A 100-year retrospective and current carbon budget analysis for the Sooke Lake Watershed: Investigating the watershed-scale carbon implications of disturbance in the Capital Regional District's water supply lands

by

Byron Smiley
B.Sc., University of Victoria, 2012

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Geography

University of Victoria

Supervisory Committee

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Abstract

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Northern forest ecosystems play an important role in global carbon (C) cycling and are considered to be a net C sink for atmospheric C (IPCC, 2007; Pan, et al., 2011). Reservoir creation is a common cause of deforestation and when coupled with persistent harvest activity that occurs in forest ecosystems, these disturbance events can significantly affect the C budget of a watershed. To understand the effects of these factors on carbon cycling at a landscape level, an examination of forest harvest and reservoir creation was carried out in the watershed of the Sooke Lake Reservoir, the primary water supply for the Greater Victoria area in British Columbia. Covering the period between 1910 and 2012, a detailed disturbance and forest cover dataset was generated for the Sooke Lake Watershed (SLW) and used as input into a spatially-explicit version of the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3). The model was modified to include export of C out of the forest system in the form of dissolved organic C (DOC) into streams. The fraction of decaying C exported through this mechanism was tuned in the model using DOC measurements from three catchments within the SLW. Site-specific growth and yield curves were also generated for watershed forest stand types, in part, by using LiDAR-derived site indices. C transfers associated with disturbances were adjusted to reflect the disturbance types that occurred during the 100-year study period.

Due to the removal of C resulting from wildfire, logging and residue burning, as well as deforestation disturbances, total ecosystem C stocks dropped from 700 metric tonnes of C per hectare (tC ha^{-1}) in 1910 to their current (2012) level of ~550 tC ha^{-1} across the SLW. Assuming no change in management priorities and negligible effects of climate change, total ecosystem C stocks will not recover to 1910 levels until 2075. The cumulative effect of reservoir creation and expansion on the C budget resulted in 14 tC ha^{-1} less being sequestered (111,217 tC total) across the watershed by 2012. In contrast, sustained yield forestry within the Capital Regional District's tenure accounts for a 93 tC ha^{-1} decrease by 2012, representing an impact six times greater than deforestation associated with reservoir creation. The proportionally greater impact of forestry activity is partly due to current C accounting rules (Intergovernmental Panel on Climate Change) that treats C removed from the forest in the form of Harvested Wood Products as C immediately released to the atmosphere as carbon dioxide. Cumulative DOC export to the Sooke Lake reservoir was ~30,660 tC by 2012, representing a substantial pathway for C leaving the forest ecosystem. However, more research is required to understand what fraction of terrestrially-derived DOC is sequestered long term in lake sediment. The results of this study will assist forest manager decision making on the appropriate management response to future forest disturbance patterns that could result from climate change and to improve climate change mitigation efforts.

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Glossary

Adjusted Maximum Likelihood Estimation (AMLE): the statistical estimation methods used within rLOADEST for this study

Akaike Information Criterion (AIC): a method of model selection that employs the log-likelihood of a given model and balances it against the number of estimated parameters used

Akaike Information Criterion Corrected (AICc): AIC corrected for small sample sizes

Analysis Unit (AU): a grouping of forest types, for example, by tree species and site quality

Autotrophic Respiration (Ra): Respiration by photosynthetic organisms (plants)

Biomass Carbon: carbon in live forest biomass, including from foliage, branches, stemwood, coarse and fine roots

British Columbia Ministry of Forests, Lands and Natural Resources Operations (BCMFLRO): the provincial ministry responsible for administration and regulation of British Columbia's forests

Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3): a model for simulating forest carbon dynamics from various scales from an operational scale to national scales. Forest carbon dynamics can be simulated retrospectively, and projected into the future

Capital Regional District (CRD): The local government body that administers and manages Greater Victoria's water supply area

Coastal Forest Chronosequence Project (CFC): a ground plot network with five sites on both the east and west sides of Vancouver Island, established in 1992 and re-measured in 2002. Each site has ground plots in each of 4 different forest seral stages (regeneration, immature, mature and old-growth) to examine, over a period of a few years, long term changes in forest succession

Dead Organic Matter (DOM): carbon in dead material including from snag stemwood and branches, coarse woody debris, dead coarse and fine roots, and pools for the organic and mineral soil horizons

Dissolved Inorganic Carbon (DIC): carbon dissolved in water (< 0.45 micrometers) precipitated from inorganic material such as carbonate minerals in the sediment, as well through oxidization from organic material

Dissolved Organic Carbon (DOC): carbon dissolved in water (between 0.7 and 0.22 micrometers) sourced from organic material such as leached plant material and mineral soil layers

Dissolved Organic Carbon (DOC) fraction parameter: the parameters used to tune the fraction of carbon leaving both the slow aboveground and belowground DOM pools – adjusting the proportion from the default (1) where 100% of carbon lost from these pools is released to the atmosphere, to a value less than 1 where the difference exits the slow DOM pools to DOC

Disturbance Matrix (DM): a three column table (Source, Sink, Proportion of Source Pool to Sink Pool) used within CBM-CFS3 for each unique disturbance type to redistribute carbon pools post-disturbance

Good Practice Guidance (GPG): a report published by the Intergovernmental Panel on Climate Change on good practices for producing greenhouse gas inventories

Greater Victoria Water Supply Area (GVWSA): land area within the Capital Regional District devoted to supplying Greater Victoria residence with a stable quantity and quality of water

Gross Primary Production (GPP): the total amount of carbon fixed in the process of photosynthesis by plants in an ecosystem, such as a stand of trees

Growth and Yield (G&Y) Curves: predicted changes in forest volume based on a combination of species, composition and age and site quality

Harvested Wood Products (HWP): all wood material that leaves a harvest site to be transformed into products such as pulp, paper, or lumber

Heterotrophic Respiration (Rh): Sum of all decomposition releases, not counting direct losses due to disturbances (The conversion of organic matter to CO_2 by organisms other than plants)

Intergovernmental Panel on Climate Change (IPCC): a scientific intergovernmental body under the United Nations with the objective of stabilizing atmospheric greenhouse gas concentrations to prevent anthropogenic interference with the climate system

Net Biome Production (NBP): Total ecosystem carbon stock change (includes releases due to disturbance)

Net Biome Production (Cumulative) (ΣNBP): NBP summed year-over-year reflecting the cumulative effect of C fluxes from the study area

Net Biome Production (Cumulative) with Dissolved Organic Carbon Export (ΣNBP^{DOC}): NBP summed year-over-year including dissolved organic carbon as a carbon export mechanism reflecting the cumulative effect of C fluxes from the study area with dissolved organic carbon export

Net Ecosystem Production (NEP): Biomass production minus decomposition (NPP-Rh)

Net Primary Production (NPP): Sum of all biomass production (i.e. growth that results in positive increment) and growth that replaces material lost to biomass turnoff during the year (GPP-Ra)

Operational Adjustment Factor 1 (OAF1): a constant adjustment factor over the entire rotation used in modelling growth and yield within the Table Interpolation Program for Stand Yields (TIPSY) volume predictor program. OAF2 is used to adjust for a constant occurrence within the stand (such as unproductive growing site)

Operational Adjustment Factor 2 (OAF2): time sensitive adjustment factor that increases losses towards stand maturity and is used in modelling growth and yield within the Table Interpolation Program for Stand Yields (TIPSY) volume predictor program. OAF2 is used for time sensitive effect or occurrence that increases over time (some diseases)

Particulate Organic Carbon (POC): carbon sourced from organic material that is greater than 0.22 micrometers

Scenario 1 - Alternative Management Scenario 1 (SC1): water supply without deforestation or forest management (i.e. no forest harvesting or reservoir raising (flooding) between 1910 and 2012 within the original ownership boundary (disturbances in Lot 87 and Kapoor land maintained))

Scenario 2 - Alternative Management Scenario 2 (SC2): water supply without forest management (i.e. reservoirs are created and raised as in Baseline model runs, however, no forest harvesting occurs between 1910 and 2012 within the original ownership boundary (disturbances in Lot 87 and Kapoor land maintained))

Site Index/Site Class: a measure of potential site productivity defined as the average top height that free growing, undamaged trees of a given species can achieve in 50 years growth above breast height

Sooke Lake Watershed (SLW): refers to the study area and is bounded by both hydrological and administrative/ownership boundaries

Table Interpolation Program for Stand Yields (TIPSY): a growth and yield program for managed species that retrieves and interpolates yield tables in databases generated from TASS and SYLVER models

United Nations Framework Convention on Climate Change: an international environmental treaty with the objective of stabilizing atmospheric greenhouse gas concentrations to prevent anthropogenic interference with the climate system

Variable Density Yield Prediction version 7 (VDYP7): a growth model program that provides stand yield prediction for unmanaged (natural) forest stands

Vegetation Resource Inventory (VRI): British Columbia’s photo-based, two phased vegetation inventory consisting of photo interpretation and ground sampling

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I would like to thank my supervisors Tony Trofymow and Olaf Niemann for their guidance and support over the course of this project. Without having worked with me much prior to this project, Olaf took a chance and agreed to be my co-supervisor. In doing so, he provided valuable insights that greatly improved the calibre of this research, a contribution for which I am immensely grateful. Extending back into my years as an UVic undergraduate, Tony became my mentor, encouraging and fostering the academic I was striving to be. He had faith in my abilities, most times even before I did. Without Tony's assistance I would not have been able to reach this level of achievement. Joel Ussery of the Capital Regional District Integrated Water Services (CRD-IWS) was an avid supporter of the project from the very beginning. His counsel and understanding during this project were just as vital as the access he provided to CRD resources and project materials. Also, the effort, instruction and patience of my directed studies supervisor Dan Peters were greatly appreciated.

