensing to decisions on human health and food security:

- What factors can enhance the effectiveness of remotely sensed data of land use and land cover in decision support systems for human welfare?
- What are the lessons learned from successful and unsuccessful examples of previous applications?

- What are the scientific and institutional impediments to applying remotely sensed data of land use and land cover in decision support systems on human welfare?
- What are the key issues for data availability and integration with other data sources, such as socioeconomic data?
- What are important steps for improving coordination between scientists who interpret land remote sensing data and decision makers who potentially benefit from the remote sensing data and derived products?

PREVIOUS NRC WORK

The workshop built on previous National Research Council studies that resulted in publications encouraging the development and funding of remote sensing applications that benefit human welfare. The publication *Earth Observations from Space: History, Promise, and Reality* (NRC, 1994) provided a bibliography of more than 300 publications on remote sensing topics as well as a roadmap of the U.S. remote sensing program and can be considered a starting point in terms of identifying remote sensing applications. Other NRC studies on remote sensing include *Prospects for Developing Countries* (NRC, 1997), *Supporting Research and Data Analysis* (NRC, 1998b), *Assessment of Mission Size Trade-offs* (NRC, 2000a), *Ensuring a Climate Record* (NRC, 2000b), *The Role of Small Satellites* (NRC, 2000c), *National Spatial Data Infrastructure Partnership Programs* (NRC, 2001), *Toward New Partnerships in Remote Sensing* (NRC, 2002a), *Transforming Remote Sensing Data into Information and Applications* (NRC, 2002b), and *Using Remote Sensing in State and Local Government* (NRC, 2003b). In addition, the report *People and Pixels* (NRC, 1998a) directed attention to social concerns related to collection and analysis of remotely sensed data. The report *Down to Earth* (NRC, 2003a) summarized the importance and applicability of remotely sensed data for sustainable development, and drew upon experiences in African countries to examine how future sources and applications of geographic data could provide reliable support to decision makers as they work toward sustainable development.

INTENDED IMPACT OF WORKSHOP

Decisions are being made by the U.S. government about the future of the nation's remote sensing capabilities. In January 2004, President Bush announced the New Vision for the Nation's Space Exploration Program. An anticipated result is the development of new space-based technologies that will benefit mankind in the same way we now benefit from the more than 1,300 National Aeronautics and Space Administration (NASA) and other U.S. space-based technologies now in commonplace application.

Such technologies contribute to U.S. industry, improve quality of life, and help save lives (White House, 2004). It is timely for scientists of various disciplines to identify areas of great need and to determine how space-based capabilities can best benefit humanity.

This workshop was held to identify areas in Earth sciences research that have resulted in socioeconomic applications, specifically in the realm of food security and human health. As of this writing, a separate NRC Committee on Earth Science and Applications from Space is conducting a "decadal" study to generate consensus recommendations from the Earth and environmental science and applications community regarding a systems approach to space-based and ancillary observations, research, and related operational programs. The decadal study is unique in that it looks into a range of Earth science systems research and applications that are linked to societal objectives. This report attempts to provide information that will be relevant and useful to the decadal study committee in formulating recommendations for future research in Earth and space sciences.

STRUCTURE OF WORKSHOP

The workshop was structured around the two major human welfare issues selected by the organizing committee for particular focus: human health and food security. The first morning of the workshop consisted of plenary presentations on these topics. For each issue, an overview presentation was followed by case studies from the perspectives of both scientists producing information from remotely sensed data and practitioners using the information for decisions about human welfare.

The plenary session was followed by concurrent breakout sessions on each of the two topics. The first breakout sessions addressed the opportunities and challenges for land remote sensing. The subsequent breakout sessions addressed data availability and integration with other data sources from the user perspective. Each breakout group produced a summary of key points presented in the final plenary session.

The workshop focused the discussions on land remote sensing, yet it is noteworthy to mention that human welfare also benefits from ocean, ice, and atmosphere remote sensing. Ocean remote sensing contributes heavily to climate research and El Niño monitoring, and coastal remote sensing has direct applications to fisheries, oil spill mitigation, search and rescue, and coastal recreation. While these applications undoubtedly impact human welfare, the workshop's statement of task limited the discussions to land-based remote sensing technologies, and the absence of such discussion does not indicate its lack of relevance.

FINDINGS

This report summarizes the major points and ideas presented at the workshop. The report is based on background papers, presentations, and reports from the breakout sessions, with input from the organizing committee. Workshop participants did not address in detail the technical issues arising from integrating disparate data types into decision support systems that address human welfare, but the workshop committee did prepare a bibliography of references dealing with this topic (Appendix B). The information in this report is intended to be useful for other NRC committees and panels involved with recommending future research priorities in the Earth and space sciences. The issues addresses by workshop participants are also applicable to social scientists and policy makers regarding the importance of continual communication between remote sensing scientists and decision makers on human welfare.

2

The Current State: Opportunities for Applying Land Remote Sensing to Human Welfare

Remotely sensed land use and land cover data, in combination with other types of data, could profoundly influence decisions on human welfare, such as those related to subsistence and precision agricultural techniques, animal and human health, poverty mapping, and related environmental variables such as biodiversity.[1] Satellite data have the potential to reveal human, agricultural, and environmental interactions on a range of scales. The data could influence decisions addressing many health, agricultural, and environmental change problems threatening the sustainability of some of the planet's most disadvantaged communities. This section summarizes presentations made at the workshop, including an overview of the use of land remote sensing for human welfare applications, and case studies in the food security and human health domains.

SOURCES OF REMOTELY SENSED DATA

Space-based remotely sensed data are obtained via several satellite platforms. Data obtained through satellite sources (listed in Box 2-1) provide a means of linking issues of the environment (such as resources and infrastructure), disease (such as malaria or cholera), and poverty (such as nutrition). Medium-resolution Landsat and SPOT data have traditionally

[1]This material is derived largely from a white paper submitted by Dr. David Rogers, Oxford University, in preparation for the workshop. *Advances in Parasitology,* Volumes 47 (2000) and 62 (in press) contain a variety of papers on the applications of satellite imagery to vector and disease monitoring, mapping, and spread.

BOX 2-1
Examples of Remote Sensing Platforms

Meteosat is a European, geostationary, earth observation satellite positioned to cover Europe and Africa. It uses both visible and infrared wavelengths to display weather-oriented imaging of the planet. Meteosat is one of several geostationary satellites positioned around the equator to cover the Earth's surface. Meteosat is operated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), formerly an entity of the European Space Agency.

Advanced Very High Resolution Radiometer (AVHRR) is a radiation detection imager used by the U.S. National Oceanic and Atmospheric Administration (NOAA) to remotely determine cloud cover and the temperature of land, water, and sea surfaces with global daily coverage at approximately 1 km spatial resolution. These polar-orbiting series of satellites provide regional and global data useful for tracking forest fires and hurricanes. The data have also been used to determine land cover based on phenological variations in vegetation.

***Systeme Pour l'Observation de la Terre* (SPOT)** is a remote sensing system integrating a series of optical remote sensing satellites to provide Earth imagery at resolutions from 2.5 to 20 m for commercial use in various fields including land use planning, agriculture, forestry, geology, and water resources. The SPOT-VEGETATION sensor provides daily coverage at 1 km resolution. SPOT satellites are operated by the French Space Agency, *Centre National d'Etudes Spatiales.*

Medium Resolution Imaging Spectrometer (MERIS) is an imaging spectrometer satellite that primarily measures sea color in oceans and coastal areas via solar radiation reflected by the Earth. Ocean color data provide information about the ocean carbon cycle and thermal regimes of the upper ocean. This information is useful for scientific investigations as well as management of fisheries and management of coastal zones. MERIS is funded by the European Space Agency.

been used to examine detailed environments from space. Satellite data collected by the U.S. National Oceanic and Atmospheric Administration (NOAA) and from the National Aeronautics and Space Administration (NASA) Earth Observation System provide daily imagery of coarser spatial resolution, which is nevertheless useful for understanding seasonal events associated with agriculture and the transmission of many diseases. Such data reveal large- or small-scale patches of environmental similarity (spatial clusters of similar climate, soil, or topography are labelled "eco-

Moderate Resolution Imaging Spectroradiometer (MODIS) is a sensor used by the National Aeronautics and Space Administration (NASA) to detect electromagnetic energy at 250 to 1,000 m spatial resolution. The images provide a complete electromagnetic picture of the globe every two days, allowing rapid biological and meteorological changes to be captured. MODIS is part of the Earth Observation System, a multinational and multidisciplinary mission managed by NASA to study earth-sea-atmosphere interactions in order to understand their singular and cumulative effects on global climate change and the environment.

Landsat satellites capture high-quality, moderate-resolution images of the Earth's land mass, coastal boundaries, and coral reefs every 16 days at approximately 30 m spatial resolution. The space-based land remote sensing data are acquired to support observation of changes on the Earth's land surface and surrounding environment. The Landsat program is jointly managed by NASA and the U.S. Geological Survey.

IKONOS is a commercial earth imaging satellite collecting high-resolution data. This satellite orbits the Earth every 98 minutes and provides images with 1 and 4 m resolution.

QuickBird is a high-resolution commercial satellite owned and operated by DigitalGlobe. With a Ball Global Imaging System 2000 sensor, QuickBird uses remote sensing to a 0.61 m pixel resolution degree of detail. This satellite is an excellent source of environmental data—useful for analyses of changes in land usage, agriculture, and forest climates—and social data, such as house size, lot size, quality of roofing, and presence of cars, all of which reveal information about the vulnerability of the occupants to risk.

SOURCES: ESA, 2006; EUMETSAT, 2006; NASA, 2006; NCAR, 2006; NOAA, 2006; Satellite Imaging Corporation, 2006; Space Imaging, 2006; Spot Image, 2006; USGS, 2006.

zones") and thus provide a unique view of the environmental context of human activities over broad regions.

MONITORING FOR FOOD PRODUCTION AND SECURITY

Workshop participants considered the current and future opportunities for applying remote sensing in the context of improving food security worldwide. The workshop considered food security as sufficient agricultural productivity and access to food. Two extremes of technological intensity in agricultural systems were considered. The first extreme is the use of precision agriculture to maximize crop yields. Precision agriculture, or variable rate technology (VRT), combines the tools of global positioning system (GPS) technologies, remote sensing tools, geographic information systems (GIS) data, communications, and spatial statistics to identify variations within an agricultural field that can be considered individual management units. The second extreme is the avoidance or mitigation of food crises and famine in areas reliant on subsistence agriculture. In developing countries, remote sensing applications are useful for predicting and minimizing breakdowns in food production that often cause food crises and famine. Because it takes a considerable amount of time for remote sensing technologies to evolve into applications useful for human welfare, workshop participants also considered the history of the use of remotely sensed data as applied to agriculture.

The History of Remotely Sensed Data in Agriculture

Data from the Landsat series of sensors have been the cornerstone of remote sensing applications for monitoring agricultural yields since the 1970s.[2] A series of large application programs were initiated in preparation for Landsat. The U.S. Landsat-based agricultural remote sensing programs were driven by crop identification and area estimation programs such as the Corn Blight Watch Experiment (MacDonald et al., 1972), the Large Area Crop Inventory Experiment (MacDonald and Hall, 1980), and the Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS).

The Corn Blight Watch Experiment was developed in response to the southern corn leaf blight (SCLB) fungus, first noted in cornfields in the southern and midwestern United States in 1970. A highly virulent strain of SCLB caused extensive and widespread damage to corn crops in those states and destroyed approximately 15 percent of the U.S. corn crop (Zadoks and Schein, 1979). This provided an opportunity for multiple agencies (e.g., NASA and the U.S. Department of Defense) to evaluate remote sensing technologies using the high-altitude Air Force RB57 aircraft equipped with cameras to collect data on selected flightlines over an eight state area in the Midwest (Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, Ohio, and Wisconsin). From a practical standpoint, the experiment failed to detect the SCLB until the corn crop

[2]This material on the history of Landsat applications to agricultural monitoring is derived largely from a white paper submitted by Dr. Chris J. Johannsen, Purdue University, in preparation for the workshop.

was severely damaged. However, it did demonstrate the importance of temporal coverage for crop identification and the performance of timely analyses of vegetative growth. More importantly, the results illustrated the feasibility of using aircraft multi-spectral photographic and scanner data for crop identification and condition assessment, and the potential of remote sensing techniques in detecting crop disease (Bauer et al., 1971).

After the launch of the Landsat mission, the Large Area Crop Inventory Experiment (LACIE) of the 1970s was initiated by NASA, the National Weather Service, and the U.S. Department of Agriculture (USDA) to create and test a wheat crop forecasting system. The crop monitoring system was designed to provide information on the area planted with a particular crop and to provide information on crop health based on temporal remotely sensed data and ancillary data such as weather data and USDA reports. While the program called attention to the possibilities for developing various useful applications of remote sensing data, the project did not anticipate problems of differentiating crops from satellite imagery (Mitchell, 1976). Similar to the Corn Blight Watch Experiment, LACIE never matched the ambitious goals set by its sponsors (Mack, 1990); however, the LACIE program similarly brought to light the capabilities of remote sensing technologies. Should LACIE and the Corn Blight Watch Experiment be conducted today with intervening advances, the experiments, it could be argued, would be successful.

The AgRISTARS program of the 1980s expanded on the LACIE partnerships to examine wheat, corn, and rice on a global basis (NASA, 1981). The AgRISTARS program was successful in demonstrating the value of timely data and limited ground reference information for identifying crops and predicting yield. The USDA Foreign Agriculture Service still uses the approaches developed from AgRISTARS.

The Corn Blight Watch Experiment, LACIE, AgRISTARS, and Famine Early Warning System Network (FEWS NET) programs recognized the utility of multi-temporal remotely sensed data for consistent and accurate crop identification, and firmly established the feasibility of using multi-spectral scanner data and digital analysis techniques for crop identification and aerial estimations. The Landsat System whetted the appetite for satellite data for many uses, especially in the research community. However, plans for operational use of the Landsat platform were weakened because of the inability to sustain operations with only one operating satellite, changes in management, and other issues.

Applications of Remote Sensing for Agricultural Monitoring and Support

The use of remotely sensed data for agricultural applications in the industrialized world, including precision farming, was presented by Chris J. Johannsen, professor emeritus of agronomy at Purdue University, and is summarized in Box 2-2. Dr. Johannsen showed workshop participants how farmers have used remote sensing data to more effectively manage their farms, with specific mention of the use of Landsat data for the Corn Blight Watch Program (CBWP) and the AgRISTARS program focused on global wheat, corn, and rice production.

The presentation provided the context for subsequent discussion focused on opportunities for more contemporary sensor technologies for agricultural monitoring. In particular, the availability of high-resolution imagery (e.g., less than 5 m spatial resolution) from commercial vendors has provided a better match to the scale of data that individual farmers need for farm-level monitoring. IKONOS and Quickbird data provide the opportunity for high-resolution crop monitoring, but the high cost of data limits the extent to which these technologies are actually utilized. While the application of high-resolution technology for frequent crop monitoring may not be feasible for agriculturalists in less developed countries due to these cost issues, the ability of remotely sensed data to provide general data on soils could offer immediate benefits. Workshop participants voiced some concern regarding the current number of sensors in orbit applicable to crop monitoring and the uncertainty of funding for future remote sensing missions with an emphasis on agricultural uses.

Monitoring of Subsistence Agriculture

Food production and income generating activities are far more complex among systems labelled subsistence agriculture than that term implies. Farming in such systems invariably involves consumption production (food for the household) but may also involve small-scale commercial production. In addition, such households increasingly rely on off-farm employment, remittances, and other non-food-producing activities. Typically, the more subsistence oriented the farming is, the more that system is constrained by the biophysical and socioeconomic environments in which it exists.

Remotely sensed data, in combination with other types of data, can reveal valuable information about environmental conditions that can subsequently impact the livelihoods of farmers. Environmental constraints on subsistence agriculture are revealed by comparing spatial distributions of agricultural indicators—such as the local abundance of humans, crops,

BOX 2-2
Land Remote Sensing Applications for Agricultural Support

Chris J. Johannsen, Purdue University

Precision agriculture enables farmers to predict and maximize crop yields and determine the extent of damage from storms or other events. The basic premise of precision farming is that identified variations within an agricultural field can be considered individual management units. VRT can be applied to the specific management units within a field by adjusting tillage according to soil type, adjusting seed variety and rates, and adjusting the rates of fertilizer or pesticide application. Adoption of GPS-based auto steer guidance systems can increase the accuracy of seeding and pesticide applications. Remotely sensed data can be used to determine vegetation activity and the locations of drought-prone areas, areas where growth tends to be favorable, areas to keep fallow, and areas prone to weed or insect infestation. Thirty percent of farmers who are equipped with yield monitors are effectively recording and using yield data, while the other seventy percent observe differences in yield but do not keep records (Lowenberg-DeBoer and Erickson, 2001).

Remotely sensed data potentially play an important part of an early warning system (EWS) established to identify and notify farmers of agricultural pollutants or other problems that put their crops at risk. The U.S. Environmental Protection Agency (EPA) is implementing a three-phase program to test and evaluate early warning systems for drinking water infrastructures (EPA, 2005). The EWS setup for water quality assessment may include automated monitoring for contamination, with data transmitters communicating data via direct wire, phone line, radio, or satellite to data acquisition systems. Such systems would be able to validate, store, and analyze data by means of flow predictive models and GIS systems. When an appropriate alarm is triggered, the information is transmitted to decision makers who can then notify and orchestrate the appropriate response to the event.

There are barriers to practical application of EWS: EWS cannot be established everywhere to monitor all potential contaminants at all times. Most EWS are currently deployed in source water to detect a contaminant, where contamination has already been found. When analyzing data, most hydrological models assume uniform conditions for large areas of land. The greatest barrier to automated EWS, however, is the cost of transmitting data on a real-time basis.

Potential applications of remotely sensed data depend on the types and values of crops, geographic features such as soils of the area being farmed, farmer's use of fertilizer, irrigation and other types of management, the remote sensing expertise available to the farmer, and the timeliness of remotely sensed data. Cost is a large barrier to the application of precision farming. Most applications occur when appropriate data are available at the right time, at an affordable cost, and when there is access to expertise to use the data. Progress is steadily being made with improvements in data quality, user-friendliness of software, and access and affordability of remotely sensed data. To expand the application of precision farming, systems have to become more automated, data and software formats must become more uniform to allow data sharing, and continued sources of application funding will also be required. In addition, more providers of remotely sensed data are required, and a greater emphasis on data calibration within all parts of the VRT system is needed.

and cattle—with spatial distributions of ecozones, which are defined by similar seasonal patterns of vegetation, soil, or climate. Correspondence analysis commonly shows exceptionally good correlation between agricultural indicators and ecozones. Human farming systems are vulnerable to climate variability and other forces in much the same way as habitats and other ecological features are. By identifying particularly vulnerable ecozones, informed development policies aimed at reducing food insecurity may be formulated.

The Famine Early Warning System (FEWS)

Remote sensing technologies can be used, along with other data collection methods, to monitor agriculture in developing countries with populations dependent on subsistence agriculture, and its applications focus on the need to avoid food crises. Monitoring circumstances that can lead to an extreme breakdown in food production is a primary concern. Workshop participants considered the use of remote sensing technologies to monitor food security in Africa via the Famine Early Warning System Network (FEWS NET) (see Box 2-3 for a history of FEWS and FEWS NET).

Signs of imminent famine can be identified by combining remotely sensed data, precipitation data, and surface water data to characterize and model hazards threatening vulnerable livelihoods. Conventional ground-based networks of hydrometeorological data are sparse and unable to provide data in realistic time frames to be effective in predicting famine (Washington et al., 2004). Remotely sensed data, combined with numerical modeling and GIS, are important tools for FEWS NET (see Box 2-4 for Current FEWS NET programs).

Monitoring rain-fed agriculture and rangeland conditions is a key input to food security assessment in sub-Saharan Africa. Satellite remote sensing has played a vital role since the 1980s by complementing sparse conventional surface climate monitoring networks. Estimates of vegetation vigor, rainfall distribution, and surface water supplies are forthcoming from current systems. Future remote sensing missions, planned and proposed, promise to provide increasingly higher-quality coverage in terms of spatial resolution, frequency of acquisition, and sensor technology. Full implementation of these missions will be vital to famine early warning in Africa because surface climate monitoring networks, unfortunately, continue to weaken and will not likely improve any time soon.

While the environmental conditions monitored by remote sensing are critical, experience with FEWS reveals that these data are most useful in combination with socioeconomic data on the livelihoods of local populations. The combination of environmental data and knowledge of

BOX 2-3
FEWS and FEWS NET

In response to the 1985 Ethiopian famine that resulted in more than 1 million deaths and an outpouring of worldwide aid, most of which arrived too late, the U.S. Agency for International Development (USAID) established the Famine Early Warning System in an effort to prevent future food security disasters. Beginning in 1986, FEWS provided timely and accurate information about drought-induced famine conditions in Africa so that decision makers could address food shortages and other causes of food insecurity.

While the FEWS mission to improve food security in 17 drought-prone African countries remained the same, the need arose to establish more effective, sustainable, and African-led food security and response planning networks that reduce the vulnerability of groups to both famine and flood situations. In July 2000, the U.S. government built upon earlier FEWS operations to create a partnership-based Famine Early Warning System Network.

The U.S. Geological Survey (USGS) Earth Resources Operations and Science (EROS) Data Center (USGS/EDC)—in cooperation with USAID, NASA, NOAA, and Chemonics International Incorporated—work to provide the data, information, and analyses needed to support FEWS NET activity. NASA and NOAA collect and process satellite data that provide the spatial coverage and temporal frequency necessary for monitoring both vegetation condition and rainfall occurrence throughout the entire African continent. Chemonics maintains staff in 17 African countries to provide ground-based input into FEWS NET activity. Chemonics is ultimately responsible for providing warning of potential problems.

FEWS-Chemonics publishes a monthly bulletin distributed to decision makers around the world. The USGS/EROS Data Center provides technical support services to FEWS in the use of remote sensing and GIS technologies, and provides long-term data archive and distribution services. The African Data Dissemination Service provides Internet access to the data collected for FEWS NET activity.

SOURCE: FEWS NET, 2006.

livelihoods and coping capabilities determines vulnerability to local food shortages.

Box 2-4 summarizes a presentation made by James Verdin of the U.S. Geological Survey on how FEWS NET uses and treats remotely sensed data in its efforts to predict incidents of food insecurity. Dr. Verdin concluded that future missions using remote sensing platforms to track surface and environmental variables would greatly benefit the ability to monitor food security in Africa and much of the planet.

Workshop participants noted the success of FEWS NET in applying remote sensing data and, more recently, integrating these data with

BOX 2-4
Famine Early Warning System Network: Use of Remote Sensing to Monitor Food Security in Africa[a]

James Verdin, U.S. Geological Survey

The Famine Early Warning System Network interprets vulnerability and food security hazards to populations by quantifying which and for how long populations face food insecurity. Remotely sensed data are used to fill in the gaps in ground-based observations, as the routine monitoring of rainfall, vegetation, crops, and market prices is made more meaningful by assembling information on how households access food and income.

Remotely sensed data are used to develop vegetation index imagery to identify changes in seasonal landscape that could indicate drought (Hutchinson, 1991). Below are some of the tools used by FEWS NET to measure and analyze conditions in Africa:

- The Normalized Difference Vegetation Index (NDVI) calculates the amount of vegetation in a given area by measuring the difference between near-infrared and red light, since chlorophyll in leaves absorbs red light but reflects infrared. By comparing current NDVI values with historical values, it is possible to spot agricultural areas that are significantly less productive than in the past and, thus, in danger of crop failure.
- Rainfall estimates (RFEs) blend geostatistical rainfall data with imagery taken from thermal infrared and microwave sensors to estimate crop yields, create geospatial crop water balance models, and evaluate the availability of moisture to a crop relative to its needs over the course of the growing season (Xie and Arkin, 1997). FEWS NET uses the RFE 2.0 from the NOAA Climate Prediction Center, which provides daily estimates of 24-hour precipitation totals with an approximate 10 km grid cell resolution. RFE data fill the large spatial gaps in FEWS NET rainfall monitoring, while the available ground-based data significantly reduce the bias inherent in estimates based on satellite data alone. The Water Requirement Satisfaction Index (WRSI) is the ratio of actual crop evapotranspiration to the amount that would occur with a full water supply (Frère and Popov, 1986; Verdin and Klaver, 2002; Senay and Verdin, 2003). Maize yield estimates based on the WRSI (calculated with RFE) were found to agree ($r = 0.8$) with official reports in a test with 1996-1997 data for Zimbabwe (Verdin and Klaver, 2002). The figure below is an example WRSI map for the West African Sahel.
- The improved spatial resolution offered by Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) time series, dating back to 1981, will continue to play a vital role in monitoring climate. The Visible Infrared Imager Radiometer Suite (VIIRS) on the upcoming National Polar-orbiting Operational Environmental Satellite System (NPOESS) is crucial to maintain continuity into the future for wide-area, high-frequency vegetation index imagery.

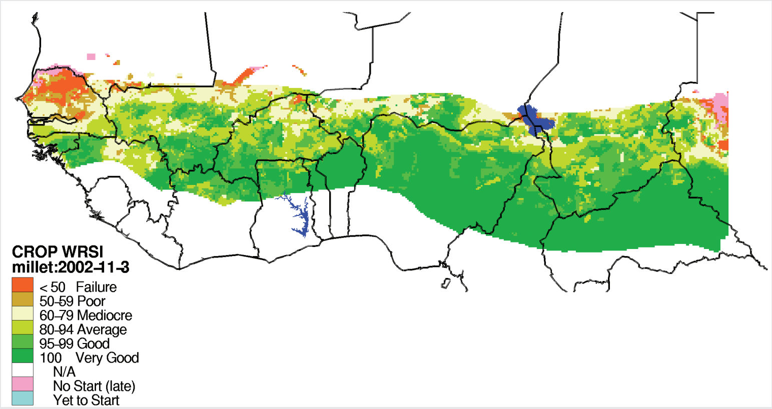

FIGURE: Map of the WRSI for the Sahelian countries of West Africa, 2002. Intervals of WRSI correspond to levels of crop performance. Growing conditions for millet that year were especially poor for northern Senegal and southern Mauritania. SOURCE: FEWS NET, 2004. Image provided by Gabriel Senay, USGS. Used with permission.

- Building on the success of the Tropical Rainfall Measuring Mission, the Global Precipitation Measurement (GPM) mission will ensure the future of remote sensing estimates of rainfall. The GPM international constellation of satellites will increase the availability of microwave estimates of precipitation, reducing and ultimately eliminating the need for reliance on thermal infrared image data.
- Tracking trends in the water surface elevation of major lakes and reservoirs can provide valuable insight into the relative abundance of water for human consumption, agriculture, and pastoralism. NASA and USDA have successfully adapted systems for radar altimetry of the oceans to monitoring water bodies in Africa. The proposed Water Elevation Recovery (WatER) mission promises to map changes in water height and slopes of inland water surfaces with centimeter accuracy. If authorized, the mission would be of great benefit over the wide regions of Africa (and much of the Earth) that lack adequate conventional stream gauging.

[a]For more information, see Appendix F for white paper authored by James Verdin.

livelihood analysis. Participants did not have information on the actual effectiveness of the information on decision making and the degree to which this information has reduced food insecurity. Such information would be needed for a full evaluation of this remote sensing application.

Remote sensing platforms supply much of the data used in famine early warning. However, remotely sensed data are useful for predicting food shortages and vulnerabilities only when combined with other environmental, political, economic, and social data. Richard Choularton, contingency and response planning advisor at FEWS NET, presented the use of remotely sensed data to provide actionable information to decision makers trying to prevent or respond to famines and food crises. FEWS NET focuses on how populations in different areas access food and income and how they spend their income. FEWS NET combines socioeconomic data with remotely sensed data and other monitoring tools to estimate the likely impact of hazards such as drought, floods, or locusts on populations. Box 2-5 summarizes Richard Chourlarton's presentation to the workshop participants.

MONITORING FOR HUMAN HEALTH

Human health in the broad sense results from a combination of multiple factors including food production, availability, and distribution; environmental health hazards; contagious and infectious diseases; chronic health issues; and health care delivery. All of these factors have traditionally been considered separately by a variety of organizations. Workshop participants viewed the potential for land remote sensing to help integrate these many factors.

Applications for Human Health

Infectious diseases affecting humans and animals in the tropics have spatially and seasonally varying impacts that can be studied using satellite data. There are two different ways to conduct research involving remotely sensed data in human health studies: using process-based and pattern-based models. Both are useful and important. Process-based or mechanistic models that simulate the underlying biological processes of disease transmission and spread are applied to foretell the future and predict the outcome of different land use, environmental, or policy scenarios. For most diseases, however, the current understanding of the processes has been insufficient; thus, the use of statistical analyses, or pattern-based, approaches can establish strength of certainty in understanding how the processes work. Statistical approaches reveal associations among different variables and do not determine the cause-and-effect relationships

BOX 2-5
**Famine Early Warning and Remote Sensing—
A User Perspective**

Richard Choularton, FEWS NET

The mission of FEWS NET is to provide decision makers with accurate, timely, and actionable information to prevent food crises and famine. While remote sensing has been one of the most valuable and successful tools used by FEWS NET to achieve such an objective, remote sensing products alone cannot provide a holistic understanding of intertwining environmental, political, economic, and social conditions. Many parts of the world have few alternative sources of information or have inaccurate data (such as census data). Remotely sensed data can provide a means for indirectly locating otherwise uncounted populations, though the results may not be accurate.

Recent literature points to famines and disasters as being a part of broader structural and contextual events (Kreps, 2001; Tierney et al., 2001; NRC, 2006). The combination of remote sensing data with livelihood-based analyses and the identification of the stages of a disaster have enabled FEWS NET to inform and support decisions. Livelihood-based analysis examines how populations in different areas access food and income and how they spend their income. Remote sensing data coupled with livelihood-based analysis can enable users to interpret how hazards such as drought or floods are likely to impact populations. The Turner model of the stages of disaster looks into what causes disasters by identifying the six stages of disaster (incubation period, triggering event, onset, response, recovery, and full adjustment) (Turner and Pidgeon, 1997). In combination with remote sensing data, this model has been useful to FEWS NET in determining the stage of famine and responding with the appropriate course to mitigate a food crisis.

The key to an effective response is the ability to predict a food crisis well in advance. Data provided through remote sensing technologies not only make it possible to predict food crises and famines ahead of time, but also can help determine the most effective way to respond to these crises. However, regardless of the amount of data and analysis available, analysis has little value without action.

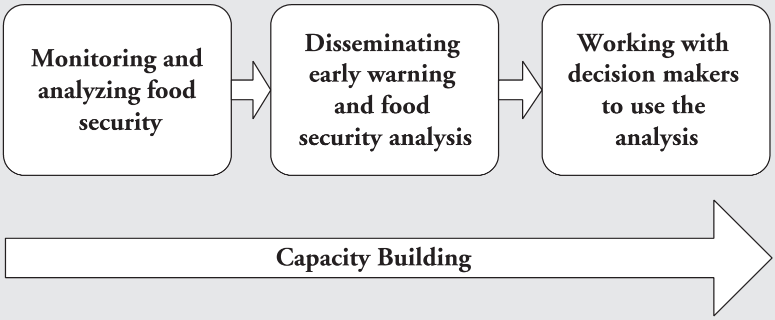

FIGURE: A summary of FEWS NET's operational plan, which incorporates remotely sensed data and livelihood-based food security analysis into decision-making support systems. SOURCE: Richard Choularton, FEWS NET. Used with permission.

required to build process-based models. Nevertheless a careful application of pattern-based approaches can suggest fundamentally important links between environmental drivers (including climate) and demographic processes (birth, death, infection, recovery). These links can then begin to inform a process-based modelling approach. The pattern-based technique is extremely flexible and achieves respectable levels of accuracy with remarkable consistency. Satellite data bridge the pattern-based approach to infectious disease modelling by providing environmental data over large areas at multiple spatial and temporal scales. Without the large spatial or temporal extents provided by remotely sensed data, the process-based modelling approach would be extremely difficult.

Disease spread, however, is made more complicated by ever-expanding regional and global transportation infrastructures. Remotely sensed data, especially in combination with other GIS data, can be used to determine the relationships between environmental conditions across the world's air- and seaport network and the dramatic emergence and re-emergence of disease fostered by the transport of pathogens. By analyzing these relationships and understanding past trends, we can better predict and anticipate future disease patterns and movements.

Case Studies

Information derived from remotely sensed data, combined with traditional means of ground-based data collection, can be useful in identifying statistical patterns of disease origin and spread. Two case studies—hantavirus and cholera—were presented at the workshop.

Hantavirus

Terry Yates presented a case study describing how a 1993 outbreak of a novel and potentially deadly hantavirus in the American Southwest was linked to a species of deer mouse, and how the spread of the disease was exacerbated by climatic variability from El Niño conditions (see Box 2-6). This case study shows how remote sensing data can help monitor disease incidents and disease progression.

Remotely sensed data were used to relate known instances of infection, local rainfall, vegetation, topography, and deer mouse habitat and population. With this information, future potential outbreaks of the disease can be predicted and measures could then be taken to educate affected populations on steps to avoid contact with the carrier.

BOX 2-6
Opportunities and Challenges in Using Land Remote Sensing: A Case Study in Forecasting the Spread and Risk of Infectious Disease

Terry L. Yates, University of New Mexico

Hantaviruses are a group of negative-stranded RNA viruses, some of which are known to be highly pathogenic for humans. Diseases caused by hantaviruses were thought to be largely restricted to Europe and Asia until 1993 when an outbreak of hantavirus pulmonary syndrome (HPS) caused by a previously unknown hantavirus, Sin Nombre virus (SNV), occurred in the southwestern United States. Initially, there was a fatal outcome in more than 50 percent of human cases of the new virus. The deer mouse, *Peromyscus maniculatus*, was found to be the virus's primary reservoir (Nichol et al., 1993). Since the discovery of SNV, some 27 additional hantaviruses have been described in the New World (Schmaljohn and Hjelle, 1997; Peters et al., 1999).

While the cause of the outbreak in 1993 may be speculative, more than 10 years of ecological monitoring in the American Southwest and the results of retrospective serosurveys for SNV using archived rodent samples suggest a climate-driven trophic cascade model for SNV outbreaks in North America. It appears that increased late winter and spring precipitation in the southwestern United States driven by the El Niño-Southern Oscillation was responsible for an increase in plant primary productivity, which in turn resulted in increased rodent population densities. A direct but delayed correlation exists between increases in deer mouse population densities, increases in density of infected rodents, and increased incidence of HPS. Furthermore, retrospective data show that SNV and other New World hantaviruses have been present, essentially in their current form, in the Western Hemisphere for at least decades and probably have been coevolving with their rodent hosts in the New World for approximately 20 million years.

An understanding of the relationship between climate change, ecology, and hantaviruses may enable development of improved predictive models for the prevention of human infection and improve the understanding of biocomplexity on a rapidly changing planet. A complex trophic cascade, in which impacts on one trophic level permeate through other levels, triggered by climate fluctuation can be a model for predicting HPS risk to humans. In addition, data from studies in North and South America suggest that certain human land use patterns that result in a reduction of biological diversity favor reservoir species for hantavirus and significantly increase human risk for HPS. These data make it clear that understanding the ecology of infectious diseases will require a long-term, multidisciplinary effort that is essential to public health efforts of the future.

Although on a broad regional scale there is an increased risk to humans from the trophic cascade triggered by increased precipitation input into the environment, the actual risk to humans is highly localized and depends on a complex series of variables. Other factors, such as landscape heterogeneity, microclimatic

continued

BOX 2-6 Continued

differences, rodent disease, local food abundance, and competition, may be involved as well, and such complexity will have to be taken into account before a predictive model of HPS risk can be developed on a fine-grained scale.