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Chapter 1 - Introduction

1–1.0 Background

Interrelated Processes in forest C budget Analysis

Northern forest ecosystems play an important role in global carbon (C) cycling and are considered to be a net C sink for atmospheric C (IPCC, 2007; Pan, et al., 2011). In this respect, these forest environments sequester and store more carbon than they emit to the atmosphere. Although dependent on the spatial and temporal scale of analysis, the sink strength of a forest area (and potential shift to a C source) is determined by processes that drive biomass production (i.e. photosynthesis, moisture regime, ambient temperature and geological parent material), forest decay, and the frequency, intensity and permanence of disturbances such as fire, harvest, disease or deforestation due to urbanization, agriculture, mining or reservoir creation. As well, lateral transfers of C into or out of a forest ecosystem through aquatic systems can also impact the ecosystem C balance. While naturally highly variable, the C sequestration potential of forests can be optimized by forest management practices (Man, et al., 2013). Maintaining or increasing the C sink potential of forest areas can improve the likelihood of reaching global Carbon dioxide (CO_2) stabilization targets. Understanding the net C balance of forest lands by monitoring C sinks and sources and modelling past and future C budgets can assist forest managers, allowing them to adjust forest management plans in an effort to mitigate climate change.

Process 1 – Biomass production and decay

Dynamics of forest biomass production, defined as Net Primary Production (NPP)[1], and decomposition, defined as Heterotrophic Respiration (Rh), are a result of specific forest

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[1] Refer to Glossary for further details on terminology

attributes including forest age, site productivity (growth potential) and species composition. These environmental factors are further influenced by the degree of human impact whereby forest management activities related to sustainable harvest, wood-based bioenergy, or fire and insect suppression (Stinson, et al., 2011) can result in altered Net Ecosystem Productivity (NEP) (NPP minus Rh) relative to a natural, unmanaged forest. These characteristics, both before and after a stand destroying-disturbance, such as harvest or fire, impact the balance between uptake of C through photosynthesis (sink), and release of C through respiration (source).

Process 2 - Disturbances

Compared to NPP and Rh, the impact of disturbance is generally spatially and temporally discrete, influencing short term C losses to the atmosphere, or removal of C as harvested wood products (HWP). Whether forested regions or landscapes are net C sources or sinks depends primarily on the degree and type of disturbance. A disturbance is defined as “any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability or the physical environment (Pickett & White, 1985), affecting biogeochemical interactions in general and C cycling processes in particular (Liu, et al., 2011). Disturbances can range from low intensity insect infestation or disease outbreak that increase forest mortality over several years, to stand-destroying wildfire that consume aboveground biomass C and releases the C to the atmosphere. These types of disturbances commonly result in continued or renewed forest growth. Other disturbances, such as land clearing for mining or reservoir creation, initially impact the land base similar to a harvest or wildfire but result in the land being deforested, with no post-disturbance forest regeneration. Many terrestrial ecologists believe that substantial CO_2 emissions have occurred from the disturbance and destruction of terrestrial vegetation and soils (Schlesinger & Bernhardt, 2013). In the first half of the 20th century, C released from land disturbance (including clearing for agriculture) may have exceeded that released from fossil fuel combustion (Houghton, et al., 1983). Whether the effects of disturbance are short term (e.g. wildfire or harvest) or permanent (e.g. deforestation) will determine the influence an ecosystem has on C accumulation in the atmosphere (Schlesinger & Bernhardt, 2013).

Process 3 – Lateral transfer of C via Dissolved Organic C

While past work has shown that a significant amount of terrestrially-sourced C is deposited in ocean basins (Schlesinger & Melack, 1981; Degens, et al., 1991; Regnier, et al., 2013; Fichot & Benner, 2014), very little attention has, until recently, been paid to the dynamic processes that occur at the watershed scale between forest land and inland aquatic systems. The interface between large river systems and open ocean mineralizes over half the terrestrial origin dissolved organic carbon (DOC) transported by river systems (Fichot & Benner, 2014) Away from the ocean margins, Vorosmarty, et al. (1997) estimated that the construction of large dams has increased the quantity of continental river water by 700%, leading to implications for C cycling on a global scale. Lateral transport of terrestrial C via streams and rivers is an integral component of the global C cycle (Hope, et al., 1994) yet the role of inland aquatic environments is rarely included in C modelling efforts and is also not taken into account in official greenhouse gas budgets established under the Kyoto protocol (Watson, et al., 1998). The biogeochemical reactions in lowland lakes and wetlands are strongly interrelated to the reactions occurring in the upland terrestrial environment and the river and groundwater runoff systems that link the ecosystem components together (Schlesinger & Bernhardt, 2013). C cycling within a watershed can be affected by the interactions between soil chemistry, terrestrial flora, microbial processes, and hydrological phenomena (Raymond & Saiers 2010). A disturbance to any one of these components can significantly impact the movement of C via fluvial systems as well as the C balance of the watershed as a whole. Land use changes are one of the potential reasons why increased lake and stream DOC concentrations have been observed over the last 30 years across much of North America and Europe (Porcal, et al., 2009). As much of the C lost from flowing streams originates within the terrestrial ecosystem, the fate of this terrestrial C, be it released to the atmosphere or stored in sediment, can occur meters to kilometers away from where the C was originally fixed (Cole, et al., 2007). Understanding the movement of C within a coupled terrestrial-aquatic system is vital for managing the effects disturbances may have on water quality and quantity within a watershed. This also has implications for climate change mitigation through optimizing C storage. C budget analysis that explicitly includes the potential sources and sinks of both forest land and inland aquatic components will improve landscape level C budgets and help to close the global C cycle budget (Raymond & Saiers, 2010; Schulte, et al., 2011).

Reservoir creation disturbance: Enhanced modelling of C exchange

Reservoir creation, whether for water supply, flood control or hydro-electricity, can have pronounced effect on the C budget of a watershed. While the initial impacts of establishing a reservoir are analogous to other forestland disturbance, such as fire or harvest, the deforestation that results can have long term implications for the landscape level C balance. For example, hydro-electric reservoir creation is considered to be a method of generating C-neutral energy (St. Louis, et al., 2000), yet estimates suggest that worldwide, land clearing and the subsequent decay of dead organic matter (DOM) from reservoir creation is responsible for 4% of anthropogenic CO_2 emissions (St. Louis, et al., 2000). Barros et al. (2011) looked at strictly reservoirs created for hydroelectricity and found that natural plus human-induced emissions from those reservoirs represent only 4% of C emissions from fresh waters and 16% of all human-made reservoirs, representing a significantly smaller estimate. The increased inland water volume and aquatic sediment deposition of DOC through mineralization resulting from reservoir creation could, over time, counter the sudden release of C that occurs during reservoir creation (Einsele, et al., 2001). Integrating the aquatic components of forest ecosystems into modelling efforts will enable more accurate determination of anthropogenic impacts on the C cycle, specifically for hydrologically altered watersheds.

Modelling C dynamics with CBM-CFS3

Modelling forest C dynamics is typically driven by empirical volume yield curves or by simulated photosynthesis (Kurz, et al., 2009). The Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3) is a landscape-level model for forest ecosystem C dynamics that uses data commonly collected by foresters and forest managers including forest inventory, growth and yield (G&Y) curves, natural and human-induced disturbance and land use change information as inputs to simulate forest C dynamics on an annual basis[2] (Kull, et al., 2011). G&Y curves that describe forest growth (in merchantable volume) are converted to aboveground stand-level biomass (Boudewyn, et al., 2007) and belowground biomass by component (Li, et al., 2003) using allometric equations. These G&Y curves were validated against ground plot data from within the Sooke Lake Watershed (SLW) (refer to Chapter 3 Section 2.4). The C pool structure of CBM-CFS3 includes both live biomass C (e.g. live stemwood and foliage) and DOM (e.g. coarse woody debris, snags) (Figure 1-1); transfers between these pools occur at varying rates depending on what forest constituents are represented within the pool.

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[2] See Chapter 3–4.1.1 *CBM-CFS3* for more details on model inputs and structure.

Transfers between pools in the form of biomass turnover and litterfall transfers have been validated against literature reviews and available datasets (Kurz, et al., 1992; Kurz & Apps, 1999). Through decay, disturbance or export (e.g. HWP), the model allows for C transfers out of the forest ecosystem to the atmosphere. Decay dynamics are determined through a temperature dependent decay rate (Kurz, et al., 2009) and were calibrated against a Canada-wide decomposition experiment (Trofymow & CIDET Working Group, 1998). Current model assumptions do not allow for changes in decomposition due to increased precipitation or changes in forest growth as a result of climate change.

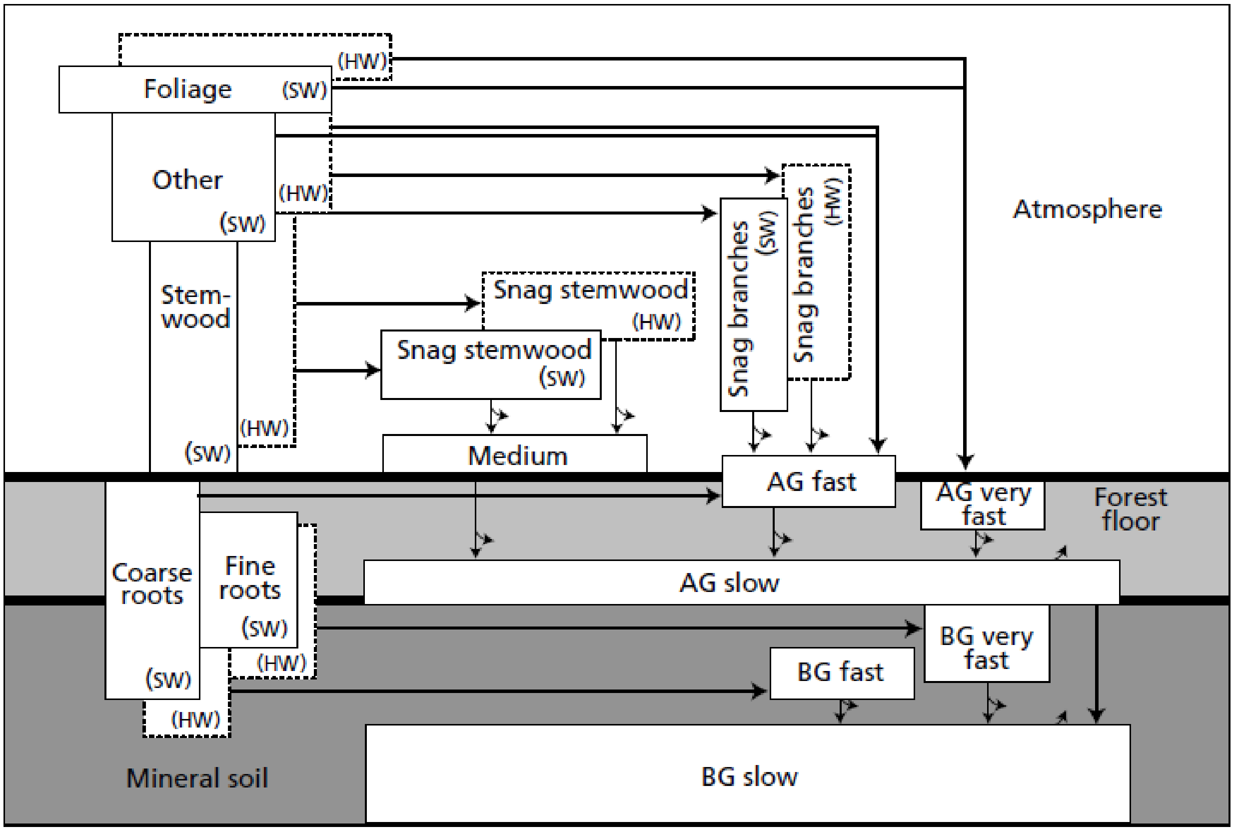

Figure 1-1 - CBM-CFS3 carbon pool and flux structure (Softwood=SW, Hardwood=HW, Aboveground=AG, Belowground=BG; Arrows represent transfers of C between pools and decomposition releases to the atmosphere)

As well, CBM-CFS3 cannot explicitly model mixed-age or mixed species stands; to reflect these stand attributes, G&Y curves that exhibit these qualities should be used (Kull, et al., 2011). Past work with this model uses default parameters that assume all C losses from the forested land base via DOC in the inland aquatic system are released to the atmosphere. Although the capacity exists to fractionate DOC to both atmospheric release and long term storage in aquatic sediment, it has yet to be parameterized. CBM-CFS3 has been widely used to model annual C uptake and emissions at the regional and landscape level for international C reporting by governments and operational C budgets by forest companies (Kull, et al., 2007) and evaluated against Canada's National Forest Inventory ground plot database (Shaw, et al., 2014). Also, the model has been applied retrospectively to reconstruct past C budgets of diverse landscapes (Trofymow, et al., 2008; Bernier, et al., 2010).

1–2.0 Rationale

The 2012 Strategic Plan for the Greater Victoria Water Supply System (Capital Regional District, 2012) identified adapting to climate change as a high priority goal and identified several key strategies and actions needed to address goals for the lands in the GVWSA which included:

- Improved understanding of potential effects of climate change on forest ecosystems and watershed hydrology in the GVWSA
- Knowledge of potential climate change effects to inform development of forest management and restoration plans
- Understand the C sequestration potential associated with ecosystems in the water supply area.

Achieving these needs requires the compilation of historic spatial disturbances and forest cover inventories for GVWSA lands, and the amalgamation of these data with current forest inventory information. Such data are critical in preparing retrospective and current C budgets which can then be verified against other monitoring (eg. LiDAR) and ground plot data collected for these lands. Testing results from retrospective model runs can be used to better parameterize models and thus improve the estimate of current fluxes and stocks and increase the confidence in the models when projecting estimates under different climate change or forest management scenarios. In the future, verification of near-term model projections could also be made against data from enhanced forest and water monitoring programs being planned by the CRD.

As a contemporary C budget has not been conducted for the SLW, the consolidated Forest cover-Disturbance geodataset that includes all known anthropogenic disturbances will encompass the Baseline management scheme from which alternative management scenarios can be compared. The high value placed on the SLW as the primary source of water for the region, as well as the high prevalence of old growth stands and unique disturbance history culminate in an appealing and topical case study of how forest management, specifically that which includes reservoir creation, can impact the C budget of a watershed.

Current forest C budget research regarding the relative importance of dissolved organic carbon (DOC) as a dynamic C export mechanism from terrestrial systems is lacking. As the dynamics of inland aquatic systems are missing from the current generation of C models (Cole, et al., 2007), an active area of research is in coupling and integrating models of different cover types (forestland, wetland, crop, reservoir) to account for C exchange across whole landscapes. A significant issue when attempting to integrate the C dynamics of both the terrestrial and aquatic components in modelling efforts is the inherent complexity of the interactions between these systems. Yet, beginning to interrogate the interactions between the aquatic and terrestrial C components will enable insights into role they play in the C balance of a watershed.

1–3.0 Objectives

There were three primary objectives of this research. The first was to examine and quantify the effect that conversion of forest land to reservoir and forest harvest between 1910 and 2012 has had on the landscape C budget of the SLW, Victoria's main water supply area (Figure 1-2) (Trofymow & Niemann, 2012); second, to advance the understanding of C export from the terrestrial system via DOC; and third, to investigate the impact that alternative management scenarios may have on the current landscape C budget.

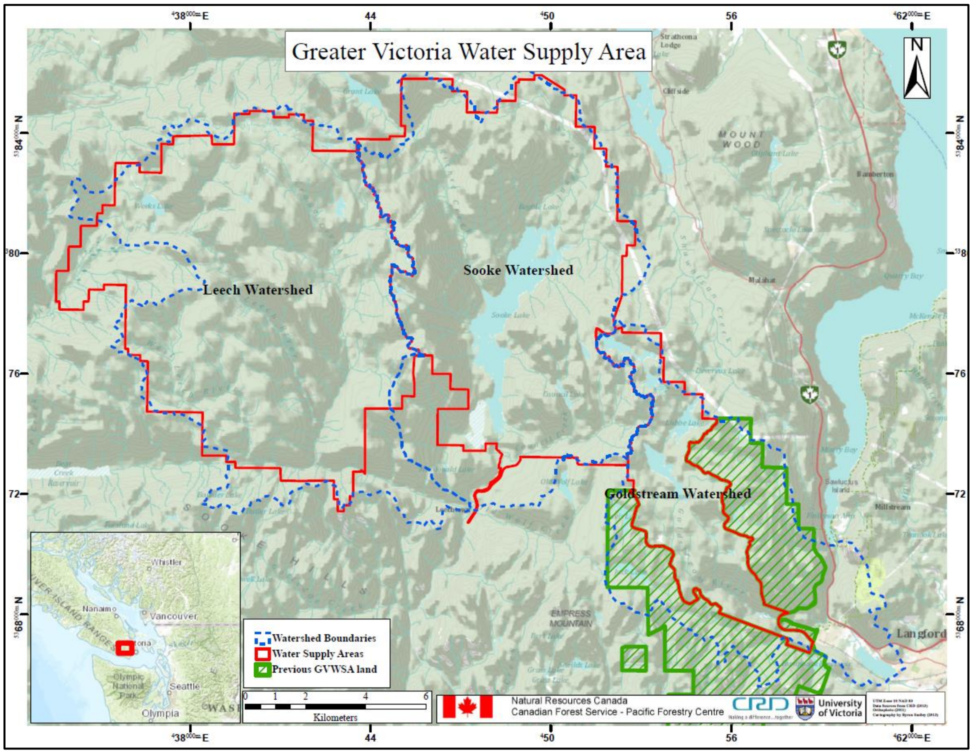

Figure 1-2 - Greater Victoria Water Supply Area: Watershed and Ownership Boundaries

To accomplish this, a Forest cover/Land cover-Disturbance geodataset was assembled depicting the forest changes that have occurred in the SLW study area (Figure 1-3) from 1910 to 2012. Using this dataset as the primary input, the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3) was run to create a retrospective and current C budget for the SLW, the primary catchment within the Greater Victoria Water Supply Area (GVWSA). The historic

Baseline C budget of the SLW will be compared to two alternative management scenarios in which the land management regime prescribes: 1) No reservoir creation or forestry operations within the original lands acquired by the GVWSA, and 2) Reservoir creation and expansion maintained as per Baseline scenario but no forestry operations within the original land holdings of the GVWSA[3]. These contrasting management scenarios will elucidate the influence that different forest management decisions can have on the landscape level C budget of a water supply watershed. The export of C from the terrestrial environment via fluvial processes will be estimated using three gauged catchments periodically measured for DOC. Using CBM-CFS3, the fraction of C export through DOC as opposed to direct release to the atmosphere will be parameterized and applied to the full extent of the SLW. The CRD's strategic mandate to improve the understanding of the potential effects climate change may have on forest ecosystems and water quality/hydrology, and the determination of how forest management plans could amplify or reduce these impacts, will be partly addressed by this research.