Understanding the biological complexity of natural and human-dominated ecosystems will be required before ecological and evolutionary forecasting can be employed on the scale needed to safeguard the public health against hantaviral and other zoonotic disease outbreaks. Large-scale, long-term, multidisciplinary studies also will be needed to determine if foreign or genetically modified pathogens are being introduced into our ecosystems.

Near-real-time forecasting of risks of these types of diseases will be possible only if remote and other types of sensing become utilized on a continental or global scale.

Cholera

Rita Colwell presented a case study using remotely sensed data to correlate water surface temperature and population densities with known cases of cholera infection (see Box 2-7). The case study illustrates the linkages between human populations and biological systems in coastal areas. Remotely sensed data have been a major factor in understanding these linkages.

By using remotely sensed data along with socioeconomic and other ancillary data, researchers are able to determine populations at risk for cholera infection, and educational outreach can be targeted to those populations. In the case study presented to workshop participants, women in Bangladesh were taught to filter their drinking water by pouring it through old sari cloth folded eight to ten times. Such folding created a 20-micron mesh filter (as determined by electron microscopy), reducing the number of zooplankton in the drinking water and potentially preventing the ingestion of infectious levels of cholera bacteria. This case study is a prime example of how integrating remotely sensed data with socioeconomic and other data can provide new applications by incorporating multidisciplinary information with existing remote sensing technologies.

BOX 2-7
Ecology and Epidemiology of Cholera:
A Paradigm for Waterborne Diarrheal Diseases

Rita Colwell, University of Maryland College Park and Johns Hopkins University

Diarrheal diseases are among the leading global causes of death by infectious disease, third only to acute respiratory infections and AIDS, and particularly acute among children under 5 (WHO, 1999). Cholera is a diarrheal disease caused by the bacterium *Vibrio cholerae* that infects the intestine, and is transmitted through ingestion of water or food that is contaminated by the cholera bacterium. Pathogens such as *V. cholerae* can exist in a viable yet inactive state, like many other gram-negative bacteria that also enter dormancy when faced with adversity. Direct fluorescent and molecular genetic assays of water samples collected from the Chesapeake Bay and off the coast of Maryland and Delaware demonstrated that vibrios are present year-round, yet their levels were hard to determine with traditional methods of culturing. Similar results were obtained in the Bay of Bengal and the rivers and ponds of Bangladesh.

With remote sensing, however, data can be gathered to supplement existing information that would be useful across multiple disciplines. For instance, it is known that the zooplankton and phytoplankton populations are highly correlated, since zooplankton consume phytoplankton. Phytoplankton blooms are strongly correlated with seasonal above-average temperatures at the surface of the sea. Sea surface temperature (SST) can be monitored with remote sensing instruments, and these SST measurements can be used to estimate phytoplankton and zooplankton blooms. Ocean temperature and height patterns were found to be linked to cholera outbreak patterns in Bangladesh, India, and South America. During the El Niño years, the associated warm water patterns were correlated with new cholera outbreaks during 1991-1992 on the South American coast of Peru. Using remote sensing, research has shown that copepod and *Vibrio* populations are coupled to salinity, temperature, and sea height and hence to both seasonal and interannual climactic patterns in a complex, nonlinear manner. Simply stated, there is a positive correlation between the seasonal increased sea surface temperature and sea surface height and subsequent outbreaks of cholera that occur in the late spring and fall months in Bangladesh. Thus, remote sensing has the potential to contribute to a global warning system for increased plankton production and associated cholera outbreaks.

3

Challenges and Potential for Applying Land Remote Sensing to Human Welfare

Though there have been great advances in the use of remotely sensed data in the Earth sciences and global climate research in the past several decades, the potential for applying remotely sensed data to a range of human welfare issues is largely undefined and unrealized. What does remotely sensed data offer that other capabilities do not? How can realizing the potential enable decisions that benefit human health and welfare? What can be done to overcome the barriers to the use of remotely sensed data for human welfare purposes? Workshop participants again assembled into two groups to discuss these questions as they relate to food security and human health issues, respectively.

Workshop participants noted that as in other areas of science, the integration of knowledge gained from remotely sensed data into decisions on human welfare can be categorized into four separate processes: observing, explaining, projecting (forecasting), and applying in practice. Remote sensing applications are usually associated with observing and then, to a lesser extent, with explaining and projecting. Remote sensing provides a means to indirectly observe patterns or changes, which then informs explanations of causal relationships and processes. Projections are based on observations, understanding of processes, and assumptions about the future. Modeling tools developed for making projections are tested and refined by further observations. The modeling tools can then be used to aid decision makers in responding to crises or implementing longer-term development strategies. Creating a thread linking observation, explanation, and projection to application is vital to providing appropriate information to the domain of decision makers.

Chapter 2 of this report offers examples of how the use of remotely sensed data can contribute to human health and welfare. This chapter summarizes workshop discussions regarding opportunities and challenges in the application of remotely sensed data of attributes of the land surface such as land cover, human infrastructure, productivity of vegetation, and seasonality for improving food security and human health.

Workshop participants recognized that environmental and socioeconomic information provided by remote sensing and other sources constitutes only one aspect of effective decision making. The political, economic, and institutional setting defines the framework in which such information can be used. Decision makers need relevant information to make informed decisions that will have significance and impact and also need robust institutional capabilities to be able to support and carry out their decisions. While good information and institutional capabilities are both critical for effective decision making, it is often the lack of the latter that inhibits good decision making from being actualized.

THE POTENTIAL OF REMOTE SENSING APPLICATIONS FOR FOOD SECURITY

Although substantial donor resources are dedicated to providing food aid, the ability to monitor food availability and predict food shortages is of equal—or arguably greater—importance in promoting food security. Food security issues can be divided into three general elements: food availability, accessibility, and utilization. Integrating remote sensing information into decision-making networks can improve the capacity of decision makers to make effective choices in each of these domains. Remote sensing technologies provide seasonal information that is cheaper, more timely, and available over larger areas than traditional sources of information on food accessibility. Greater investments in remote sensing infrastructures could aid policy makers in forecasting future food availability and accessibility and to plan appropriately, perhaps by instituting multigenerational development efforts.

The production and delivery of food resources to populations in need involves interactions between a complex array of social and environmental factors. Decision makers must understand where food shortages are likely to occur and be aware of the location and accessibility of surplus food resources. Remote sensing identifies vulnerabilities based on environmental variability and can enhance land-based environmental data. Incorporating information from remotely sensed data, in combination with administrative and agricultural records over long periods of time, can allow decision makers to identify areas more statistically prone to food crises and to identify the physical accessibility and quality of needed resources. In order to lessen the severity of food crises, decision makers must be aware of factors that contribute to them, including general human and livestock health and the quality and availability of clean water supplies. Strategically deciding to fix wells and improve human and livestock health prior to a crisis may ultimately be of greater long-term benefit than supplying food, because health and income sources will then be more resistant to crises and require less food aid.

A key challenge in the effective use of remotely sensed data is getting the appropriate data products into the hands of the appropriate decision makers, in time frames reasonable for action. Although there are examples of government agencies (such as the U.S. Geological Survey, Environmental Protection Agency, and regional multi-government agency groups such as the South African Development Community), international agencies (such as the United Nations Food and Agriculture Organization), and nongovernmental organizations (NGOs) (such as conservation NGOs including the World Wildlife Fund and Conservation International) developing the required technical knowledge to take advantage of remote sensing technologies, there is generally insufficient communication between the community interpreting remote sensing data and the policy-making community. The challenge is to develop the capacity for these groups to communicate so that the remote sensing community understands the needs of policy makers and policy makers understand the capabilities of remote sensing.

To help decision makers comprehend the potential of remotely sensed data applications, data must be provided in the form of knowledge delivery and as a tool for decision making, rather than as a list of observations or prescriptions. The integration of data is key: when combined with socioeconomic data, remote sensing data can be useful for direct applications to decisions about human welfare. The Famine Early Warning System Network (FEWS NET), for example, has monthly briefings with the U.S. Department of Agriculture and other organizations and distributes a two-page executive overview describing the status of food security in Africa several times a month (see Appendix C). Such communication distills data analysis down to concise points, identifying areas of risk on a country-level map for high-level decision makers. By learning what information decision makers need, FEWS NET can translate remotely sensed data into information that contributes directly to effective planning for potential food shortages. To date, there has been no indication of the long-term changes and practices due to FEWS NET activities. An evaluation of programs such as FEWS NET is needed, since the effectiveness of its methods has not been fully analyzed.

To process and provide the appropriate remotely sensed data and information, infrastructures created by groups such as FEWS NET must consist of teams of remote sensing specialists, ground receiving stations, and web-based data archives. FEWS NET's infrastructure allows fairly effective communication among specific agencies, providing ample opportunity for policy makers and the remote sensing community to communicate the needs and abilities of each. In many cases, however, decision makers are unable to react to what has been learned from remotely sensed data. The crisis may already exist and procurement cycles may be out of phase with the timing of data used for policy decisions.

Remote sensing infrastructures do not exist, and expertise is not available in many at-risk areas to take advantage of the current state of the technology of remote sensing applications. NGOs often fill this gap by providing critical expertise, particularly in developing countries. Many NGOs, intergovernmental organizations, and aid organizations are international in scope, and often have excellent in-house technical resources (such as the United Nations Food and Agriculture Organization). In developing countries, national universities can play a critical role in developing local remote sensing infrastructures by disseminating remote sensing resources and training future generations of remote sensing specialists. Many universities in less developed nations have connections to U.S. land-grant institutions that can provide them with means to acquire useful and necessary skills to tackle local problems. Despite an awareness of the value of remote sensing applications, however, there are often only limited resources dedicated within organizations focused on remote sensing applications.

To realize the full potential of remote sensing for food security issues, integrated approaches are necessary that relate the real-time connections between food, water, and health. The importance of remote sensing applications to food security goes beyond disaster relief. The scientific community can be most useful to decision makers by integrating the biophysical domain with social data. Livelihood analysis, as done by FEWS NET, is an example of socially informed remote sensing analysis and the benefits of cross-disciplinary collaborations. Remote sensing, natural, and social scientists are beginning to develop approaches to integrate the natural and social sciences with remotely sensed data and can work together with decision makers to apply remote sensing information to decisions about human welfare.

THE POTENTIAL OF REMOTE SENSING APPLICATIONS TO HUMAN HEALTH

Remotely sensed data provide a spatial perspective on human health issues not typically incorporated into human health research and applications. Remotely sensed data, as applied to human health and welfare, can assist in taking into account multiple factors affecting health, such as food production, availability, and distribution; environmental health hazards; contagious and infectious diseases; chronic health issues; and health delivery. All of these factors have traditionally been considered separately by a variety of organizations. Health professionals do not typically observe the human land uses and ecological conditions affecting human health from the viewpoint of the remote sensing satellite. For health professionals, who often view issues in terms of point estimates or community averages, the visual and spatial perspective from remote sensing fosters a more integrated approach.

Remotely sensed data, in combination with other data, can provide spatial information on environmental conditions for understanding distributions of water-borne disease, air quality, soil, and vegetation as they influence community health and livestock. Remotely sensed data also provide spatial information on land use and infrastructure, which aids in determining where people live, where vulnerable populations live, the distribution of urban populations, and the quality of roads and other infrastructure for health care delivery. Interdisciplinary and international collaboration are needed between remote sensing scientists, ecologists, and human health scientists to realize the full potential of remote sensing applications.

The successful application of remotely sensed data to public health issues depends on several factors, including the need for cooperation between the remote sensing and public health communities. From the remote sensing side, successful application depends on the following:

1. Identifying what parameters on the Earth's surface need to be measured remotely and for use in health applications;
2. Determining the relevant variables that can be extracted from existing remote sensing satellites, such as human infrastructure and habitats for disease vectors;
3. Developing multi-resolution sensors at multiple spatial and temporal resolutions to monitor a range of health phenomena, especially sensors that are able to detect conditions in urban areas with complex mixtures of vegetation, buildings, and roads;
4. Educating local health officials on possible contributions of remotely sensed data; and most importantly,
5. Maintaining the continuity of current satellite coverage so that change of environmental conditions and their effects on health can be monitored over extended time frames.

It would be helpful if collected data, such as those listed in Table 3-1, were integrated with socioeconomic data on population distributions and livelihoods to realize the potential for human health applications. If data directly and indirectly measure disease, the data can be used

TABLE 3-1 Environmental Conditions and Change Requiring Monitoring by Multiple Types of Remote Sensing (e.g., optical, radar, microwave)

Condition	Observations	Benefits	Examples of Remote Sensing Technologies and Existing Sensors
Water	• Water quality (e.g., temperature, oxygen content) • Water availability • Water locations and types (e.g., wetlands, lakes) • Rainfall	Monitor conditions conducive to water-borne disease growth or migration (worms, flu, meningitis, cholera, malaria, West Nile virus, AIDS); wetland mapping	Radar, multi-spectral optical (Landsat)
Air and atmosphere	• Ozone measurements • Particulates • Heat and temperature • UV measurements • Wind dynamics • Dust movements	Air quality, atmospheric chemistry, climate change—monitoring these conditions allows for indirect measurement of diseases such as asthma	Thermal reflectances (MOPITT)
Soil and vegetation	• Soil moisture • Vegetation types • Vegetation productivity	Habitats for disease vectors	Multi-temporal, multi-spectral optical (MODIS, Landsat)
Land use and land cover	• Land cover • Livestock • NDVI • Cropland extent	Soil, water, and livestock interactions; land-sea interface; detection of floodplains, ice cover	Multi-temporal, multi-spectral optical (MODIS, Landsat)

continued

TABLE 3-1 Continued

Condition	Observations	Benefits	Examples of Remote Sensing Technologies and Existing Sensors
Infrastructure	• Roads and transportation • Water access • Sewers • Communications • Waste disposal • Urban population distributions at high resolution	Disease vector tracking; improving health service response in times of emergency; developing GIS data layers for modeling housing, land cover, etc.; high-resolution population distributions that can assist in health issues associated with infrastructure (i.e., obesity as related to infrastructure); understanding of teleconnections	Very high resolution optical (IKONOS, QuickBird)

NOTE: GIS = geographic information systems; NODIS = Moderate Resolution Imaging Spectroradiometer; MOPITT = Measurement of Pollution in the Troposphere; NDVI = Normalized Difference Vegetation Index.

to map diseases, estimate the burden of disease (the suffering of the society beyond that directly caused by the disease), and target intervention strategies.

From the health researcher's point of view, there are several challenges that bar the regular application of remotely sensed data in the health arena:

1. Remotely sensed data are expensive; affordable data access is key to bringing the technology to health applications.
2. There are few in situ ground truth data accompanying remote sensing technology, which will inhibit the use of the technology. In situ data are needed to verify analyses of data derived from remote sensing and to collect other data that cannot be detected remotely.
3. Health research professionals are not typically trained to use the tools required to analyze remotely sensed data.
4. Privacy concerns inhibit the sharing of health data by the health care community. In particular, lack of locational information on disease cases inhibits spatial analyses using remote sensing.

Overcoming these obstacles will greatly enhance the toolbox of health researchers by allowing them to more easily understand the relationships among infrastructure, the physical properties of land and water, health statistics, and access to health care delivery.

To realize and maximize the potential of applying remotely sensed data to decisions about health and health care, the issues of the remote sensing and health research communities can be solved simultaneously, with cooperation between the two. Workshop participants noted that achievable, short-term (five-year) priorities include improving the understanding of ecological processes in health (e.g., from vector-borne diseases including hantavirus, cholera, and West Nile virus) and learning how to fuse remotely sensed data with traditional land-based data (e.g., settlement and population data). Most workshop participants observed that limitations in data access, data sharing, and the continuity of observations have to be addressed. Long-term priorities are to develop an end-to-end system to support health applications and multi-scale, multi-temporal data for surveillance, monitoring, and prediction.

REALIZING THE POTENTIAL OF REMOTE SENSING FOR HUMAN WELFARE APPLICATIONS: COMMON THEMES FROM HUMAN HEALTH AND FOOD SECURITY

Workshop discussions highlighted that the use of remote sensing data for human health applications is not as advanced as its application for food security issues. The interdisciplinary collaborations are not as firmly established as, for example, those between the U.S. Department of Agriculture and groups monitoring agricultural yields. Despite this difference, workshop participants identified common themes that are applicable to both domains. Although the workshop did not consider other domains in human welfare, such as disaster management, the themes are likely applicable to those areas as well. The common themes that emerged about the needs to realize the potential for human health applications include the following:

- Need for integration of spatial data on environmental conditions derived from land remote sensing with socioeconomic data;
- Need for communication between remote sensing scientists and decision makers to determine effective use of land remote sensing for human welfare issues; and
- Need for acquisition, archiving, and access to long-term data—both historical and future—and for development of the capacity to interpret data.

Integration of Land Remote Sensing and Socioeconomic Data

Remote sensing has been applied to many areas such as weather forecasting, global change research, and local applications (e.g., precision agriculture). The potential for a major contribution to human welfare is largely unrealized. The success of this use of remote sensing rests with the ability to integrate remote sensing data with socioeconomic information. The research community is only at the beginning steps of achieving this integration. There is great value in combining spatial and socioeconomic data for use by policy makers. Additional research on how this integration should occur might be considered. Socioeconomic information such as land management and land tenure is crucial at global, regional, and parcel scales, and the dynamics and differences in patterns and processes of land use that occur between these scales have to be better understood. Data that provide a means of discriminating among different agricultural or land practices (e.g., tilled versus untilled soil, differences in tillage practices) can be valuable information for agricultural policy making. An understanding of coupled urban-agricultural systems will be increasingly important as urban areas continue their rapid expansion and food and amenities are cycled between the two areas.

In addition to the benefits of combining socioeconomic and remote sensing at various scales, remote sensing data and information can be used to improve agricultural production on a seasonal basis by identifying where the crop yields are high and low and where drought or other types of water stress are likely to affect certain crops or regions unfavorably. If adaptive management techniques are to be employed, ongoing agricultural monitoring, via remote sensing as well as other methods, is necessary. The data obtained through monitoring can be used to make informed decisions about what areas are likely to experience declines in yields in a specific season and how commodity pricing may be impacted. On a larger scale, remote sensing is currently used to predict El Niño phenomena, which can have significant implications for agriculture. In the human health domain, the integration of socioeconomic information, such as locations and vulnerabilities of human populations and access to health infrastructure, with environmental conditions, such as habitats for disease vectors and potential disease outbreaks, is key to providing information that is effective in generating response strategies.

Effective Communication Between Land Remote Sensing Community and Decision Makers

To be most useful in decision making, technicians and policy analysts trained in remote sensing and geographic information analysis could become part of interdisciplinary teams. Information from such teams could provide useful information that feeds into decisions, for example, to promote sustainability while maximizing crop yields and/or avoiding food or livelihood crises. Particular emphasis could be placed on increasing user capacity within lesser developed countries and building a cohort of individuals with adequate technical and analytical training to take advantage of access to remote sensing data and information. In all parts of the world, communication between technical experts and policy makers is inadequate. Policy makers could become better informed about the utility of remote sensing data, to ensure both that resources are available to utilize these data and that data are fed into all appropriate stages of the decision-making process. Minimum data needs and levels of accuracy would be communicated. In addition, public and private sector data users would understand and implement integrated communications and knowledge management strategies. When remote sensing data and information are disseminated, activities such as culturally specific outreach and data presentation could occur to make the data meaningful to recipients.

Human health is the outcome of numerous physical and socioeconomic factors. Because remote sensing techniques can monitor human health only through indirect means, it is important for decision makers and remote sensing scientists to communicate early and often regarding data and knowledge needs and transfer. If a population is experiencing a state of relatively good health and prosperity due to the combination of environmental and socioeconomic factors, it is important to observe *any changes* in those factors that could adversely affect the population. It is important that the observations are made rapidly in order to employ adaptive management practices. For example, the ability to monitor change could allow decision makers to predict the migration and rate of disease transmission to, from, or within populated areas and improve the ability for health service response during times of crisis or emergency.

Decision makers and remote sensing scientists might consider developing a series of short- and long-term priorities in order to determine data needs and develop the ability to implement decision-making strategies. Short-term (five-year) priorities include the following:

- Understanding ecological processes and how they interact with disease occurrences;
- Fusing settlement and population data with other types of remotely sensed data into geographic information systems (GIS) layers;
- Developing risk-based decision-making practices to enable action to be taken even when data do not provide complete certainty;

- Providing opportunities for interactions among scientists from different disciplines to understand the ecological and social dimensions of health; and
- Enabling access to data at a reasonable cost.

Long-term (10-year) goals include

- An end-to-end system to support health applications, including the collection, analysis, and application of data in decision making; and
- Multi-scale, multi-temporal data for surveillance, monitoring, and prediction.

Data Access and Technical Capacity

To expand the use of remote sensing data in human welfare decision making, these data have to be more readily available, more affordable, and deliverable in useful formats. Decision makers responsible for allocating resources for remote sensing technologies might consider communicating with remote sensing practitioners to determine what data types and data scales are necessary (i.e., countrywide versus crop specific). Data could be delivered in formats more compatible with GIS applications commonly in use in order to be combined easily with other types of data. Training and capacity building in the use of remotely sensed data could be increased, especially in developing countries. Organizations such as the National Geospatial-Intelligence Agency (NGA), in partnership with the U.S. Department of State, the military, or universities, might consider distributing data for no or low cost in large quantities that could then be made accessible to new practitioners with the ability to deal with large data sets.

With the exception of the Landsat program, remote sensing platforms were generally not designed to generate data for current research and applications addressing the links between land cover, environmental conditions, and human welfare. Nevertheless, the data are potentially useful for early warning systems similar to FEWS NET. FEWS NET, now established for many years, may be supplemented by future early warning systems such as a global disease monitoring and early warning system, a poverty monitoring and early warning system, and a biodiversity monitoring and early warning system. These systems would be driven by timely and accurate remotely sensed data.

The main challenges in establishing these types of early warning systems lie in the following:

- Constructing an archive of global environmental data accessible to all;
- Developing appropriate image-processing algorithms that produce relevant, processed data layers;
- Developing robust predictive models for biodiversity, agriculture, health, poverty, and environmental changes through time;
- Linking model outputs to the formulation of environmentally sound policies that are effective at the grass-roots level; and
- Producing a monitoring and feedback system that returns quality field data from project areas, to improve the modelling process.

Since human welfare issues involve understanding change over time, archival data (historical maps, aerial photography, pre-satellite era data, and historical satellite data) are key resources that must be preserved. Continued long-term monitoring and archiving of data from current satellite platforms are vital for the same reasons. It would be beneficial for funding considerations and planning of satellite missions to be made with the long term in mind, although funding streams are often not continuous and current project durations tend to be for only one to two years. Workshop participants identified the lack of time series and real-time data from the National Aeronautics and Space Administration (NASA) and other data sources as major barriers to the application of remote sensing technologies to human welfare improvement. Decisions will also have to be made on whether resources are better spent on the collection of more remotely sensed data or on more data analysis.

Potential benefits from the use of remote sensing data and information in food security will be enhanced and made more affordable both by improvements in current technologies and by additional international competition in the development of satellites and sensors, which will increase data availability. Non-satellite technologies for remote sensing could also be advanced, including enhanced aerial photography and the use of unmanned aerial vehicles. Finally, new types of data collection, analysis, and access technologies could be developed to make comparable data for global and regional estimates of the extent of tillage, land use, and land cover change. Because of the growth of urban populations throughout the world and the limited amount of land available for agriculture, agricultural land is a resource that will require careful monitoring and protection.

4

Key Points of Workshop Discussion

The ability of land remote sensing, in combination with other types of data, to identify variables such as land cover, responses of vegetation to climate variability, and locations of human infrastructure, provides critical information in forecasting and determining appropriate responses to human and animal disease outbreaks, food shortages, and other consequences for vulnerable populations. Applications of land remote sensing to monitor crop yields, enable precision agriculture, and identify impending food shortages in developing countries offer successful examples. The use of remote sensing data for human health is not as advanced as for food security beyond a few case studies, although the potential is great.

Workshop participants identified three themes that, if fostered, would help realize the potential for the application of land remote sensing to decisions about human welfare: (1) integration of spatial data on environmental conditions derived from remote sensing with socioeconomic data; (2) communication between remote sensing scientists and decision makers to determine the effective use of land remote sensing data for human welfare issues; and (3) acquisition and access to long-term environmental data and development of the capacity to interpret these data.

Most workshop participants believed that it is critical to integrate remotely sensed data with ground-based scientific and socioeconomic data. These data, combined, provide the necessary basis for reliable environmental modeling and forecasting. Just as important is the need for increased communication between the different producers of these data, as well as decision makers. Communication is vital during all phases of developing monitoring and decision support systems, in order to ensure that the right data are obtained, analyzed, and disseminated in useful ways, at useful time scales, and to the right people. Most workshop participants said that the effective application of remotely sensed data in decisions about human welfare could be improved only if the remotely sensed observations currently made continue to be collected and are enhanced by new observations. Data collected over the long term are vital to understanding and characterizing longer-period environmental cycles.

Because of the highly technical nature of the topic, the workshop committee decided that a different venue would be more appropriate to address the specific technical issues in integrating disparate data types into decision support systems that address human welfare, although most participants believed that this topic is vital for improving the effectiveness of decision support systems. The committee includes a bibliography of resources on this topic as Appendix B.

The workshop underscored the large, unrealized potential of remotely sensed data to a range of human welfare issues that, if developed, could parallel the significant advances in the use of remotely sensed data in the Earth sciences and global climate research in the past several decades.

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Appendix A

Acronyms and Abbreviations

AIDS	Acquired Immune Deficiency Syndrome
AgRISTARS	Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing
AVHRR	Advanced Very High Resolution Radiometer
CBWP	Corn Blight Watch Program
EPA	U.S. Environmental Protection Agency
EROS	Earth Resources Operations and Science
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EWS	early warning system
FAO	Food and Agriculture Organization of the United Nations
FEWS	Famine Early Warning System
FEWS NET	Famine Early Warning System Network
GIS	geographic information system
GPM	Global Precipitation Measurement mission
GPS	Global Positioning System
HPS	hantavirus pulmonary syndrome
IKONOS	Commercial earth observation satellite collecting high-resolution multispectral and panchromatic imagery
LACIE	Large Area Crop Inventory Experiment
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurement of Pollution in the Troposphere; instrument on Terra spacecraft measuring CO and CH_4 in the troposphere

NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NGA	National Geospatial-Intelligence Agency
NGO	non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite
NRC	National Research Council
RFE	rainfall estimates
SARS	severe acute respiratory syndrome
SCLB	southern corn leaf blight
SNV	Sin Nombre virus (hantavirus strain)
SPOT	Systeme Pour l'Observation de la Terre
SST	sea surface temperature
TRMM	Tropical Rainfall Measuring Mission
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USGS/EDC	U.S. Geological Survey Earth Resources Operations and Science Data Center
UN	United Nations
VIIRS	Visible Infrared Imager Raidometer Suite
VRT	variable rate technology
WatER	Water Elevation Recovery mission
WRSI	Water Requirement Satisfaction Index

Appendix B

Bibliography of Resources—Integration of Disparate Data

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Authors and researchers at the Center for International Earth Science Information Network (CIESIN) describe improvements to the Gridded Population of the World (GPW) data set and developments in rendering global population data sets at scales that can be used for broad-scale population-environment inquiries. The paper focuses mostly on the GPW and its improvements over the last 10+ years, particularly on increasing spatial resolution improvements. The authors note some barriers to improving data, including war, redistricting (former Soviet republics), and pricing policies for data. Overall, however, barriers to data collection and processing have decreased due to technological capacity and the greater interest in census taking and map making. These improvements will help with greater data integration.

CIESIN (Center for International Earth Science Information Network). 2005. Global Spatial Data and Information: Development, Dissemination, and Use. Report of a Workshop, 21-23 September. Columbia University, N.Y. Available online at http://sedac.ciesin.columbia.edu/GSDworkshop/GlobalDataWorkshop_report_web.pdf.

The report is a summary of workshop presentations on global spatial data and information use conducted at CIESIN, Columbia University, in September 2004. Topical areas include technical data interoperability and science data integration.

de Sherbinin, A., D. Balk, K. Yager, M. Jaiteh, F. Pozzi, C. Giri, and A. Wannebo. 2002. Social Science Applications of Remote Sensing: A CIESIN Thematic Guide. Columbia University, N.Y. Available online at http://sedac.ciesin.columbia.edu/tg/guide_main.jsp.

This is an introductory remote sensing usage guide for social scientists. Key methodological concerns arise when integrating remote sensing data with socioeconomic data—with methods such as "gridding" socioeconomic data to better correspond with Earth science data or taking Earth science data and converting data to tabular formats that are useful for social scientists. The technical specifications of various remote sensing instruments are listed in a table together with descriptions of what the sensors detect. Challenges in applying remote sensing data in the social sciences include difficulties with scale, data integration, interdisciplinary research, and confidentiality.

Dilley, M., R.S. Chen, U. Deichmann, A.L. Lerner-Lam, and M. Arnold. 2005. Natural Disaster Hotspots: A Global Risk Analysis. Washington, DC: World Bank Group.

Natural Disaster Hotspots presents a global view of major natural disaster risk hotspots: areas at relatively high risk of loss from one or more natural hazards. It summarizes the results of an interdisciplinary analysis of the location and characteristics of hotspots for six natural hazards: earthquakes, volcanoes, landslides, floods, drought, and cyclones. Data on these hazards are combined with state-of-the-art data on the subnational distribution of population and economic output and past disaster losses to identify areas at relatively high risk from one or more hazards. (Annotation from *http://publications.worldbank.org/*.)

NRC (National Research Council). 1998. People and Pixels: Linking Remote Sensing and Social Science. Washington, DC: National Academy Press.

This report discusses the linkage between remote sensing and the social sciences, using examples from the Amazon, Thailand, and Guatemala, as well as an example of how data can be used in early famine warnings, climate modeling, and health applications. The report discusses some challenges in linking the two fields.

NRC. 2002. Down to Earth: Geographical Information for Sustainable Development in Africa. Washington, DC: National Academy Press.

This report summarizes the importance and applicability of geographic data for sustainable development. Geographic data describe spatial variations across the landscape at a variety of scales (local, national, global) and include such elements as climate, elevation, soil, vegetation, population, land use, and economic activity. The report draws on experiences in African countries and examines how future sources and applications of geographic data could provide reliable support to decision makers as they work toward sustainable development. The committee emphasizes the potential of new technologies, such as satellite remote sensing systems and geographic information systems (GIS), that have revolutionized data collection and analysis over the last decade. There is some discussion of data integration between the social sciences and satellite imagery.

Pelling, M., A. Maskrey, P. Ruiz, and L. Hall, eds. 2004. Reducing Disaster Risk: A Challenge for Development. New York, NY: United Nations Development Programme.

The Disaster Risk Index (DRI) measures the vulnerability of countries to three natural hazards (earthquakes, tropical cyclones, and floods), identifies the development factors that contribute to risk, and shows quantitatively how the effects of disaster can be either reduced or exacerbated by policy choices. There is little discussion of technical issues that arise from integrating disparate data types.

Rindfuss, R.R., S.J. Walsh, B.L. Turner, J. Fox, and V. Mishra. 2004. Developing a science of land change: Challenges and methodological issues. Proceedings of the National Academy of Sciences of the United States of America 101(39):13976-13981.

Land-change science (LCS) is hindered by a number of methodological and analytical difficulties that emerge from the integration of "space-time patterns" and "social-biophysical processes" and the different ways in which the two disciplines address them. Problems include aggregation and inference problems, land use pixel links, data and measurement, and remote sensing analysis. Examples are (1) *linking land and pixels*: how research is started, with land samples (parcels) or people—each starting point can lead to problems that have different solutions, (2) *data quality* *and validation*: the validity and accuracy of the link between social science and land units and pixels, (3) *spatial-temporal mismatch*: matching spatial-temporal resolution of sensor systems with the resolutions of the social or biophysical data. Other issues addressed in this paper include *classification and the use of ancillary data, spatial autocorrelation, and accuracy assessment of land change models.*

Appendix C

Examples of FEWS NET Products

(Current and archived FEWS NET products available at http://www.fews.net/south)

USAID FROM THE AMERICAN PEOPLE

Executive Overview of Food Security in Sub-Saharan Africa May 24, 2006

FEWS NET

FEWS NET Alert Status

Emergency

Highest Priority—Urgent Action Required

Chad: Newly arriving refugees from Central African Republic are now receiving full rations. The pipeline will hold through September. In eastern Chad, host to over 200,000 refugees from Darfur, 60 percent of the required food aid was pre-positioned in advance of the rainy season. Outside refugee areas, severe food insecurity remains in Kanem and Logone Occidental.

Ethiopia: Southeastern and eastern pastoral areas are likely to face an elongated dry period from June—September. Ongoing assistance, coupled with a few days of rain in April and May, has helped save lives and livelihoods. But food security conditions will remain critical for the remainder of the year.

Kenya: Despite generally favorable rains throughout the country, food security will remain precarious for most pastoralists for the remainder of 2006. High child malnutrition rates persist as their underlying causes have yet to be addressed. Flood damage in coastal and lakeshore areas have affected an estimated 17,000 people with displacement and the loss of crops and shelter.

Somalia: The *gu* rains were normal in most of the country, and availability of and access to pasture, browse and water have improved. However, 2.1 million drought-affected Somalis remain food insecure. A recent nutrition survey found over 20 percent GAM and 3.5 percent SAM in parts of Juba Valley and Gedo, where heavy rains have hindered food aid deliveries.

Zimbabwe: Although this year's maize harvest is a significant improvement compared to last year, it falls far short of domestic requirements, and Zimbabwe will again have to import a significant amount of maize (see back page). Hyper-inflation continues to undermine food access, especially for the urban poor.

Warning

Urgent Action Required

Djibouti: Acutely food insecure pastoralists still need emergency support. However, recent rains have improved food security and the availability of pasture and browse in most pastoral areas.

Mauritania: In most sorghum and millet producing zones, poor seed access and an early end to the rains have limited the local availability of cereals, bringing an early start to the hunger period. The flow of cereal imports from Senegal and Mali has declined.

Niger: Numbers of moderately malnourished children are rising, but remain lower than last year at this time. Prices are stable, and most markets are adequately supplied, due mainly to cereal imports from Nigeria. However, high prices in Zinder and Tillabery reflect the local scarcity of cereal, and households are coping by selling assets, including young female cows.

Sudan (southern): In northern Bahr el Ghazal, the impact of returning populations on existing food sources is becoming more pronounced as the May—August hunger season develops. WFP has increased food rations in the most food insecure areas, but it is unclear if these can be maintained due to lack of funding.

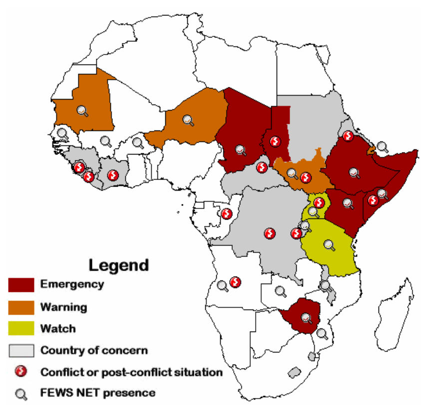
Watch

Preparedness and Monitoring Required

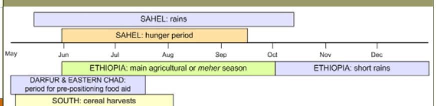
Tanzania: Crop prospects in unimodal areas are not favorable, due to late and erratic rain. Maize prices are more than twice the 5-year average, in part due to escalating transportation costs.