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[3] Of note, this management regime has been the prescribed for the GVWSA since the mid-1990s when logging activity in the area ceased.

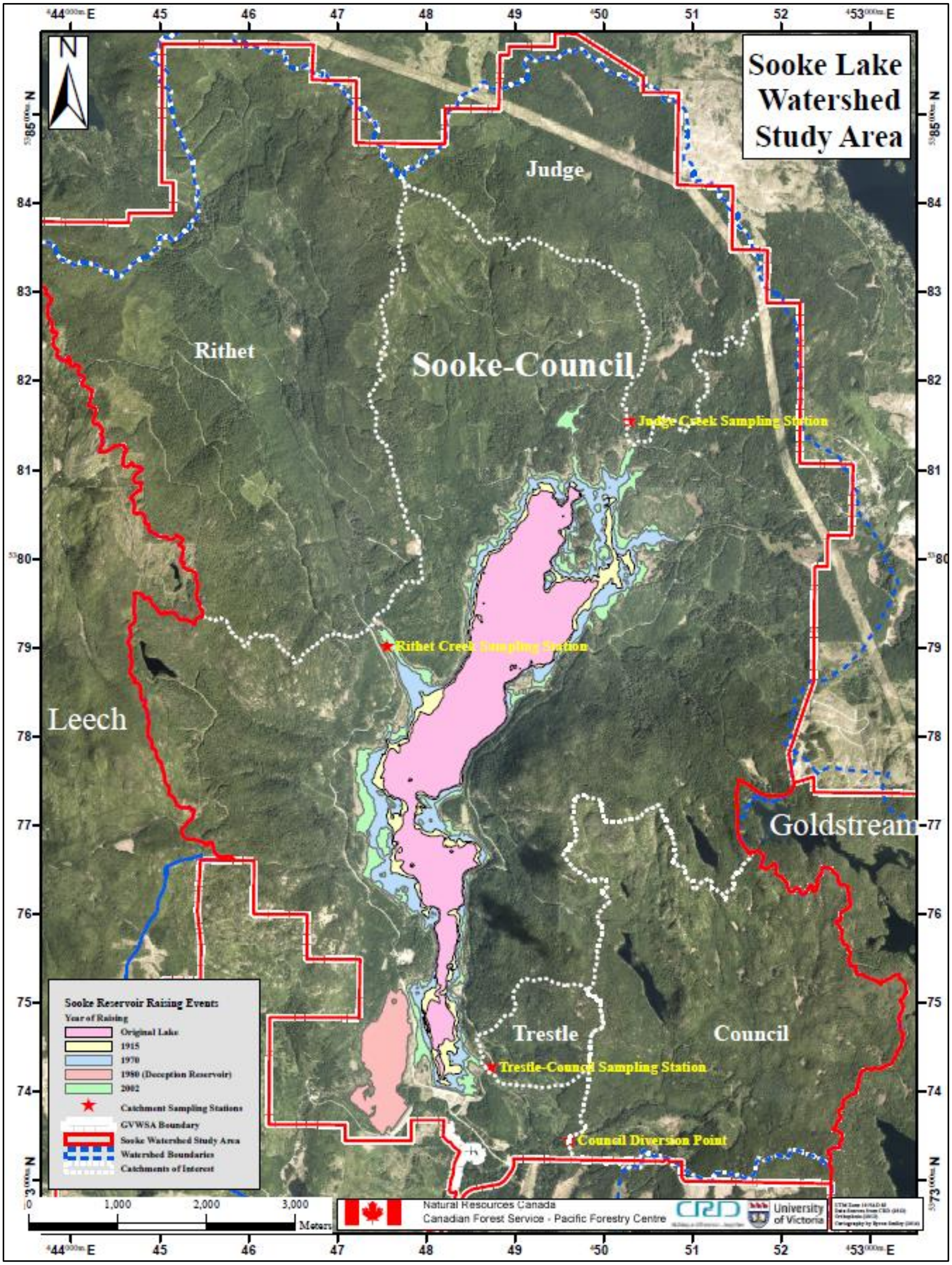

Figure 1-3 - Sooke Lake Watershed study area, catchments of interest and reservoir raising boundaries

The following chapters describe the components of this study:

Chapter 2 – Identifying and assembling historic spatial, disturbance and ground plot data for the SLW, digitization and orthorectification of historic sources and compilation of the combined Forest cover-Disturbance inventory GIS database for the SLW.

Chapter 3 –Selection of growth and yield equations and validation against available ground plot datasets; development of unique disturbance matrices and execution of Baseline model runs.

Chapter 4 – Analysis of stream DOC flux from three gauged catchments within the SLW for 1996 to 2012 to parameterize DOC transfers from the terrestrial to the aquatic system.

Chapter 5 – Application of DOC flux parameters to final baseline model runs for the entire study period (1910-2012) and comparison of the role DOC has on the landscape C budget, summarizing the contrast between the Baseline and two alternative management scenarios.

Chapter 6 – Conclusions and Projections. Includes the investigation of the impact different natural disturbance intervals have on the pre-simulation generation of Dead Organic Matter (DOM) pools from those of default parameters as well as a look forward at the predicted C budget of the SLW by 2112 based on the current forest management regime.

1–4.0 Study Area Description

The Sooke Lake Reservoir (48^0 31’30”N, 123^0 37’30”W) is located on southern Vancouver Island, British Columbia, Canada (Figure 1-2). The SLW, part of the Greater Victoria Water Supply Area (GVWSA), is approximately 40 km north of Victoria and is 8595 hectares (ha) in size of which 810 ha is now reservoir. The Capital Regional District (CRD) ownership of the Sooke Lake Water Supply Area constitutes approximately 98% of the area that drains into Sooke Reservoir (Capital Regional District, 2014) (Figure 1-3). For the purposes of this study, the Sooke Lake Water Supply Area was considered synonymous with the SLW in its entirety (i.e.

non-owned catchment lands are ignored). The SLW also includes the Council Creek watershed that is diverted into the Sooke reservoir via Trestle Creek.

The SLW lies within the Nanaimo Lowlands Physiographic region and is dominated by the Coastal Western Hemlock, Very Dry Maritime biogeoclimatic zone (Pojar, et al., 1991). It is a mild and moist climate with approximately 1640 mm mean annual precipitation, concentrated largely in the October to March wet season, and warm dry summers with an average July air temperature of 16.7 degrees Celsius. The winters are mild and typically without extended periods of sub-zero temperatures. During the winter some snowpack does exist at the highest elevations in the watershed (Zhu & Mazumder, 2008). By April, precipitation begins to taper off; June has the least variable precipitation regime while July and August experience maximum temperatures and minimum precipitation (Werner, 2007).

Due to management practices over the last 100 years, the SLW has a diverse forest structure and age distribution. In 1910 the watershed was dominated by old and mature Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) forests with little evidence of anthropogenic disturbance on the landscape. Over the last century, 2430 ha of forest was cut and replanted and 640 ha deforested for reservoirs and infrastructure. Currently, the majority of forest stands are dominated by coastal Douglas-fir with stands ranging from 0 to >300 years (Smiley, et al., 2013). Younger forest stands were planted after forest harvest while the old growth stands are natural regeneration (Greater Victoria Water District, 1991). Other tree species include Western red cedar (*Thuja plicata*), Western hemlock (*Tsuga heterophylla*), Lodgepole pine (*Pinus contorta*), Western white pine (*Pinus monticola*), Grand fir (*Abies grandis*), Red alder (*Alnus rubra*), and Bigleaf maple (*Acer macrophyllum*). Dominant understory vegetation includes salal

(*Gaultheria shallon*), mahonia (Oregon grape) (*Mahonia aquifolium*), step moss (*Hylocomium splendens*), with some sword fern (*Polystichum munitum*).