Uganda: Improved civil security is allowing IDPs in Lira District to return home and easing the congestion of camps in neighboring districts. Most IDPs still depend on food aid.

Food Security Alerts in Africa



Significant Events Timeline



Food Aid Needs and Beneficiaries

Country	Population at Risk	Food Aid Beneficiaries
Chad	207,554 (Darfur refugees); 48,300 (CAR refugees); 115,000 (host)	< 226,000 (refugees)
Djibouti	230,000	70,000
Ethiopia	> 10 million	10.9 million (PSNP + emergency)
Kenya	3.6 million	3.6 million
Mauritania	580,000	350,000
Niger	1.8 million	TBD
Somalia	2.1 million	621,163
South Sudan	1.9 million	1.9 million
Tanzania	3.7 million	564,726
Uganda	2.1 million (incl. IDPs)	1.6 million
Zimbabwe	n/a	n/a

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FEWS NET

Executive Overview of Food Security in Sub-Saharan Africa
Special Focus: Southern Africa **May 24, 2006**

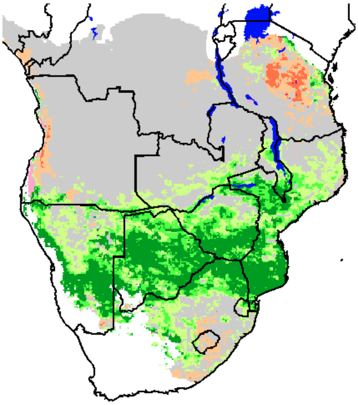
Southern Africa: Improved production in countries where it is most needed

As harvests get underway in Southern Africa, following generally excellent seasonal rains, estimates show improved production compared to 2004/05 in those countries where food insecurity has been of greatest concern over the past year. Figure 1 illustrates that this year's maize growing conditions have been very good, with green areas indicating above-average maize performance. Because farmers in South Africa cut back on the area planted to maize, their exportable surplus will be much smaller than last year. While maize production has improved in Zimbabwe, the country will still need to import substantial quantities that may not be available within the region.

In **Malawi,** second round production estimates indicate a maize crop of 2,350,000 MT, almost double last year's harvest of 1,259,330 MT. Sharp increases in cassava and potato harvests are also expected. In **Mozambique**, good rains in the south and end of season rainfall in the north will result in maize and tuber production increases over last year. Mozambique's maize production for 2005/06 is estimated to be around 1,500,000 MT, compared to about 1,371,000 MT in 2004/05. Production in the south has improved by about one-third. **Zambia** could produce up to 1,500,000 MT of maize, leaving a surplus over domestic requirements. Similarly**, Botswana** and **Namibia** expect improved harvests compared to last year. In **Angola,** maize and bean production in the southern and central regions will be reduced due to mid season drought, but sorghum, millet and cassava harvests have not been severely impacted. Crop production estimates are expected in early June.

Figure 1. Southern Africa: Maize crop conditions for the 2005/06 growing season

Water Requirements Satisfaction Index (WRSI) for maize (May 20, 2006)



Source: FEWS NET/USGS

In **Zimbabwe**, FEWS NET agrees with the USDA maize harvest estimate of 1,000,000 to 1,100,000 MT, a large improvement over the estimated 650,000 MT last year. After successfully importing over 1 million MT in the marketing season just ending , Zimbabwe will still face a major import challenge during the 2006/07 hunger season (October 2006 — March 2007). Despite the improved harvest, hyper-inflation continues to restrict food access, especially in urban areas, and many households depend on remittances from Zimbabweans abroad to secure their food supply. The threat of severe food insecurity will persist and could worsen when the hunger season sets in later in the year.

In **South Africa**, production declined sharply after farmers reduced acreage planted to maize by 45 percent, following a record harvest and large carry over stocks from 2004/05. In the 2005/06 season, South Africa is estimated to harvest only 6,320,000 MT of maize, just over half of the 11,716,000 MT harvested last season. This planned reduction will leave South Africa with a much smaller exportable surplus than last year. Although the SADC region's maize import needs should be substantially lower this year, South Africa's surplus will not meet the region's total requirements. Nonetheless, the commercial imports of the SACU countries (Botswana, Lesotho, Swaziland and Namibia) should be covered.

The prospects of improved harvests in many countries have lowered prices in most markets, but not in Zimbabwe. This downward trend is expected to continue during the marketing season, but consumer prices will still remain higher than average. The significant reduction in South Africa's exportable reserves could mean higher import prices by December for importing countries who wait too long to fill their commercial orders.

The improvement in grain and tuber production in countries that had deficits last year suggests that overall food aid requirements should decline. However, in many countries in the region, the poorest households and those affected by HIV/AIDS will still face some food and non-food needs. Support for non-food interventions is usually under funded and particularly encouraged.

For more information on Southern Africa, please visit www.fews.net/south

FEWS NET

TANZANIA
Food Security Update
March / April 2006

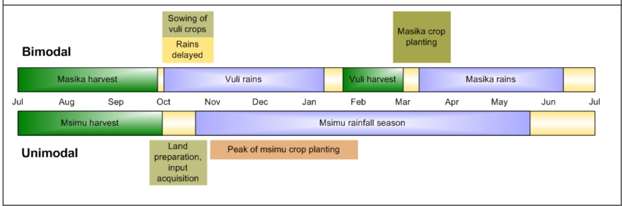
ALERT STATUS:
NO ALERT
WATCH
WARNING
EMERGENCY

Summary and Implications

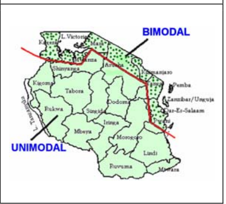
Across much of central, eastern and some parts of the southern highlands of Tanzania, the delayed start of the *msimu* season has negatively impacted agricultural activities, especially planting, limiting seasonal income earning opportunities. While recent rainfall has provided some relief to crops and pasture, a shortened *msimu* season may reduce crop production in some unimodal agricultural areas of Tanzania (central, some parts of southern highlands and eastern regions). At the same time, armyworms (*Spodoptera exempta*) have infested cropping areas and pastures in northern, central and southern Tanzania. The delayed *msimu* season in unimodal areas coincided with a failed *vuli* season in bimodal areas, and follows a poor 2004/05 *msimu* season that left 600,000 people food insecure and another 4 million at risk of food insecurity. In response to the subsequently diminished purchasing power of many households and rising maize prices, the government has been providing 3.7 million Tanzanians with free or subsidized maize.

Seasonal Calendar

Timeline of critical events



Tanzania rainfall regimes



Current Hazard Summary

- The delayed start to *msimu* rains has shortened the agricultural season in unimodal areas and diminished cereal production prospects. The delay in agricultural activities has affected income-earning opportunities at a time when cereal price are at historic highs.
- Seed shortages have limited the extent of *msimu* and *masika* planting.
- Armyworm infestations threaten crops and pastures. Control operations continue but have not been able to eradicate the pest completely.
- Banana Bacterial Wilt (BBW), now prevalent in Uganda, could cross over into the Kagera Region of Tanzania, threatening an important food and income source.
- Water levels in rivers, lakes and dams remain low, as hydrological drought continues in the central parts of the country. Power rationing and outages have resulted.

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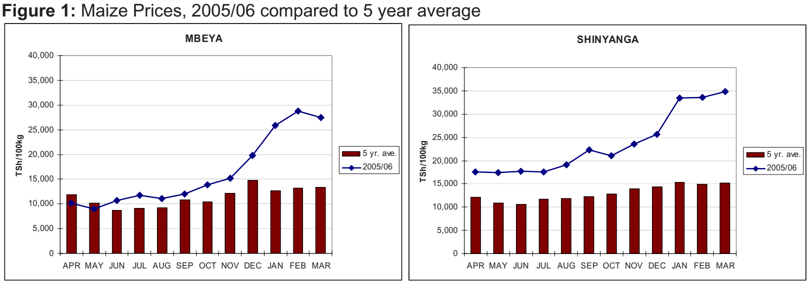
Food availability and access

There has been a food shortage in Tanzania that led to high food prices and food access problems for low-income market dependant households in both rural and urban areas of the country. This was caused by poor performance of *2004/05 msimu* crop, compounded with failure of 2005/2006 *vuli* season, and excess outflow of food grains to neighboring countries to the south that were facing food shortages and having higher prices compared to Tanzania. Although markets have been adequately supplied, household purchasing power has been eroded over the last year by failed and delayed seasons, which have reduced incomes and inflated cereal prices (see Figure 1). As a result the food insecure population increased from 600,000 to 3.7 million people. The government used its stocks in its strategic grain reserve, adjusted its budgets to source funds for distribution of food and appealed to donor community (both internal and external).

The distribution of free and subsidized maize to 3.7 million Tanzanians affected by drought and crop failure has improved household food security. With a few exceptions, these distributions have not halted maize prices, which continue to rise in most markets. The demand for food assistance is therefore expected to continue until the *msimu* harvests that start in May.

Figure 1: Maize Prices, 2005/06 compared to 5 year average



Limited amounts of maize are currently being harvested in some valleys and in low-lying and irrigated fields. Perennial crops, legumes, tubers and green maize are available in Mbeya, Iringa, Ruvuma and Rukwa regions. In Mbeya and Iringa regions, stocks of fresh produce of round and sweet potatoes, beans, green peas, peas and Persian fruits are available for purchase by traders along the road to Dar es Salaam. In Rungwe District, piles of green bananas (cooking bananas) are found in local markets and along roadsides for purchase by traders who buy and transport them to major markets. This has improved availability of these food commodities on Mbeya, Iringa, Morogoro and Dar es Salaam markets.

The Strategic Grain Reserve (SGR) has this year distributed 70,094 MT of maize, earmarked for free distribution or subsidized sale, to regions where, according to the January RVA, households were facing food insecurity. The balance of the maize stock held by SGR as of April 23 was 3,206 MT. This indicates that the SGR need to be replenished.

Although maize prices in Tanzania are still higher than prices in neighboring Kenya and Uganda, the flow of imports from Kenya into Tanzania has steadily declined since the free distribution and subsidized sales of maize began. Meanwhile, Tanzanian maize exports to Malawi have declined from 25,335 MT recorded in February to 5,000 MT in March.

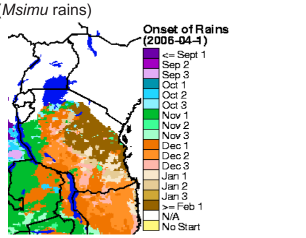
As of March 13, private traders in Tanzania held 84,059 MT of wheat, 41,554 MT of maize, 10,346 MT of rice and 383 MT of pulses. Private traders are expected to acquire additional stocks from imports: 49,200 MT of wheat, 83,741 MT of maize and 20,000 MT of rice. These additional stocks are expected from, Mexico, USA, China, UAE and Thailand.

Seasonal progress

The onset of rains was delayed by up to 40 days or more across large areas of Tanzania. Figure 2 presents the onset of rain imagery and Figure 3 gives the anomaly of the start of the season.

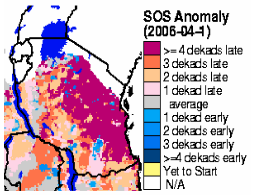
Should rains conclude in May, as usual, the abbreviated *msimu* season will result in below average yields. Household incomes were already significantly reduced by the failure of last year's *msimu* season; another poor season could prolong the indebtedness of many households and cause further destitution.

Figure 2: Onset of rains, unimodal areas (*Msimu* rains)



Source: USGS

Figure 3: Start of season anomaly

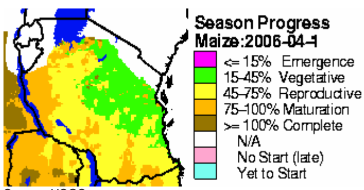


Source: USGS

Analysis of satellite imagery illustrates the impact of the delayed season on potential crop production. Should the rains stop in May as normal, maize that is currently at vegetative stage (see Figure 4) is likely to fail.

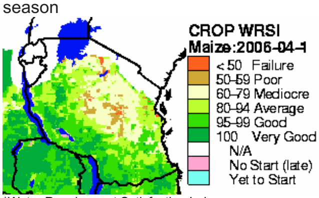
The impact of the current rainy season on crop performance varies considerably, even within villages, where maize crops status can range from knee high, to tasselling, to ripe. Wilting maize crops have been observed in several districts, including Southern highland districts where maize crops can also be found performing well (as in Njombe, Iringa, Chunya, and Mbarali). Figure 4 below shows the progress of maize crop in unimodal/ *msimu* rainfall areas and Figure 5 shows the water requirement satisfaction index through to the end of *msimu* season.

Figure 4: Progress of Maize crop



Source: USGS

Figure 5: WRSI* Extended through end of season



*Water Requirement Satisfaction Index
Source: USGS

According to the Regional Vulnerability Assessment (RVA), farming households were lacking adequate seed due to the poor production and seed retention from the 2004/05 *msimu* season. The RVA determined that 3,434 MT of seeds were required to support 618,816 households in planting for the late planting of *msimu and masika* season. FAO was able to distribute 263 MT of various seeds (93 MT of maize, 88 MT of sorghum, 82 MT of beans) and about 25,000 cassava cuttings to 92,028 households. FAO secured an additional 40 MT of maize seed and 60 MT of sorghum seed, enough to provide for 29,472 households, but not in time for planting in the current season. This seed will be held for the next planting season, beginning in October 2006, should rains begin on time.

APPENDIX D

Workshop Agenda

Contributions of Remote Sensing for Decisions About Human Welfare
The National Academies
500 5th Street, N.W., Room 201, Washington, D.C.
January 30-31, 2006

Monday, January 30

8:30 a.m. Welcome and Introductory Remarks
Ruth DeFries, Chair, Committee on Earth System Science for Decisions About Human Welfare: Contributions of Remote Sensing

PLENARY SESSION
SESSION 1: Applications of Land Remote Sensing for Human Welfare Decision Support: Opportunities and Challenges

8:45 Opportunities and Challenges in Using Remote Sensing to Support Human Health Applications—A Broad Perspective
David Rogers, Oxford University

9:15 Applying Remote Sensing to Infectious Disease from the Scientific and Technical Perspective
Terry Yates, University of New Mexico

9:45	Applying Remote Sensing to a Public Health Example: The User Perspective *Rita Colwell*, University of Maryland
10:15	Break
10:30	Opportunities and Challenges in Using Remote Sensing to Support Food Security Applications—A Broad Perspective *Chris Johannsen*, Purdue University
11:00	Famine Early Warning System: Use of Remote Sensing to Monitor Food Security *James Verdin*, U.S. Geological Survey
11:30	Famine Early Warning System: The User Perspective *Richard Choularton*, FEWS NET
12:00 noon	Lunch

CONCURRENT SESSIONS

1:00 p.m.	**SESSION 2:** **Opportunities and Challenges in Using Land Remote Sensing** **Session 2a: Opportunities and Challenges in Land Remote Sensing for Human Health Applications (Room 201)** *Moderator: Rita Colwell* **Session 2b: Opportunities and Challenges in Land Remote Sensing for Food Security (Room 202)** *Moderator: Joel Michaelsen*
3:30	Break
3:45	Reports from Breakout Sessions and Wrap Up
4:30	Adjourn

Tuesday, January 31

CONCURRENT SESSIONS

8:30 a.m.	**SESSION 3:** **Data Availability and Integration in Land Remote Sensing** **Session 3a: Data Availability and Integration in Land Remote Sensing for Human Health and Welfare (Room 201)** *Moderator: Ruth DeFries* **Session 3b: Data Availability and Integration in Land Remote Sensing for Food Security (Room 202)** *Moderator: Roberta Balstad*
11:00	Break
11:15	Reports from Breakout Sessions and Wrap Up
12:00 noon	Lunch

PLENARY SESSION

1:00 p.m.	**SESSION 4:** **Implementing the Use of Land Remote Sensing for Human Welfare: Next Steps**
1:15	The applicability of the workshop discussion in the areas of food security and human health to other human welfare issues: • NASA Decadal Survey Applications: *Tony Janetos*, The Heinz Center • Poverty Alleviation: *Marc Levy*, CIESIN
2:15	Next Steps
3:45	Closing Remarks: *Ruth DeFries*, Chair
4:30	Adjourn

Appendix E

Speaker Biographies and List of Workshop Participants

SPEAKER BIOGRAPHIES

RICHARD CHOULARTON is the contingency and response planning advisor for the Famine Early Warning Systems Network (FEWS NET). He is a specialist in planning emergency responses to humanitarian crises including famines. As a practitioner, Mr. Choularton's main focus is on improving the use of good analysis in decision-making and planning processes in order to foster more timely and appropriate response to humanitarian crises. This includes the use of remote sensing to support early warning and response efforts. Prior to FEWS NET, Mr. Choularton served as the global focal point for contingency planning for the United Nations World Food Programme and as a member of the Inter-Agency Standing Committee Working Group for Preparedness and Contingency Planning. Mr. Choularton holds a B.A. in history and political science from Vanderbilt University and an M.Sc. in risk, crisis, and disaster management from the University of Leicester, U.K.

RITA COLWELL is chairman of Canon U.S. Life Sciences, Inc., and distinguished university professor at both the University of Maryland at College Park and Johns Hopkins University Bloomberg School of Public Health. Her interests are focused on global infectious diseases, water, and health, and she is currently developing an international network to address emerging infectious diseases and water issues, including safe drinking water for both the developed and the developing world. Dr. Colwell served as the eleventh director of the National Science Foundation, 1998-2004.

Dr. Colwell is a member of the National Academy of Sciences; the Royal Swedish Academy of Sciences, Stockholm; the American Academy of Arts and Sciences; and the American Philosophical Society. Dr. Colwell holds a B.S. in bacteriology and an M.S. in genetics from Purdue University, and a Ph.D. in oceanography from the University of Washington.

ANTHONY C. JANETOS has been vice president of the Heinz Center since March 2003; he joined the center as a senior fellow in June 2002. Dr. Janetos also directs the center's Global Change Program. Before coming to the Heinz Center, he served as vice president for science and research at the World Resources Institute and senior scientist for the Land-Cover and Land-Use Change Program in the National Aeronautics and Space Administration (NASA) Office of Earth Science. He was also program scientist for NASA's Landsat 7 mission. He was a co-chair of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change and an author of the International Panel for Climate Change Special Report on Land-Use Change and Forestry and the Global Biodiversity Assessment. Dr. Janetos is chair of the National Research Council (NRC) Panel on Earth Science Applications and Societal Needs. Dr. Janetos graduated *magna cum laude* from Harvard College with a bachelor's degree in biology and earned a master's degree and a Ph.D. in biology from Princeton University.

CHRISTIAN J. JOHANNSEN is professor emeritus of agronomy and director emeritus of the Laboratory for Applications of Remote Sensing (LARS) at Purdue University. Dr. Johannsen first joined the agronomy faculty at Purdue University in 1963. He served as a program leader of LARS from 1966 to 1972. From 1972 to 1985, he held research and extension positions at the University of Missouri and was a visiting scientist at the University of California (1980-1981). In 1985, he returned to Purdue University as director of the Agricultural Data Network. From 1988 to 1996 he served as director of the Natural Resources Research Institute (renamed the Environmental Sciences and Engineering Institute in 1994), which had LARS within its structure. In 1996-1997, he was a visiting chief scientist with Space Imaging Inc. developing agricultural applications of remote sensing. He has served on many national and international committees and activities including the NRC Committee on the Geographic Foundation for Agenda 21 (2001-2003), the Steering Committee for Space Applications and Commercialization (1999-2003), the Space Studies Board (1998-2001), and the Committee on Earth Studies (1995-1998).

MARC LEVY is associate director for science applications at the Center for International Earth Sciences Information Network (CIESIN) and is an adjunct faculty member of the School of International and Public Affairs. His training is in political science, and he has published on environmental sustainability indicators, the effectiveness of international environmental institutions, social learning and environmental policy making, and environment-security connections. He led CIESIN's work on the Environmental Sustainability Index and the Human Footprint, serves as a project scientist of the Socioeconomic Data and Applications Center, coordinates CIESIN's work for the Millennium Development Project, and directs work measuring state capacity. Before coming to CIESIN, Mr. Levy had teaching appointments at Princeton University and Williams College. He is a convening lead author for the Millennium Ecosystem Assessment, a member of the State Failure Task Force, and co-chair of the Planning Committee of the 2003 Open Meeting of the Human Dimensions of Global Environmental Change Research Committee.

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Appendix F

White Papers

Famine Early Warning and Remote Sensing—A User Perspective

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The principal objective of the Famine Early Warning Systems Network (FEWS NET) is to provide actionable information to decision makers to prevent and respond to famines and food crises. Remote sensing has been one of the most important and successful tools used by FEWS NET to achieve this objective over the last 20 years.

Remote sensing provides a suite of invaluable tools for monitoring critical environmental processes that affect food insecurity. However, remote sensing products alone cannot tell the full story because food crises occur at the confluence of a complex web of interlocking environmental, political, economic, and social vulnerabilities.

Thus, a livelihood-based food security framework is used to interpret the potential impact of natural hazards on food and livelihood security. This type of analysis relies on baseline studies of how different populations are able to exploit the resources available to them. FEWS NET focuses on how populations in different areas access food and income and how they spend their income.

The combination of livelihood-based analysis, remote sensing, and other monitoring tools enables FEWS NET to interpret the likely impact of hazards such as drought or floods. This paper tries to illustrate how FEWS NET uses remote sensing to develop analyses to support decisions to combat food crises.

Recent literature stresses that famines and disasters are parts of broader processes. One such model is Turner's stages of disaster model (Turner and Pidgeon, 1997). This model examines the aetiology of disasters and thus is useful for examining the role of remote sensing in famine early warning. Turner's model defines six stages of disaster, as shown in Table F-1.

At each stage in this process, remote sensing tools are used to support food security analysis and decision support. This paper briefly illustrates how remote sensing is used with livelihood-based analysis to achieve FEWS NET's objectives at different stages of disasters.

TABLE F-1 Stages of Disaster

Disaster Stage	Description
Incubation period	The period during which the conditions develop that create the context for a disaster
Triggering event	The hazard that is normally associated with the disaster
Onset	The immediate consequences of the event
Response	The period when efforts are focused on saving lives and assets
Recovery	The period when efforts are focused on rebuilding, reestablishing livelihoods, etc.
Full adjustment	Societies do not return to a prior state of normalcy, rather a new post-disaster normal evolves

NOTE: This model has been adapted from Turner's socio-technical systems model also used by the United Nations World Food Programme in its Disaster Mitigation Guidelines.

INCUBATION PERIOD

Food crises occur when a complex web of factors conjoin, normally resulting in food shortages, malnutrition, sale of productive household assets (such as land or plough animals), distress migration, increased morbidity, excess mortality, and numerous other negative consequences.

The causal factors behind a food crisis develop and deteriorate over time. In the most food-insecure countries, the majority of the population is rural and dependent on rain-fed agriculture. These populations are highly vulnerable to changes in rainfall. Remote sensing of climatic conditions and derived agroclimatalogical analyses allow FEWS NET to monitor both short- and long-term changes that can impact food security. Livelihood analysis is then used to interpret the potential impact of these trends.

The current crisis in pastoral areas of the Horn of Africa, where more than 5 million people are currently facing pre-famine conditions, illustrates the use of remote sensing to inform food security early warning. This crisis whose epicenter is in northeast Kenya, southern Somalia, and southern Ethiopia has been triggered by the failure of the *deyr*, or October to December rainy season. Rainfall estimates (RFE) and crop water models such as the Water Requirement Satisfaction Index (WRSI) have enabled FEWS NET to identify and monitor the development of this drought (see Figure F-1).

While the current drought is the immediate trigger of the crisis, the crisis is rooted in a number of other factors, including a series of poor rainfall years over the last decade. A comparison of rainfall over the last decade helped to develop a longer-term understanding of the problem. Total annual rainfall, using satellite-derived rainfall data, was compared to a nominal minimum amount of precipitation required for viable pastures

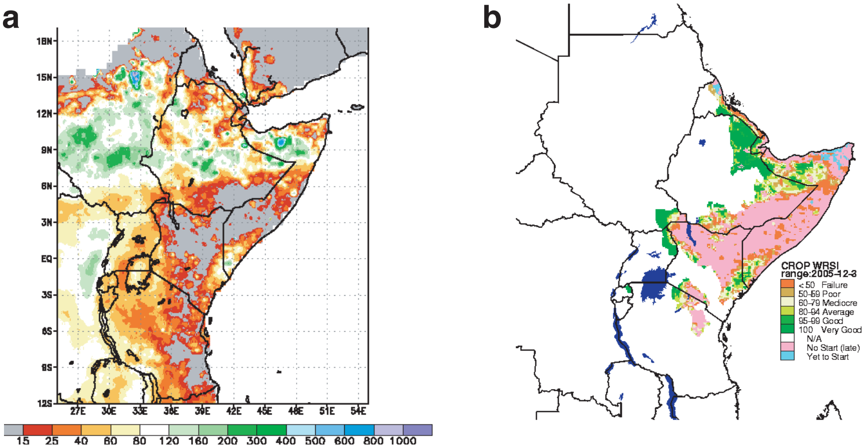

FIGURE F-1 Drought in the Horn of Africa. (a) Percentage normal precipitation (October–December 2005); (b) Rangeland condition—Extended WRSI December 2005. SOURCE: (a) FEWS NET/NOAA; (b) FEWS NET/USGS.

in the region (300 mm per year). Figure F-2 shows the results of this analysis.

TRIGGERING EVENT

Whether a hazard develops slowly like a drought or quickly like a flood, remote sensing helps analysts to define when a triggering event has occurred and to define its scope. In most countries where FEWS NET operates, information is sparse and not easy to access. Remote sensing allows FEWS NET to define where a hazard has occurred, its extent, and its severity. Using this information and livelihood baselines, FEWS NET is quickly able to provide decision makers with an analysis of the hazard's impact on food security.

For example, a dry spell in February 2005 hit southern and central Mozambique during a critical time in its agricultural season. The dry spell was identified as a triggering event and its impact analyzed using FEWS NET's livelihood baseline. In this example, even though Mozambique was facing its worst drought in five years, FEWS NET analysis determined that household food deficits would not necessarily emerge in all areas, because reliance on maize production varied in the affected areas. Cassava is widely cultivated in the Coastal Inhambane and Gaza Zones (31 in Figure F-3), Inharrime River Banks Zone (32), and Intermediate of Inhambane Zone

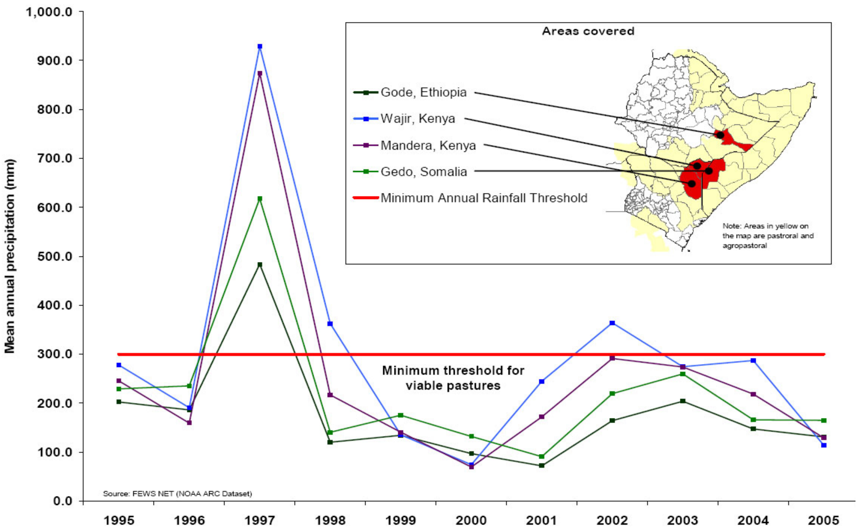

FIGURE F-2 Total annual rainfall (mm) for selected pastoral areas in the Great Horn of Africa in relation to the minimum threshold for viable pastures: 1995-2005. SOURCE: FEWS NET/NOAA ARC Dataset.

(33) and this crop was developing well. In addition, access to markets is relatively good in these areas. Households in these zones can also expand income from cashew sales and remittances in drought years.

In contrast to these areas, the analysis showed that drought would likely have a more significant impact on household food security for those living in the Semi-Arid Interior Zone (34) of Gaza and Inhambane provinces. Households in this zone are highly dependent on maize production and cropping is limited to only one season. When rains fail, market purchases, labor exchange, and consumption of wild foods complement poor households' crop production. However, market access tends to be inadequate because the area is quite remote and households have limited resources with which to purchase food. To make matters more difficult, during a drought, households are forced to divert their time and income to secure sufficient water, limiting even further what they can spend on food.

In this example, remote sensing allowed FEWS NET to identify a triggering event and livelihood analysis enabled FEWS NET to quickly interpret the information to determine the food security impact several months before it was felt and almost nine months before impacts became most acute.

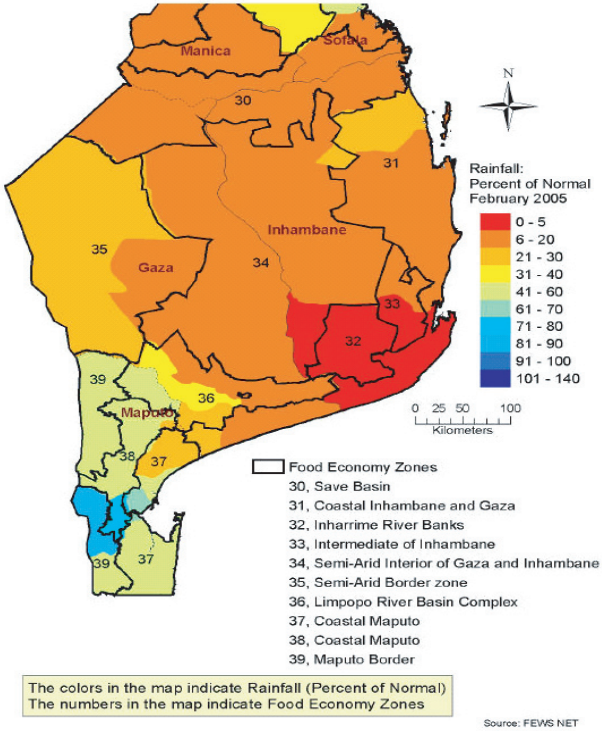

FIGURE F-3 Livelihood zones in the areas of southern Mozambique facing rain deficits. SOURCE: FEWS NET.

ONSET

When a crisis manifests itself, response agencies first need to assess the situation to determine how they will respond. However, in many countries, targeting scarce resources to undertake assessments is a challenge. Remote sensing allows FEWS NET and partners to target areas impacted by hazards, such as drought or floods, and thus maximize the use of assessment resources.

RESPONSE

Increasingly, the value of information collected and analysis conducted for early warning is being recognized as a tool to guide emergency response activities. While this is dominantly in the areas of food security and livelihood analysis, it also includes remote sensing data.

This was done for the FEWS NET Darfur Rain Timeline and Seven Day Forecast, which combines remotely sensed climate data with operational data (refugee camp locations, warehouse locations, roads, airports, etc). At the onset of the Darfur crisis, one of the most remote areas in Africa, there was a race against the rains to pre-position sufficient humanitarian supplies before the rains washed out roads preventing the delivery of aid to hundreds of thousands of displaced Darfurians. The Darfur Rain Timeline (Figure F-4) combines operational data on the location of displaced populations, transport infrastructure, and the normal position of the intertropical convergence zone (ITCZ), which in the Sahel region of Africa represents the leading edge of seasonal rains as they move northward at the onset of the rainy season and then retreat southward at the end.

RECOVERY

Remote sensing also helps food security analysts monitor conditions that support recovery following a famine or crisis. For example, the Niger crisis in 2005 peaked just as the country was experiencing one of the best rainy seasons in recent history. Remote sensing products such as the ITCZ analysis and WRSI provided early and regular updates on the progress of the rainy season. Another recent example can be found in northern Somalia, which experienced famine conditions after four years of drought between 2000 and 2004. In this case, RFE and vegetation analyses over the course of late-2004 and 2005 showed positive conditions for livestock, the mainstay of livelihood in the area. In both Niger and Somalia, ground-based data are scarce and difficult to access; thus, remotely sensed climate data and derived agroclimatalogical products fill in important gaps for analysts looking at the recovery from crisis, not only the descent into crisis.

CONCLUSION

Remote sensing is an invaluable tool for famine early warning and for supporting decision making to respond to crises. In addition, remote sensing can support the recovery process of famine-affected populations. When remote sensing data are put in context by using livelihood-based food security analysis, the result is a more insightful and valuable analysis, leading to more effective and earlier actions to mitigate food insecurity.

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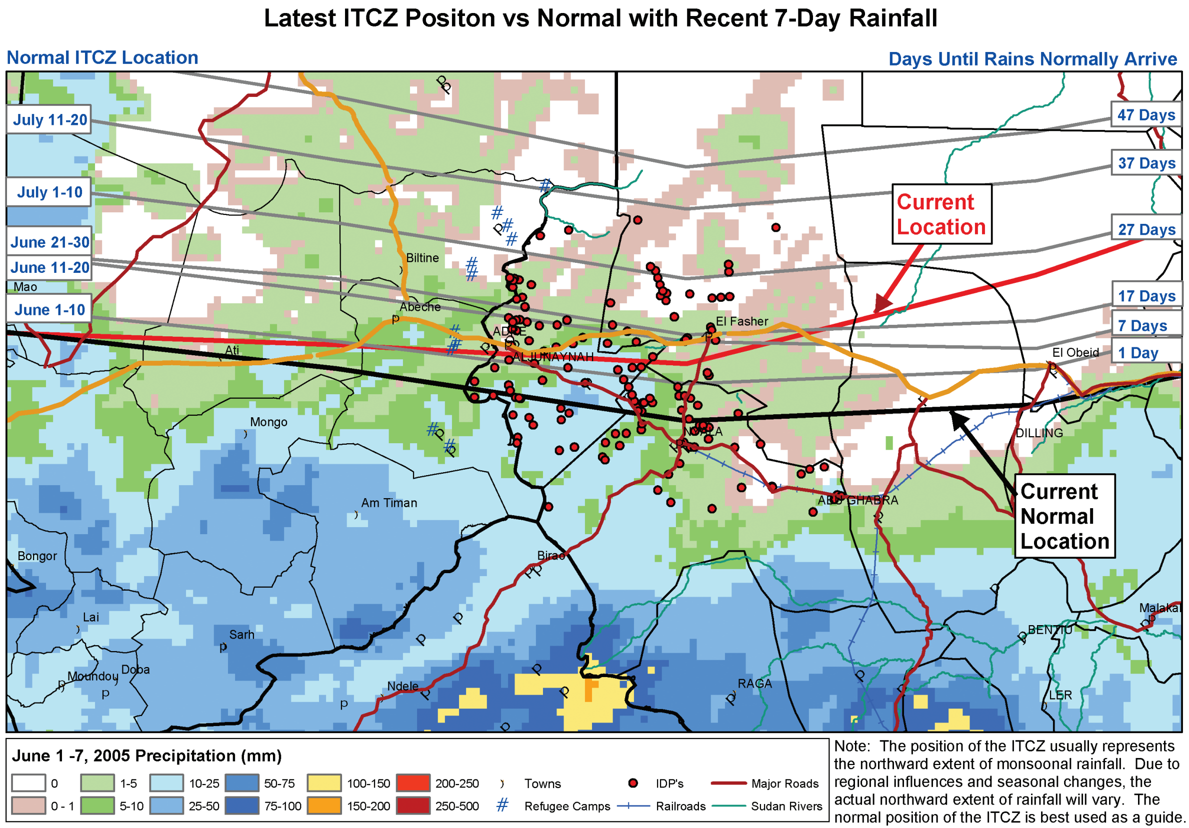

FIGURE F-4 Darfur Rain Timeline. SOURCE: FEWS NET.