1–5.0 Study Area History

Prior to European settlement, there were no documented large scale disturbances within the SLW. Minor land disturbances including a farm and small scale fish camps existed along the shoreline of Sooke Lake before it was converted to a reservoir for Greater Victoria (Axys Environmental Consulting Ltd. and Aquatic Resources Ltd., 1994). A donkey trail was constructed along the eastern shore of the lake in approximately 1886 (Axys Environmental Consulting Ltd. and Aquatic Resources Ltd., 1994) and further cleared and converted to a rail line in 1930. As well, numerous access roads were built, permeating the watershed, although most were in close proximity to the lakeshore. The first significant disturbance event occurred during the land clearing and dam construction for the first reservoir between 1911 and 1915. This raised the level of the lake by approximately 3.7 meters and expanded the area of the lake from 370 to 450 ha.

Between the late 1920s and the end of the 1930s significant clear-cutting and broadcast slash burning occurred in the adjacent Council Creek watershed. Until 1975 the Council Creek catchment drained into Sooke River downstream of the dam location and was therefore not considered part of the Sooke Water Supply Area. In 1975 a diversion was built to pipe Council Creek into Sooke Reservoir via Trestle Creek. Since then, Council Creek has been diverted into Sooke Reservoir during the winter months (F. Hall, pers. comm. 2014). The Greater Victoria

Water District (GVWD)[4] did not gain ownership of the Council Creek watershed (and therefore was not in control of land management) until 1998.

In the early 1930s intensive clear-cutting and broadcast slash burning was conducted in the northeastern area of the SLW. At the time, this area lay outside GVWD tenure and therefore downstream water quality was not a land use consideration. Within the GVWD land base the SLW remained largely undisturbed until the mid-1950s when they began using income from forest harvesting activities to pay for water infrastructure upgrades (Axys Environmental Consulting Ltd. and Aquatic Resources Ltd., 1994). High-grading of old-growth Western red cedar poles may have occurred in the 1910 to 1950 time period using roads that existed at the time (pers. comm. J. Ussery); however, no record of this in the forest cover maps or ancillary sources could be found.

Preceded by significant shoreline clearing activities, a new dam was constructed in 1970 approximately 100 meters downstream of the existing dam and the reservoir was raised a second time in order to maintain a reliable water supply for Greater Victoria's expanding population (Axys Environmental Consulting Ltd. and Aquatic Resources Ltd., 1994). This expansion of the reservoir from 450 ha to 610 ha increased the usable storage capacity to 50 million cubic meters and raised the water level another 16 meters (Axys Environmental Consulting Ltd. and Aquatic Resources Ltd., 1994). BC Hydro installed a transmission line right-of-way across 6.7 kilometres of the northeastern section of the SLW in 1980 that required 182 hectares of forest land to be cleared. In 1980 Deception Reservoir was constructed directly adjacent to the west side of the southern basin of Sooke Reservoir, expanding the reservoir area within the SLW to 670 ha.

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[4] The Greater Victoria Water District (GVWD) was the precursor to the Capital Regional District in relation to the administration of Greater Victoria's water supply infrastructure.

Because of its relatively high levels of nutrients this reservoir is only used to supplement flow into Sooke River south of the reservoir for fisheries purposes. Sustained yield forest harvesting continued until the mid-1990s when management for water quality and supply became the exclusive priority for the SLW. Forest harvesting ceased in the mid-1990s as a result of public opposition and a legal decision that some activities associated with logging were outside the authority of the GVWD. However, soon thereafter shoreline land clearing commenced to enable a third reservoir expansion in 2002 to 810 ha, increasing the height of the reservoir by another 6 meters (Werner, 2007). Since 2002 no major disturbances have occurred in the SLW as it remains solely managed for water supply.

1–6.0 References

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Chapter 2 - Data Collection and Compilation

2–1.0 Introduction

To ensure accurate assessments of forest resource values on their tenure, land managers collect forest attributes including trees species composition, growth potential (site productivity), stocking density, forest age, and past disturbance attributes (i.e. date, type) that are periodically updated in comprehensive forest cover inventories. Tools have been developed to use these data to model the growth and yield of timber over time; enabling the prediction of future (or past) forest product volume on a land base. As CBM-CFS3 was designed to use these commonly collected forest attributes as input data to calculate C stocks and stock changes, a comprehensive Forest cover/Land cover-Disturbance geodataset is required for model input. This chapter describes the identification and assembly, digitization and compilation of inventory and disturbance sources for the SLW for the years 1910 to 2012. Current site productivity (site index) values within the available forest inventories were incomplete for older forest stands and therefore were required to be generated from other data sources. The development of site index values from LiDAR-derived height biometrics is also documented in this chapter[5].

With assistance of CRD staff, a data catalog was assembled documenting all available historical documents and maps for the GVWSA lands within the CRD's possession (Appendix A). Based on known major disturbance events within the SLW, specific maps were selected from this catalog to be scanned, digitized and orthorectified (relevant forest/land cover maps are exhibited in Figure 2-1). Also, several trips to the British Columbia Archives were conducted to identify other possible data sources to fill timeline gaps. While the CRD had a significant

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[5] LiDAR was collected in 2006 for the Sooke Lake watershed. As LiDAR's ability to capture stand height is limited for stands younger than 20 years, a LiDAR-derived site index was not developed for these stands.

collection of airphotos for the time period 1948 to present, the National Air Photo Library (NAPL) was contacted to ascertain whether older image collections existed for the study area. Historical air photos were identified from the NAPL for the Sooke (Figure 2-2), Goldstream and Leech areas in order to assemble a historical orthophotomosaic for the areas.

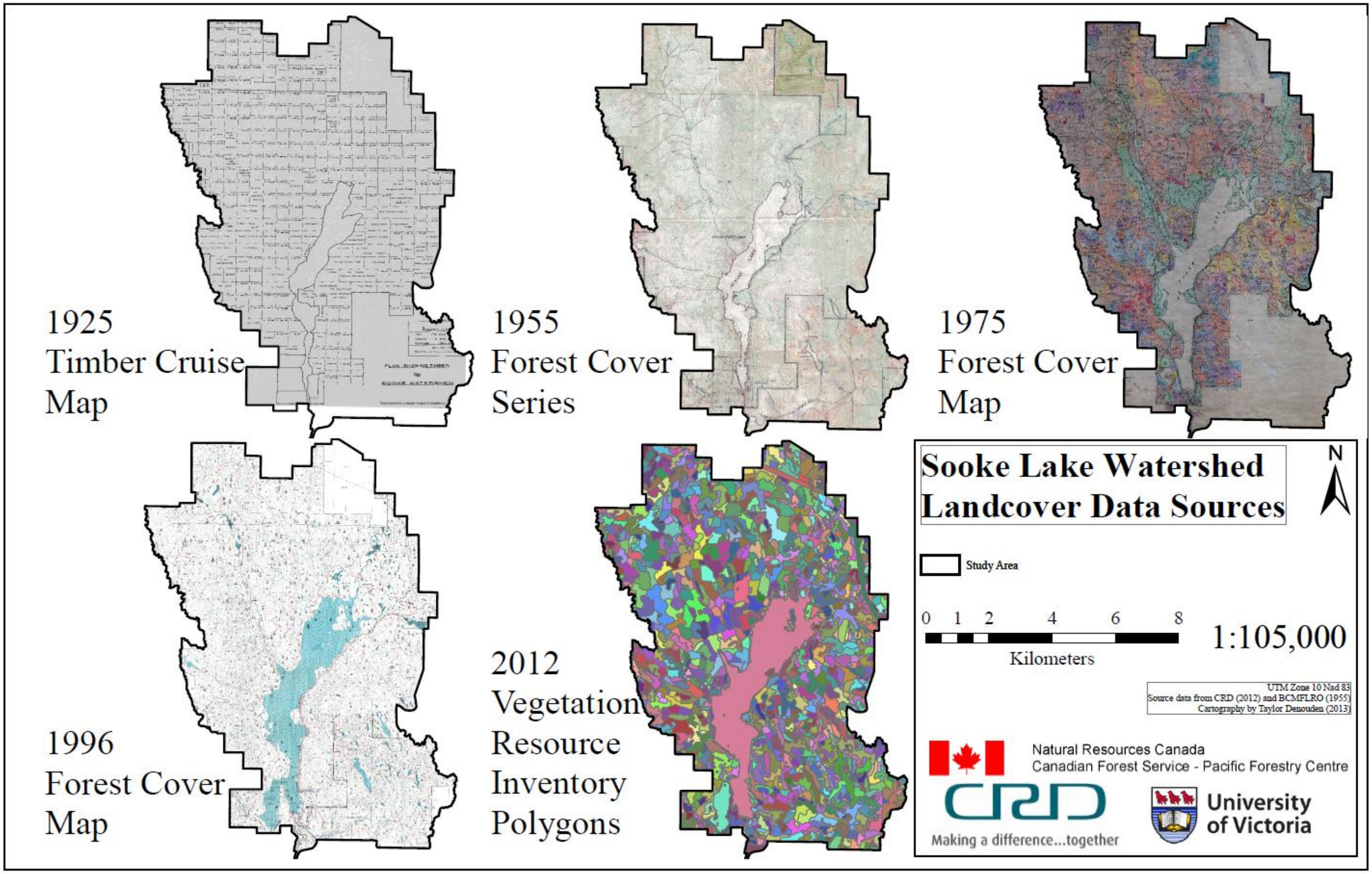

Figure 2-1 - Sooke-Lake Watershed Land cover/Forest cover and Disturbance Data Sources: 1910 to 2012