Land Remote Sensing Applications for Human Welfare Support

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INTRODUCTION

The Landsat Program was our first civil, non-weather satellite program, from which we could identify and map land resources. It was seen from its beginning as contributing to human welfare. For the first time on a regional basis, we were able to identify vegetation and soil patterns, inland water bodies, urban areas, road networks, and other features that were important to users and planners of many disciplines. While the Landsat Program put this nation in the forefront of remote sensing opportunities, it did not remain that way through the decades. From the beginning, the program was billed as a "research" satellite, and attempts at fostering operations were based on the revenues to be returned by commercializing the effort. The original model envisioned for remote sensing satellites was similar to that of the communications satellites, which were successfully transferred to commercial operations (NRC, 1995).

The Landsat System did whet the appetite for the use of satellite data for many purposes, especially in the research community. Plans for operational use of Landsat were weakened by the inability to sustain operations with only one operating satellite, changes in management, and other issues. The weather satellites had a distinct advantage when their series of satellites could show weather patterns on a global basis and more recently demonstrate the tracking of hurricanes, especially the prediction of landfall with specific times and location such as with Hurricane Katrina. The past hurricane season solidified congressional approval of the funding of the National Polar-orbiting Operational Environmental Satellite (NPOESS) into the foreseeable future.

APPLICATIONS

The applications program for remote sensing has had a varied approach. Early in the efforts of the National Aeronautics and Space Administration (NASA) from the late-1960s through the mid-1970s was a University Applications Grant Program directed by Joseph Vitale. This program provided funds for university researchers to acquaint potential users with remotely sensed data and to train them through directed educational programs. Additionally the grants encouraged the development of college remote sensing courses to expose undergraduates and graduate students to remotely sensed data. Later during the 1980s through the 1990s, Alex Tuyahov at NASA Headquarters provided funds to encourage application development projects. Agencies such as the U.S. Geological Survey (USGS), U.S. Department of Agriculture (USDA), the National Park Service, and others provided grants with application thrusts on a changing basis.

A series of large application programs were initiated in preparation for Landsat. The Corn Blight Watch Program was in response to the Southern Corn Leaf Blight (SCLB). SCLB was first noted in 1970 in a number of cornfields in the Southern and Midwestern United States. This was an opportunity for NASA, USDA, Environmental Research Institute of Michigan (ERIM), and the Laboratory for Applications of Remote Sensing (LARS) to evaluate remote sensing using an Air Force RB57 aircraft with cameras, collecting data on selected flight lines over a seven-state area in the Midwest (Ohio, Indiana, Illinois, Iowa, Missouri, Wisconsin, Minnesota, and Nebraska). ERIM flew a 12-channel scanner over selected flight lines in the western half of Indiana, thereby providing a contrast to the photographic approach. From a practical standpoint, the program failed to detect SCLB until the corn crop was severely damaged. However, it did demonstrate the importance of temporal coverage for crop identification and the performance of timely analyses of vegetative growth, and it established the feasibility of digital, maximum-likelihood classification of aircraft multi-spectral scanner data for crop identification and condition assessment (Bauer, 1985).

With the launch of Landsat, a project called the Large Area Crop Inventory Experiment (LACIE) was initiated by NASA, USDA, and several universities. The purpose was to identify wheat throughout the Midwestern United States, and then expand to other countries such as Russia during its third year. LACIE developed a systematic approach to the analysis of Landsat data without ground truth information using temporal data collection and ancillary data such as weather data and USDA reports. The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) program expanded on the LACIE partnerships and looked at wheat, corn, and rice on a global basis. AgRISTARS was successful in demonstrating the value of timely data and limited ground reference information for identifying crops and predicting yield. The USDA Foreign Agriculture Service still uses the approaches that were developed during AgRISTARS.

Many National Research Council (NRC) studies have resulted in publications encouraging the development and funding of remote sensing application that benefit human welfare. The publication *Earth*

Observations from Space: History, Promise, and Reality (NRC, 1995) provided a bibliography of more than 300 publications on remote sensing topics as well as a good roadmap of the U.S. remote sensing program. NRC studies since that time have included remote sensing topics such as prospects for developing countries (NRC, 1997), supporting research and data analysis (NRC, 1998), ensuring a climate record (NRC, 2000a), the role of small satellites (NRC, 2000b), and assessment of mission size trade-offs (NRC, 2000c), National Spatial Data Infrastructure partnership programs (NRC, 2001), transformation of remote sensing data into information and applications (NRC, 2002a), new partnerships in remote sensing (NRC, 2002b), and use of remote sensing by state and local governments, (NRC, 2003b) to name a few. Additionally, a publication of strong interest to human welfare was *People and Pixels* (NRC, 1998), which for the first time directed attention to social concerns related to collection and analysis of remotely sensed data.

HIGH-RESOLUTION DATA

Most of our spatial data needs or wants are in the <5 m range for land resources mapping especially when we concentrate on human welfare. Note that there is a significant difference between "needs" and "wants," and we are usually told what "we can get." With the launch of commercial satellites providing high-resolution data such as Space Imaging and DigitalGlobe, we were provided with many of our "wants" as we started to see the benefits of 1 m data in obtaining information about urban land use categories, wetland communities, crop condition variations, forest inventories, and many other areas. The availability of this type of data in the future will depend on resolving many issues: concerns of high data costs especially when observing large areas, the financial viability of commercial companies, providing data for civilian uses during times of global conflicts, and other factors.

APPLICATIONS FUNDING

Through the history of the U.S. remote sensing program we have seen changes within NASA and other funding agencies relating to applications. If one follows the trend from the late 1960s to the present, you will see a "sine curve" effect, where the emphasis on applications is positive for about 8-10 years followed by an emphasis on research with a disregard for applications. The University Applications Grant Program of the 1960s was followed by a strong scientific pursuit during the mid 1970s, with a revival of the applications thrust in the mid 1980s. This seems to follow the change and emphasis of administrations as well as the national mood at the time. We are currently in a research emphasis with applications funding directed to other federal agencies, who are also emphasizing research leaving little direction on applications. This has a discouraging effect on users and potential users of remotely sensed data.

THE FUTURE

My emphasis in the use of remote sensing has been directed toward agriculture. Fortunately, farmers took a strong interest in precision agriculture or site-specific management, where they were farming a field according to the needs of soils, drainage, fertility, crops, and similar factors for each specific location within the field. The use of global positioning systems (GPS) on farm equipment (especially on combines), so that a yield map could be made during harvest, caused farmers to ask for remotely sensed images during the growing season to assess problem areas within a field and to predict their yields prior to harvest. Geographic information systems (GIS) were employed to overlay images, maps, and data to make assessments at the end of a crop yield and to plan for the next year. This means that farmers are in a better position to plan for safe food supplies because they are using some of the technologies that are now being suggested for food security. Sensors are being developed and used to monitor vegetables as they move on a conveyor belt to identify damaged or unusual appearing fruits or vegetables as they are harvested or processed.

The SCLB of the early 1970s provided the stimulus for observing the Soybean Rust that is currently of concern to Midwestern and Southern U.S. farmers. Remote sensing was used to monitor soybean fields for premature crop changes possibly caused by the Rust. Fortunately, we did not have ideal growing conditions for the Rust during 2005, but further plans for monitoring the soybean crop are being developed for the 2006 growing season. Many U.S. soybean researchers have been studying Soybean Rust in Brazil during this winter to further their knowledge about this disease.

Foreign satellite data may lessen our concerns about the lack of a Landsat Program, even though a recent memo was released by the Office of Science and Technology Policy (OSTP) stating that a Landsat capability is not feasible on NPOESS and that NASA will pursue a plan for a free-flyer satellite to obtain future Landsat data. In the meantime, no attention or recognition has been given to RapidEye Corp., a German satellite company planning to launch a series of five satellites with bands similar to Landsat during 2007. This will be an operational satellite that could be employed for land use research and applications. Additionally, the Belgian government has teamed with South Africa to plan the launching of a hyperspectral sensor after 2007, which could provide significant data for land use analysis and future applications.

In summary, a number of National Research Council boards have conducted remote sensing or related studies over the past 35 years that are valuable in their historical context. The current study related to food security and human health needs is very timely, because decisions will and are being made by our government on the future of this nation's remote sensing capabilities. The agricultural aspects of these topics are important in reaching valid and beneficial recommendations.

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Land Remote Sensing for Decisions on Human Welfare: Opportunities and Challenges

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Human actions are usually determined by our view of the world around us, our ability to connect one observation with another, and our interpretation of those connections in meaningful ways. Remotely sensed satellite data provide us with a relatively new and certainly unique opportunity to improve the situation of the whole of humankind through better habitat and environmental management. Satellite data are especially promising for understanding human, agricultural, and environmental interactions at a range of scales and for dealing with the many health, agricultural production, or environmental change (degradation) problems that threaten the sustainability of some of the planet's most disadvantaged communities.

This paper highlights some of the progress to date, speculates on the future potential of this technology, and finally makes a plea for the continuation of relevant earth observation missions into the future.

ENVIRONMENTS

High-resolution Landsat and SPOT data have traditionally been used to examine environments from space. Their detailed views appeal to our own acute visual powers and our usual wish to see as much as possible of environmental detail. Multi-temporal NOAA and TERRA satellite data give us seasonal imagery of poorer spatial resolution, which is nevertheless much more useful for understanding seasonal events associated with agriculture and the transmission of many tropical diseases. Temporal Fourier analysis allows us to produce novel images from such multi-temporal data that capture habitat seasonality in unique ways; the processed data are statistically independent (i.e., orthogonal) and biologically meaningful. Such data may be clustered to reveal large- or small-scale patches of environmental similarity ("ecozones") and thus provide a unique view of the scenery of the human as environmental tragedy.

AGRICULTURE

Subsistence agriculture is constrained by the environment in ways that may be revealed by comparing the clusters of agricultural indicators (the local abundance of humans, crops, and cattle; i.e., "farming systems") with the ecozones derived from satellites. Often there is an exceptionally good pattern match (formally revealed by the ecological technique of correspondence analysis). The distributions of human farming systems are as much a victim of their environments as are the distributions of tigers or tsetse flies. This has implications for the developmental routes along which subsistence agriculture should, or should not, be supported by development programs.

HUMAN AND ANIMAL HEALTH

Infectious diseases in the tropics have spatially and seasonally varying impacts that can most usefully be studied using satellite data. We distinguish statistical, or "pattern-matching," models from "process-based," or mechanistic, models applied to such diseases. While we prefer the latter for their ability not only to foretell the future, but also to predict the outcome of "what if?" modelling exercises of alternative intervention strategies, we nevertheless must acknowledge that, for most diseases (even important ones such as malaria), currently we only have sufficient information to follow the pattern-matching route. Nevertheless a careful application of this approach can suggest fundamentally important links between environmental drivers (including climate) and demographic processes (birth, death, infection, recovery), and these perceived links can begin to inform a process-based modelling approach. Satellite data thus neatly bridge the two rather different approaches to infectious disease modelling. Examples from the wide field of vector-borne diseases are given. The pattern-matching technique is extremely flexible and achieves respectable levels of accuracy remarkably consistently. It is critical at this point to ask if this flexibility means that we are describing simply the data or the disease itself. It is suggested that an information-theoretic approach within a maximum likelihood discriminant analytical framework provides sufficient checks and balances to ensure a robust outcome.

We deal briefly with the issue of data quality. No health statistics are ever complete, and none appear unbiased. When we construct our models we must try to allow for sampling errors and biases, in order to extract as much information from the background noise as is possible. A variety of mathematical (bootstrap) and more ecologically-based (environmental envelope expansion) techniques may help us to get the maximum amount of information from the data. We borrow and adapt a maxim from modelling in general, and epidemiology in particular, and warn that "all maps are wrong, but some are useful."

BIODIVERSITY MONITORING

The same techniques applied to tropical diseases may be used to describe the distribution of individual species of conservation importance, and communities of species, thus providing a common currency for resolving conflicts between human agricultural expansion on the one hand and conservation concerns on the other.

ENVIRONMENTAL CHANGE

Time series of satellite data may be used to examine environmental trends over time. There are considerable difficulties in detecting change in both high- and low-resolution imagery, brought about partly by design changes in the satellite platforms (spectral characteristics, overpass frequency) and degradations of both the satellite orbit and instrument performance over time. If adjustments can be made for these, we have series of images stretching back about 30 (Landsat) or 20 (NOAA AVHRR) years.

POVERTY MAPPING

Poverty is a multi-dimensional constraint on development in many tropical countries. Many of the dimensions of poverty are environmental (food, fuel, water, health), and we have recently explored the environmental-poverty links at a variety of scales in Africa, using sets of socioeconomic data that are more traditionally analyzed using small-area mapping techniques developed by the World Bank. We find relationships between satellite-derived environmental variables and poverty indices that are at least as strong as those discovered using the more traditional techniques that tend only to exploit the correlations within (socioeconomic survey) data sets. The great advantage here is that environmental variables are more likely to point to the *causes* of poverty than merely its correlates.

SMALL-WORLD EFFECTS—
EMERGING AND REEMERGING DISEASES

International trade and travel have effectively reduced the distance between areas of the world that have completely different suites of animals, plants, and diseases, thereby increasing the chances of international transport of pathogens. By examining environmental conditions across the world's air- and seaport network, we can begin to make sense of some dramatic international movements in the past (mostly of insect vectors of disease) and therefore predict and anticipate similar movements in the future.

OPPORTUNITIES

None of the satellites used for these studies was designed with health or welfare applications in mind. Famine early warning systems, now established for many years, may now be supplemented by global disease monitoring and early warning systems feeding into poverty monitoring and early warning systems. In turn, environmental protection could arise from a biodiversity monitoring and early warning system, all driven by timely and accurate remotely sensed data.

CHALLENGES

The challenges involve constructing an archive of global environmental data (through the Global Earth Observation System of Systems) accessible at zero cost to all; developing appropriate image-processing algorithms producing relevant, processed data layers; developing robust predictive models for biodiversity, agriculture, health, poverty, and environmental changes through time; linking model outputs to the formulation of environmentally sound policies that are effective at the grass-roots level; and producing a monitoring and feedback system that returns quality field data from project areas, to improve the modelling process.

REFERENCE

Advances in Parasitology, Volumes 47 (2000) and 62 (in press) contain a variety of papers on the applications of satellite imagery to vector and disease monitoring, mapping, and spread.

Famine Early Warning Systems Network: Use of Remote Sensing to Monitor Food Security in Africa[1]

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INTRODUCTION

In sub-Saharan Africa, large and widely dispersed populations depend on rain-fed agriculture and pastoralism; hence, climate monitoring and forecasting are important inputs to food security assessment. Conventional hydrometeorological networks are sparse and often report with significant delays (Washington et al., 2004). Consequently, the requirements of famine early warning have inspired creative uses of remote sensing, numerical modeling, and geographic information systems. Satellite vegetation index imagery has been used since the mid-1980s to identify anomalies in seasonal landscape green-up that indicate drought (Hutchinson, 1991). Satellite rainfall estimates (RFE) (Xie and Arkin, 1997) fill in gaps in station observations and serve as input to drought and flood index maps and models that illustrate the implications of spatial and temporal precipitation patterns.

The Famine Early Warning System Network (FEWS NET) employs a livelihoods framework to geographically characterize vulnerability and interpret hazards (Boudreau, 1998). By assembling information on how households access food and income, routine monitoring of rainfall, vegetation, crops, and market prices is made more meaningful. Implications for key food security questions are more readily derived, such as: Which population groups are facing food insecurity, and for how long? What are the best ways to mitigate adverse trends or shocks to their livelihood systems?

The National Oceanic and Atmospheric Administration, U.S. Geological Survey, National Aeronautics and Space Administration, and others (including the U.S. Department of Agriculture, FEWS NET/Chemonics,

[1]Portions of this white paper also published in Verdin, J., C. Funk, G. Senay, and R. Choularton. 2005. Climate science and famine early warning. *Philosophical Transactions of the Royal Society B* 360(1463):2155-2168.

and the U.S. Agency for International Development) routinely review a suite of remote sensing and forecast products to produce a weekly Africa Weather Hazards Assessment. Hazards are superimposed on livelihood zones, and each source of food and income for the relevant profiles is evaluated to determine if a food or income gap will result. Population groups at high risk of acute food insecurity can be identified and quantified, as can prospects for the duration of the problem.

LAND REMOTE SENSING

Current season monitoring by FEWS NET makes extensive use of satellite image products to achieve early detection of drought. Vegetation index images have been used since the mid-1980s to monitor the crop and rangelands of semiarid sub-Saharan Africa (Hutchinson, 1991). The Normalized Difference Vegetation Index (NDVI) exploits the contrast between red and near-infrared reflectance of plant canopies. It is proportional to leaf area index, intercepted fraction of photosynthetically active radiation, and density of chlorophyll in plants (Tucker and Sellers, 1986). Maximum value composites for dekads (WMO, 1992), nominally 10-day periods, are used to overcome cloud cover problems. Images from several different sensors are used to make the NDVI composites used by FEWS NET. They include the NOAA AVHRR, SPOT Végétation, and NASA Moderate Resolution Imaging Spectrometer (MODIS). The time series of AVHRR NDVI images, calculated by the NASA Global Inventory Monitoring and Modeling Studies group (Tucker et al., 2005), has 8 km resolution and is continuous since July 1981. SPOT Végétation NDVI images have 1 km resolution and have been available since 1998, while the MODIS NDVI images used by FEWS NET have 500 m resolution with a continuous series available since 2000.

Typically, a seasonal trace of mean NDVI over a crop or rangeland zone of interest is made to illustrate green-up and senescence. Traces for a long-term mean and recent years are also shown for comparison purposes. Figure F-5 gives an example for an important maize-growing region of Zimbabwe.