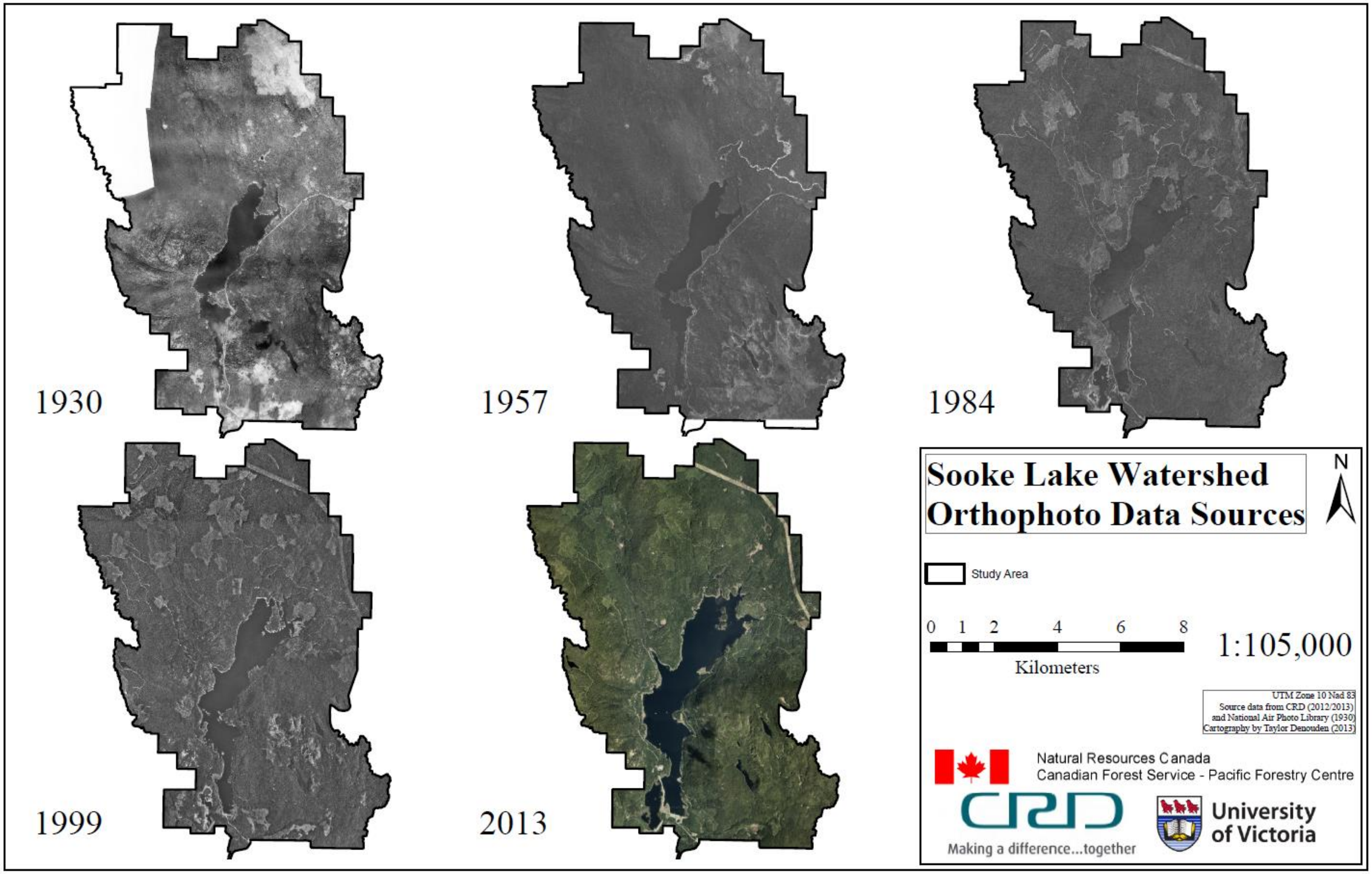

Figure 2-2 - Sooke Lake Watershed Orthophoto/imagery mosaics: 1930 to 2013

Taylor Denouden, a Co-op student assisting with the project, began work at the Pacific Forestry Centre (PFC) to aid in GIS file integration, reconciliation, and forest cover/land cover and disturbance database preparation. The spatial database for the SLW was to contain all disturbance, treatment, and forest stand typing information dating back to 1910. This start date was chosen because it was the earliest year before human disturbances started to occur throughout the watershed in the form of harvesting, land clearing for reservoir flooding, and burning (Barraclough, 1995). Historic forestry maps were digitized and overlaid to capture all recorded disturbance events. Selection of historical disturbance and forest cover information was focused around periods of major disturbance, i.e. reservoir creation (1910-15), sustained logging initiation (1955-65), first reservoir expansion (1965-80[6]), and second reservoir expansion (1995-2002). Forest cover sources that were identified included a 1911 Sooke Lake map, 1955-56 maps for the Sooke, Council, Goldstream, and Leech watersheds, a 1980 Council Lands map and a 1992 Council Lands map from Kapoor Lumber. 1930 and 1937 historical airphotos for the SLW were ordered from NAPL and a 1930 orthophoto was delivered by McElhanney Consulting Services Ltd. to the CRD and PFC after being georeferenced, mosaicked and orthorectified (see Appendix A for complete list of identified/utilized data sources).

A Vegetation Resource Inventory (VRI) Phase 1 had been conducted in the summer of 2012 for the GVWSA. While some data concerns (identified by Edwards and Ussery, CRD) and topology issues[7] (identified by Smiley) had not initially been resolved, work progressed on how to best utilize the VRI dataset. Because the linked table structure the VRI is formatted in was not

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[6] This time frame includes the raising of Sooke and Deception Reservoir.

[7] Topology refers to geometry errors in a GIS dataset. These can include occasions of overlapping polygons, or gaps between polygons across a polygonal dataset.

ideal for merging with historical data sources, a “flattening” procedure was developed in order to convert the data into a useable form (see Appendix B).

2–2.0 GVWSA Data Sources

2–2.1 Sooke Lake Watershed Landbase

a) 1911 Sooke Lake clearing map

A large blueprint map from 1911 was discovered at the CRD Integrated Water Services (CRD-IWS) office which showed the original undammed Sooke Lake, historic wetlands, and areas which were cleared or being cleared for the initial reservoir raising. Due to its damaged condition and large size (approximately 3m by 1m) the map proved difficult to digitize. Therefore, the map required specialized equipment to prevent damaging or destroying the original. Through the assistance of Andrew Dyk at the Pacific Forestry Centre, a series of low and high resolution images were taken using a D-SLR camera and digitally stitched together using PCI Orthoengine (*v10.3.2*) software.

Thirty-three points on the hardcopy map were recorded and used as reference locations to tie three low resolution images together. These reference images were then processed to create the initial low resolution mosaic. Eight high resolution images were then referenced to the low resolution image and processed to create a high resolution mosaic. GIMP photo editing software (v2.8) was used to move and rescale the inset of the northeast limb of Sooke Lake to its proper location and clean up border areas and several small tears in the map. Finally, the high resolution mosaic was imported to ArcMap, where it was georeferenced using streams and topographic features as reference points.

b) 1925 Cruise block map of SLW

A 1925 timber cruise map of the SLW (not including Council) in the CRD-IWS data catalog was examined and subsequently scanned and digitized as it contained the earliest known forest cover and volume estimates for the area. Volumes for Douglas-fir, Western red cedar and Western hemlock were documented by cruise block. On the map, when timber volumes were below merchantable levels for a cruise block, basic disturbance or non-productive descriptions (i.e. “Old fire”, “Scrub”) were used to define the cruise block’s composition. These descriptions were transcribed into the Forest cover-Disturbance geodataset. Board feet values for a cruise block were converted to cubic meters per ha, and non-forest polygons were factored out of this calculation. See Appendix C (metadata) for more information of conversion method. Literature suggests that board feet (MBF) to metric conversions should account for MBF being a measure of milled lumber volume rather than standing volume of trees and the significantly higher volume not accounted for as saw kerf and unusable rounded log edges (Spelter, 2002). While Spelter (2002) suggests methods to accommodate these volume discrepancies based on individual tree diameters and lengths, no accommodations were made because of a lack of such diameter or length information in the 1925 timber cruise map. A crude imperial to metric unit conversion was instead performed with one board foot being equal to $0.00236m^3$ (Spelter, 2002; Trofymow, et al., 2008).

c) 1955/56 Forest cover maps (Leech, Sooke, Council, South West Shawnigan Lake area (Lot 87))

Through Brian Low at the Pacific Forestry Centre it was learned that Tim Salkeld from the British Columbia Ministry of Forests was storing a forest cover map series for BC that was the basis of the coarse -scale BC Interim Forest Cover Series published in the mid-1960s. In return for scanned, digitized and/or georeferenced copies, Mr. Salkeld provided all maps pertaining to the GVWSA (Leech and Goldstream watersheds inclusive) and adjacent lands. These maps, dated 1955-1956, included basic forest cover typing and known disturbance dates and types. As the CRD did not gain ownership of certain areas of the SLW drainage until 1998 (Council Lake lands and Lot 87), very little historical forest cover and disturbance information was in the CRD's possession. The 1955/56 maps proved extremely valuable as they provided forest cover attribute information of forest lands in Council and Lot 87 prior to them being disturbed. These maps enabled us to define initial disturbance dates for stands harvested and burned as far back as the early 1920s.

d) 1964 Forest cover map

A 1964 forest cover map of the SLW (not including Council) was selected from the CRD-IWS data catalog and subsequently scanned and partially digitized as it contained forest cover and disturbance attributes and polygons for the area around Sooke Lake that was inundated in the 1970 reservoir raising. Also, in order to maintain a record of the forest cover attributes of stands pre-disturbance, polygons were digitized for areas that were harvested or burned between 1964 and 1975. While this forest cover map was of a coarse nature, valuable polygon boundary and forest cover type information was gleaned from it.

e) 1975 Forest cover map

A 1975 forest cover map of the SLW (not including Council) was selected from the CRD-IWS data catalog and subsequently scanned and partially digitized as it contained more detailed and finer-scale forest cover and disturbance attributes and polygons than did the 1964 forest cover map. In order to maintain a record of the forest cover attributes of stands pre-disturbance, polygons were digitized for areas that were harvested or burned between 1975 and 1996.

f) 1980 Council lands forest cover map

Through a land exchange, the CRD acquired the Council lands from Kapoor Lumber on November 25 1998; this resulted in a unique challenge for acquiring historical forest cover and disturbance information consistent with the timeframe of the adjacent SLW inventories. A 1980 forest cover map of the Council Lake watershed was selected from the CRD-IWS data catalog and subsequently scanned and partially digitized as it contained pertinent forest cover and disturbance information for areas disturbed between 1980 and 2006.

g) 1992 Council (Kapoor) forest cover map

A 1992 forest cover map of the Council Lake watershed was selected from the CRD-IWS data catalog and subsequently scanned and georeferenced but not digitized. This map's origin was the Kapoor Lumber Ltd. Company that owned the land prior to sale to the CRD. This map was used to verify other Council watershed data sources as it contained pertinent disturbance information for areas disturbed between 1956 and 1992; however the majority of these data were available in the 2006 Modified forest cover inventory.

h) 1996 Sooke North, Sooke South and Council forest cover map

As with the 1992 Council (Kapoor) forest cover map, the 1996 Council map was not digitized but was instead used as a verification tool for other map datasets. Conversely, the 1996 SLW (North and South) maps were scanned, georeferenced and partially digitized for lands disturbed between 1996 and 2006. This enabled pre-disturbance forest cover attributes and polygonal boundaries to be extracted, principally around the area inundated during the 2002 reservoir raising.

i) 2006 Modified forest cover/forest fuel inventory

The digital 2006 Modified forest cover was provided by the CRD-IWS. As of May 2012, this dataset represented the full extent and most current description of forest cover and forest fuel knowledge that the CRD had in regards to the Sooke, Council and Goldstream watersheds. While some areas and a select number of attributes had been incrementally updated, many dataset records were relics of previously digitized forest cover maps, namely the 1975 and 1996 forest cover maps. In some cases this was a hindrance such as when height and age class values were copied from a past inventory but were not updated to reflect the increased ages or heights. Also, cases were found where stands were recorded as being logged when, through orthophoto interpretation, no logging had occurred, and vice versa. However, for the vast majority of polygons and attributes, the 2006 inventory provided very useful information, specifically in regards to stand leading species, site index values and for corroborating stand establishment dates and polygonal boundaries.

j) 2012 Vegetation Resource Inventory (Phase 1 Data)

The 2012 Vegetation Resource Inventory Phase 1 dataset was completed for the CRD by FDI Forest Dimensions Inc. and supplied to PFC on June 26 2013. This dataset contained current land cover information for the GVWSA (see Table 2-1 for land cover types). Because the linked table structure that the VRI is formatted in was not ideal for merging with historical data sources, a “flattening” procedure was developed in order to convert the data into a useable form. Once reformatted, the flattened dataset provided valuable species composition, stand height, stand age, land cover classification/composition and polygonal boundary delineation.

Table 2-1 - Description of Land cover (A), Disturbance (B), Treatment (C) and Species (D) codes found in the combined disturbance-land cover/forest cover dataset

(A) LANDCOVER CLASS CODE (LC_CLASS)		(B) DISTURBANCE CODE	
Code	**Landcover Type**	**Code**	**Disturbance Type**
TC	Treed Coniferous	Fw	Wildfire
TM	Treed Mixed	Fh	Human caused fire
TB	Treed Broadleaf	Fsb	Broadcast (slash) burn
WE	Wetland	Fpb	Partial Burn
IN	Infrastructure	Frp	Residual pile burn
SH	Shrub	Fto	Pile burn and ash trucked out
AG	Agricultural Land	Frt	Transmission line residue burn
GP	Gravel Pit	Lc	Clearcut logging
RZ	Road Surface	Lct	Clearcut logging for transmission line
BR	Bedrock	Lch	Historical clearcut logging
LA	Lake	La	Partial harvest (50% remains)
RN	Railway	Ll	Land-clearing logging
TL	Transmission Line	Llb	Land-clearing logging with biomass export
RE	Reservoir	Lr	Logging for road right-of-way
		Lsb	Logging with broadcast (slash) burn
		Lrp	Logging with residue pile burn
		Lls	Land-clearing logging with broadcast (slash) burn
		Llp	Land-clearing logging with pile burn
		Llr	Land-clearing logging for road right-of-way
		IBD	Douglas-fir Beetle (Trace or low severity)
NOTE: residue burns that occur in the same year as harvest were given a unique disturbance code (i.e. Lsb)			

[a], [b], [c]: Denote disturbance types that, because of the similarity, share a disturbance matrix (see Chapter 3)

(C) TREATMENT CODE		(D) SPECIES CODE	
Code	**Treatment Type**	**Code**	**Species Type**
P	Planted	AC	Poplar
Tp	Partial Thinning	BG	Grand-fir
G	Grass Seeded	CW	Western Cedar
M	Mechanical	DR	Red Alder
MP	Mechanical and Planting	FD	Douglas Fir
MG	Mechanical and Grass seeding	HW	Western Hemlock
PG	Planting and Grass seeding	MB	Broadleaf Maple
PTp	Planting and Partial Thinning	PW	Western White Pine
MPG	Mechanical, planting and Grass seeding	PL	Lodgepole Pine
		SS	Spruce
		RA	Arbutus

k) Orthophotography

Historical and current orthophotos of the SLW were provided by CRD-IWS for the year 1957, 1968, 1984, 2001, 2002 and 2011. Additional air photos were acquired from the National Air Photo Library (NAPL) for the SLW for the year 1930 as they represented the earliest known date of airphoto acquisition in the watershed (National Air Photo Library, 2012). Orthophotos from all years were useful in verifying disturbance dates and the spatial extent of disturbances recorded in the historical forest cover inventories, as well as lake level information (Figure 2-2).

l) LiDAR-derived Canopy Height Model (CHM) (20m)

Light detection and ranging (LiDAR) has emerged as a valuable remote sensing tool to capture the vertical structure of forest canopies (Wulder, et al., 2010). LiDAR derived biometrics, canopy closure fraction and height quartiles from 2006 at 20 meter resolution for the SLW were generously provided by the Hyperspectral – LiDAR Research Group at the University of Victoria. As VRI site index values proved to be incomplete for the SLW, the LiDAR derived height values were used to assist in the generation of continuous stand-level site index values for the study area (see Chapter 2, Section 3.6).

2–2.2 Bathymetry and Stream Water Quantity and Quality Sampling

Bathymetry and derived lake level datasets were supplied to PFC in order to ascertain the area of the original lake level, as well as the area inundated during the three lake raisings. Water quality sampling station locations, as well as the available sampled parameters at each station were provided. Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC) and Dissolved Inorganic Carbon (DIC) concentration data were selected from these parameters to be used during later project phases to investigate the aquatic flux of C from the terrestrial landscape and the fate of this allochthonous C in the inland aquatic environment (Chapter 4). To inform the dissolved C concentration data the Engineering and Infrastructure Group of CRD-IWS provided stream flow data measured at weirs adjacent to water quality sampling stations.

A fire history study done in the early 1990s (Murray, 1994) was used to inform some unknown disturbance events observed in the 1930 orthophoto. While the study’s plot data were unavailable, forest cover polygon identification numbers were present in the report tables and were used to link fire dates within the report to locations within the SLW. Also, this report documented the historical disturbance return interval by wildfire which used to inform CBM-CFS3 spin-up procedures[8] (Chapter 3, Chapter 6).

2–3.0 Data Consolidation Methods

2–3.1 Overview

Two major categories of forest cover polygons were identified and were used when merging the historical and current data sources:

- **Disturbed forests polygons (DF)** – stands that had been impacted by at least one anthropogenic or natural disturbance event over the course of the study period (1910-2012), were selected as one category.
- **Original forests polygons (OF)** – stands where no disturbance was evident for the extent of the study period.