REMOTE SENSING ESTIMATES OF PRECIPITATION

Current season monitoring also depends heavily on satellite rainfall estimates (RFE). In Africa, the primary product used by FEWS NET is the RFE 2.0 from the NOAA Climate Prediction Center. The algorithm for this product, described in Xie and Arkin (1997), involves a geostatistical blend of rainfall station data with imagery from thermal infrared and microwave sensors. Estimates of 24-hour precipitation totals are made for each grid

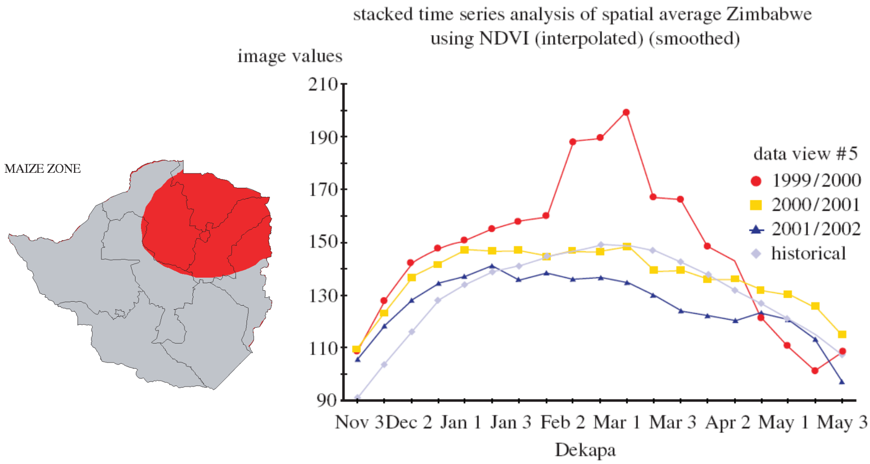

FIGURE F-5 NOAA AVHRR NDVI seasonal traces by dekad for a key maize-growing region in Zimbabwe: 1999-2000 was a year of abundant rainfall and vigorous vegetation growth; 2001-2002 was a year of drought and poor crop performance; 2000-2001 was about average.

cell at 0.1 degree resolution (approximately 10 km) and are available the following day. There are only about 400 rainfall stations across the African continent that report each day via the World Meteorological Organization's Global Telecommunication System. The RFEs consequently fill in what would otherwise be large spatial gaps in FEWS NET rainfall monitoring. The inclusion of those station data that are available significantly reduces the bias inherent in estimates based on satellite data alone. Furthermore, RFE 2.0 estimates show better agreement with surface observations than do numerical atmospheric model precipitation fields. In a test case in western Kenya, RFE 2.0 estimates agreed with observations over a dense gauge network significantly better than did numerical atmospheric model estimates, explaining 80 percent of the variance, compared to 20 percent for atmospheric model estimates (Funk and Verdin, 2003).

Satellite RFE have been especially useful as input to a geospatial crop water balance model that evaluates the availability of moisture to a crop relative to its needs over the course of the growing season. Frère and Popov (1986) originally developed the Water Requirement Satisfaction Index (WRSI) for calculation with rainfall station data. It has been adapted to use on a geospatial basis to facilitate wide-area monitoring (Verdin and Klaver, 2002; Senay and Verdin, 2003). The WRSI varies from

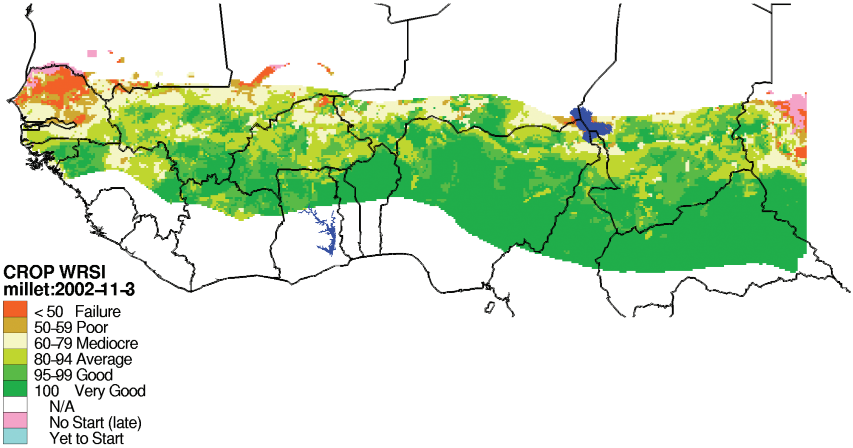

FIGURE F-6 Map of the Water Requirement Satisfaction Index for the Sahelian countries of West Africa, 2002. Intervals of WRSI correspond to levels of crop performance. Growing conditions for millet that year were especially poor for northern Senegal and southern Mauritania. Image created by Gabriel Senay, USGS. Used with permission.

0 to 100 and is the ratio of actual crop evapotranspiration to the amount that would occur with a full water supply. This quantity has been shown to be a good indicator of yield reduction due to water limitation (Doorenbos and Kassam, 1986). Maize yield estimates based on WRSI (calculated with RFE) were found to agree (R = 0.8) with official reports in a test with 1996-1997 data for Zimbabwe (Verdin and Klaver, 2002). Figure F-6 gives an example WRSI map for the West African Sahel.

REMOTE SENSING OF SURFACE WATER

Tracking trends in the elevation of the water surface of major lakes and reservoirs can provide valuable insight into the relative abundance of water for human consumption, agriculture, and pastoralism. NASA and USDA have successfully adapted systems for radar altimetry of the oceans to monitoring water bodies in Africa. Figure F-7 illustrates evidence of multi-year drought in East Africa developed with Topex Poseidon-Jason 1 data.

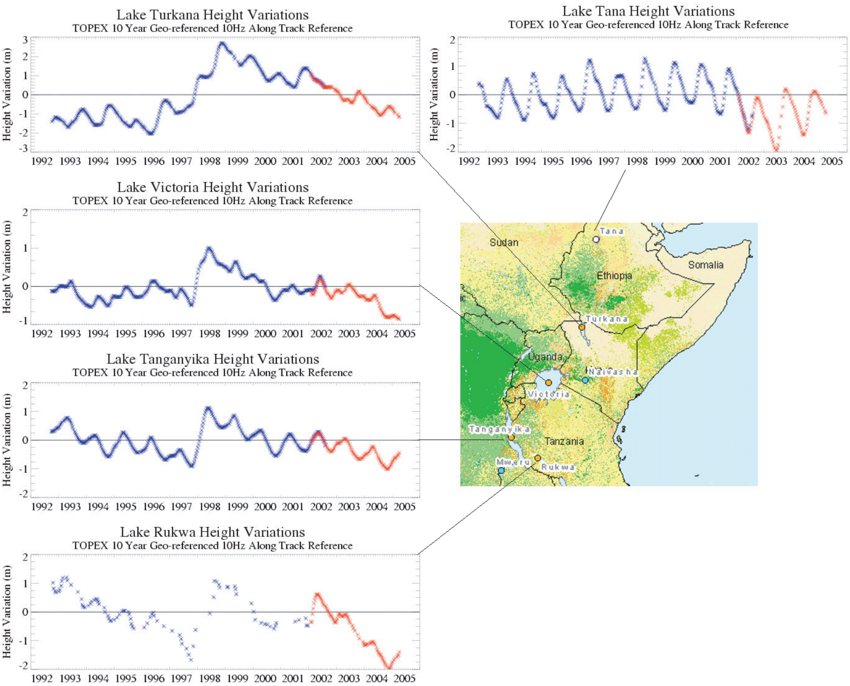

FIGURE F-7 Topex Poseidon-Jason 1 lake levels for five lakes in the Greater Horn. Time series and imagery obtained from the USDA PECAD crop explorer: available at http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/.

FUTURE OF REMOTE SENSING SYSTEMS

In terms of land remote sensing, FEWS NET is increasingly making use of the improved spatial resolution offered by MODIS. The AVHRR NDVI time series, dating back to 1981, will continue to play a vital role, however, due to its value in developing climatological norms. The Visible Infrared Imager Radiometer Suite on the upcoming National Polar-orbiting Operational Environmental Satellite System will maintain continuity into the future for wide-area, high-frequency vegetation index imagery.

The Global Precipitation Measurement (GPM) mission will ensure the future of remote sensing estimates of rainfall. GPM builds on the success of the Tropical Rainfall Measuring Mission (TRMM). The GPM international constellation of satellites will increase the availability of microwave estimates of precipitation, reducing and ultimately eliminating the need for reliance on thermal infrared image data.

The Water Elevation Recovery (WatER) mission has been proposed to explicitly map inland water body surface elevations. Building on the success of interferometric synthetic aperture radar on the Shuttle Radar Topography Mission and radar altimetry missions such as Topex Poseidon, WatER promises to map changes in water height and slopes of inland water surfaces with centimeter accuracy. If authorized, the mission would be of great benefit over the wide regions of Africa (and much of the Earth) that lack adequate conventional stream gauging.

SUMMARY

Monitoring rain-fed subsistence agriculture and rangeland conditions is a key input to food security assessment in sub-Saharan Africa. Satellite remote sensing has played a vital role since the 1980s by complementing sparse conventional surface climate monitoring networks. Estimates of vegetation vigor, rainfall distribution, and surface water supplies are forthcoming from current systems. Future remote sensing missions, planned and proposed, promise to provide increasingly higher-quality coverage in terms of spatial resolution, frequency of acquisition, and sensor technology. Full implementation of these missions will be vital to famine early warning in Africa, because surface climate monitoring networks, unfortunately, continue to weaken—a trend that is not likely to improve any time soon.

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Forecasting the Spread and Risk of Infectious Disease

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Hantaviruses are a group of negative-stranded RNA viruses, some of which are known to be highly pathogenic for humans. Diseases caused by hantaviruses were thought to be largely restricted to Europe and Asia, until 1993 when an outbreak of hantavirus pulmonary syndrome (HPS) caused by a previously unknown hantavirus, Sin Nombre virus (SNV), occurred in the Southwestern United States. The new virus initially resulted in a fatal outcome in more than 50 percent of human cases, and the deer mouse, *Peromyscus maniculatus*, was found to be its primary reservoir (Nichol et al., 1993). Since the discovery of SNV, some 27 additional hantaviruses have been described from the New World (Schmaljohn and Hjelle, 1997; Peters et al., 1999). The cause of the outbreak in 1993 has remained speculative. More than ten years of ecological monitoring in the American Southwest and the results of retrospective serosurveys for SNV using archived rodent samples suggest a climate-driven trophic cascade model for SNV outbreaks in North America. It appears that increased late winter and spring precipitation in the Southwestern United States driven by the El Niño-Southern Oscillation was responsible for an increase in plant primary productivity, which in turn resulted in increased rodent population densities. A direct but delayed correlation exists between increases in deer mouse population densities, increases in density of infected rodents, and increased incidence of HPS. Furthermore, retrospective data show that SNV and other New World hantaviruses have been present, essentially in their current form, in the Western Hemisphere for at least decades and probably have been coevolving with their rodent hosts in the New World for approximately 20 million years (Yates et al., 2002).

An understanding of the relationship between climate change, ecology, and hantaviruses may enable development of improved predictive models for prevention of human infection and improve our understanding of biocomplexity on a rapidly changing planet. We propose a complex trophic cascade triggered by climate fluctuation as a model for predicting HPS risk to humans. In addition, data from our studies in North and South America suggest that certain human land use patterns that result in a reduction of biological diversity favor reservoir species for hantavirus and significantly increase human risk for HPS. These data make it clear that understanding the ecology of infectious diseases will take a long-term, multidisciplinary effort—one that is essential to public health efforts of the future.

Although on a broad regional scale there is an increased risk to humans from the trophic cascade triggered by increased precipitation input into the environment, the actual risk to humans is highly localized and depends on a complex series of variables. Other factors, such as landscape heterogeneity, microclimatic differences, rodent disease, local food abundance, and competition, may be involved as well, and such complexity will have to be taken into account before a predictive model of HPS risk can be developed on a fine-grained scaled.

Understanding the biological complexity of natural and human-dominated ecosystems will be required before ecological and evolutionary forecasting can be employed on the scale needed to safeguard the public health against hantaviral and other zoonotic disease outbreaks. Large-scale, long-term, multidisciplinary studies also will be necessary to determine if foreign or genetically modified pathogens are being introduced into our ecosystems.

Near real-time forecasting of risks of these types of diseases will be possible only if remote and other types of sensing become utilized on a continental or global scale. One example, based on hantavirus in the American Southwest, is discussed as a possible model for a wider array of applications.

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Appendix G

Committee Biographies

Ruth S. DeFries, *Chair*, is professor at the University of Maryland, College Park with joint appointments in the Department of Geography and the Earth System Science Interdisciplinary Center. Her research investigates the relationships between human activities, the land surface, and the biophysical and biogeochemical processes that regulate the Earth's habitability. She is interested in observing land cover and land use change at regional and global scales with remotely sensed data and exploring the implications for ecological services such as climate regulation, the carbon cycle, and biodiversity. Dr. DeFries obtained a Ph.D. in geography and environmental engineering from Johns Hopkins University and a bachelor's degree in Earth science from Washington University. Dr. DeFries was elected to the National Academy of Sciences in 2006.

Roberta Balstad is senior research scientist at Columbia University and senior fellow at the Center for International Earth Science Information Network (CIESIN). Dr. Balstad has published extensively on science policy, information technology and scientific research, remote sensing applications and policy, and the role of the social sciences in understanding global environmental change. She is the author of numerous articles and books, including *City and Hinterland: A Case Study of Urban Growth and Regional Development* (1979), and editor, with Harriet Zuckerman, of *Science Indicators: Implications for Research and Policy* (1980). She was previously the director of CIESIN, director of the Division of Social and Economic Sciences at the National Science Foundation, the founder and first executive director of the Consortium of Social Science Associations

(COSSA), and president and CEO of CIESIN prior to its joining Columbia University. Dr. Balstad is the chair of the NRC U.S. National Committee for CODATA and the vice-chair of the NRC Panel on Earth Science Applications and Societal Needs. Dr. Balstad received her Ph.D. from the University of Minnesota.

Rita Colwell is chairman of Canon US Life Sciences, Inc. and distinguished university professor at both the University of Maryland at College Park and the Johns Hopkins University Bloomberg School of Public Health. Her interests are focused on global infectious diseases, water, and health, and she is currently developing an international network to address emerging infectious diseases and water issues, including safe drinking water for both the developed and the developing world. Dr. Colwell served as the eleventh director of the National Science Foundation, 1998-2004. Dr. Colwell is an elected member of the National Academy of Sciences; the Royal Swedish Academy of Sciences, Stockholm; the American Academy of Arts and Sciences; and the American Philosophical Society. Dr. Colwell holds a B.S. in bacteriology and an M.S. in genetics from Purdue University, and a Ph.D. in oceanography from the University of Washington.

Tom P. Evans is the co-director of the Center for the Study of Institutions Population and Environmental Change and an associate professor in the Department of Geography at Indiana University. His research interests are in the human dimensions of global change, geographic information systems, remote sensing, land cover change, and modeling social-ecological systems. His current research utilizes various methods of modeling land cover change with a particular emphasis on the process of reforestation. Dr. Evans completed his Ph.D. in geography from the University of North Carolina, Chapel Hill, and his B.A. in geography from Virginia Polytechnic Institute.

Nina S.-N. Lam is a professor of environmental studies at Louisiana State University. Her research interests are in geographic information systems (GIS), remote sensing, cartography, spatial analysis, and medical geography. Dr. Lam has published on topics such as spatial interpolation, cancer mortality in China, HIV/AIDS in America, land cover change detection via fractals and spatial indices, and scale and uncertainties in environmental health studies. Dr. Lam's research has centered on developing as well as applying new methodologies in remote sensing and GIS to detect patterns and find associations between environment, health, and the social condition of people. Her current research focuses on data mining of medical, social, and economic phenomena; decision making in post-catastrophe uncertainty; and rapid environmental assessment and change detection via remote sensing. Dr. Lam received her Ph.D. and M.S. in geography from the University of Western Ontario and her B.S. in geography from the Chinese University of Hong Kong.

Joel Michaelsen is a professor of geography at the University of California, Santa Barbara. His research interests are in climatology, meteorology, and statistics. He has been working with researchers at the U.S. Geological Survey on the Famine Early Warning System Network (FEWS NET), a federal early warning program that monitors, anticipates, and mitigates the impact of flooding and drought in sub-Saharan Africa and Central America. Dr. Michaelsen completed his Ph.D. and M.A. in geography at the University of California, Berkeley, and his B.A. at the University of California, Santa Barbara.

Karen Seto is a center fellow with the Freeman Spogli Institute for International Studies and an assistant professor in the Department of Geological and Environmental Sciences at Stanford University. Her research focuses on the impacts of anthropogenic activity on spatial-temporal patterns of land use and land cover change. She uses a combination of remote sensing, socioeconomic data, and field surveys to monitor and model landscape dynamics. Her current research efforts include analyzing the effects of policy reforms on urbanization and agricultural expansion in China and Vietnam. She is the remote sensing thematic leader for the World Conservation Union's (IUCN) Commission on Ecosystem Management and is a recipient of the NASA New Investigator Program in Earth Science Award and the NSF Faculty Early Career Development (CAREER) Award. Dr. Seto received her Ph.D. in geography from Boston University; M.A. in international relations, Resource and environmental management from Boston University, and B.A. in political science from the University of California at Santa Barbara.

Mark L. Wilson is the director of the Global Health Program and professor of epidemiology and of ecology and evolutionary biology at the University of Michigan. Dr. Wilson has broad research interests in infectious diseases, including the analysis of transmission dynamics, the evolution of vector-host-parasite systems, and the determinants of human risk. Most of his projects address environmental and social variation, in time and space, as it impacts on vector and reservoir populations and pathogen transmission dynamics. In addition to standard field, lab, and statistical techniques, he has been using satellite image data and GIS to undertake spatial analyses of environmental change and the ecology of risk. Spatial analytic tools are also being applied to noninfectious disease processes. Dr. Wilson received his Sc.D. and Sc.M. from Harvard University and his B.A. from Hiram College.