The rationale for this approach was to minimize the proliferation of sliver polygons created when joining [Union][9] together datasets of varying origins. Also, this method minimized the errors associated with stands of similar but different ages that were aggregated in the 2012 VRI inventory while datasets that contained the date of disturbance showed the polygons to be distinctly separate. There were also three minor categories recognized:

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[8] Spin-up procedures refer to stand initialization parameters that include the historical disturbance type and interval as well as the last disturbance event before the modelling period. These parameters determine the initial carbon dynamics and pools for the simulation period (Kull, et al., 2007).

[9] The ArcGIS tool Union creates a new coverage by splitting the polygons of the two coverages by each other and combining both coverage's attributes where they overlap and maintaining polygon geometry and attributes where they do not overlap (ESRI, 2013).

- **Non-forest polygons (NF)** – polygons that do not support forest growth (i.e. wetlands, bedrock, etc.) (see VRI Dataset Preparation for more details)
- **Deforested polygons (DE)** – polygons that had supported forest growth during the study period but remained non-forested post-disturbance as of 2012 (i.e. gravel pit, transmission line etc.).
- **Afforested polygons (AF)** – polygons that had supported forest historically but were deforested during the study period for an extended period of time (i.e. railroad right of way, gravel pit) but were subsequently replanted after 1990.

In order to capture the pre- and post-disturbance forest cover attributes of the disturbed forest polygons data sources collected both before and after known disturbances were required. As the timing of the major disturbance events within the SLW were roughly known, this methodology guided the identification and assembly of appropriate sources of forest cover and disturbance information. Table 2-2 describes the coverage of these four categories within the SLW as of 2012.

Table 2-2 - Area of different land cover within the Sooke Lake watershed as of 2012

Cover Status	Area (ha)	Percent
Afforested land (AF)	17.17	0.20
Deforested Land (DE)	641.04	7.46
Disturbed Forest (DF)	4340.94	50.50
Non-Forest (NF)	650.10	7.56
Original Forest (OF)	2945.89	34.27
TOTAL	8595.14	100.00

For original forest polygons in 2012 that had not been disturbed during the study period (and therefore were likely never disturbed on a large scale by humans) a less intensive data compilation was required. It was assumed that the VRI forest cover attributes for original forest polygons were an appropriate representation of their attributes in the past as no stand-destroying disturbance has resulted in polygon-wide change. VRI inventory attributes were back-cast from their 2012 values to those of 1910, augmented by the 1925 cruise volume data. However, due to possible natural successional changes that may have occurred to mature forest types over the course of the study period, forest cover attributes from the 1955/56 forest cover map for these original forest polygons may be included at a later date to reflect these possible changes[10].

The SLW study area is defined by a combination of catchment and ownership boundaries, both supplied by the CRD-IWS. The majority of the historical maps were collected based on GVWD property boundaries; they also well-approximated the catchment boundaries of the SLW. As the Council catchment, which has been diverted into the Sooke Reservoir, was also included in this study, the south-eastern study area boundary is defined by the Council-Goldstream catchment border. Also, the majority of the study area's western boundary is based on the Sooke-Leech catchment border. The north, northeast, and south boundaries are largely based on GVWSA ownership boundaries.

2–3.2 Reservoir Level

Initially, all pre- and post-reservoir raising lake levels (and inundated areas) were to be inferred from bathymetric survey data, verified by orthophotography. The inferred lake levels were slightly adjusted based on newly sourced data including the 1911 Sooke Lake map and the current lake level polygon delineated by the CRD and evident in the 2012 VRI inventory. These data sources, specifically the 1911 Sooke Lake map, enabled a measured original lake shoreline

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[10] Because of the broad scale polygons and attribute classes of the 1955/56 forest cover maps, the species attributes from the 1925 cruise will be a more accurate source to use as an indicator of successional change of the original forest polygons, despite absent values for some areas (i.e. Lot 87, Council catchment, non-merchantable cruise blocks, etc.)

to be used as opposed to the inferred shoreline based on the bathymetric survey. In some cases, because of this modification, other lake level polygons had to be adjusted either up or down slope to ensure a logical reservoir-raising progression. Table 2-3 shows the changing proportion of terrestrial to aquatic area within the SLW over the study period.

Table 2-3 - Area of total terrestrial and aquatic cover within the Sooke Lake watershed pre- and post-reservoir raising

Year	Watershed Cover	Area (ha)	Percent
1910	Terrestrial	8027.68	93.40
	Aquatic	567.46	6.60
1916	Terrestrial	7979.75	92.84
	Aquatic	615.40	7.16
1971	Terrestrial	7835.88	91.17
	Aquatic	759.26	8.83
2003	Terrestrial	7652.24	89.03
	Aquatic	942.90	10.97

2–3.3 Disturbance Dataset (disturbed forest polygons)

The 1911, 1955/56, 1964, 1975, 1996, and 2006 maps were the major sources of data for disturbance events (Figure 2-1). As well, a fire map of the study area was used showing wildfires and slash burns. This was provided by Gurp Thandi at the Pacific Forestry Centre[11]. As the Council area was not captured in the 1964 and 1975 maps, a 1980 forest cover map was also used to capture some polygons which were disturbed. All disturbed forest polygons from the 1964, 1975, 1980, and 1996 maps were digitized. These polygons were then unioned in a new layer with the digitized 1955/56 forest cover polygons. Within this geodataset, disturbance and

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[11] This historical fire map was source data for the BC Natural Disturbance Database produced by Steve Taylor. However, slash burns were not digitized into the BC Natural Disturbance Database but were included in the forest cover disturbance dataset (Thandi, pers. com.)

treatment type and year attributes were entered into a single text column for each disturbed polygon to simplify the consolidation of these various disturbance data sources[12].

Because age of forest stands is directly influenced by stand-destroying disturbance events the polygon geometry of the 2006 forest cover inventory captured the boundaries of nearly all past disturbance events. Starting with the 1955/56 polygons, the disturbance and treatment attributes from these polygons were manually merged into the 2006 polygons and placed in a new text field which could be used to trace the source of the data. Aerial imagery was used to inform and verify this process, which was repeated for the 1964, 1975, 1980, 1996 maps, as well as the map provided by Thandi. Those 2006 forest cover polygons which did not accurately delineate past disturbed areas were cut into multiple polygons where necessary.

The 1911 map was used to delineate the extent of the area which was cleared for the 1915 raising. The area was also assumed to have been slash-burned as was common practice at the time and is evident in historical photographs taken during clearing (Axys Environmental Consulting Ltd. and Aquatic Resources Ltd., 1994). The 1975 and 1996 maps were used to interpret the area that was cleared for the 1970 reservoir raising. The creation of Deception Reservoir occurred in 1980 with major harvest and clearing activities of non-wetland areas occurring in the years directly prior. The 2002 cleared area was delineated using the 2002 imagery, which showed cleared land around the Sooke Reservoir. Areas cleared were pile-burned on site, with all ash from these fires trucked out to prevent water contamination (Ussery, pers. com.). All cleared areas not flooded by the actual raising event in 1970 and 2002 were replanted two years following dam construction, which would have allowed the reservoir to fill

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[12] The disturbance and treatment type and year information was parsed out into individual columns in the final Disturbance-Forest cover geodataset.

to its new level. As of 2012 this planted area has yet to reach free-to-grow status and therefore was given a shrub (Scotch broom-*Cytisus scoparius*) land cover class.

New fields were added to the merged disturbance feature to accommodate multiple disturbance and treatment events in the same polygon and the disturbance and treatment data from each map source were sorted into these fields by date from oldest to most recent. For disturbance or treatment events for the same area where there was a date discrepancy between two or more map sources, the source created closest in time to the disturbance event was used. When logging events were presented as a date range, the range was simplified to the latest date (the point at which the stand was fully cleared). Disturbance events given a type but no date in the forest cover maps were inferred using the ortho-imagery in combination with the older forest cover maps to determine an approximate date based on adjacent disturbed areas (see Figure 2-2 for orthophotos).

2–3.4 Pre-Disturbance Land and Forest Cover Dataset

Pre-disturbance land cover was required for each disturbed area to allow for accurate modelling of C transfer. The disturbance dataset was used to determine which areas of the forestry maps needed to be digitized. Forest cover information was sought from the forestry maps just prior to the disturbance date. Polygons in each map were digitized based on this criterion and a single text field attribute was populated with the forest stand information. These pre-disturbance forest cover polygons were then clipped to the required disturbance boundary.

Areas inundated during the 1915 reservoir raising were inferred based on adjacent mature forest stands from the 1964 map, and missing Council and Lot 87 regions on the 1964 and 1975 map were filled using the 1955 map polygon attributes.

Polygons which were clipped and contained only disturbance information rather than forest cover were selected and eliminated [Eliminate][13] from the data since they were often small areas on the boundaries of larger stands and their presence was assumed to be due to registration issues between disturbance polygons. Any multipart polygons were exploded to single part [Multi-part to Single-part][14] and sliver polygons less than $100m^2$ or with an area to perimeter ratio less than 4 were eliminated [Eliminate] based on the polygon's longest shared boundary. At this point all of the clipped forest cover extents were unioned [Union] to create a comprehensive historic forest cover feature class.

A dataset showing all historical roads and railways in the study area was received from the CRD and was used to reflect deforestation events that had occurred through road and railway construction. From this dataset, road and railway right of ways were only selected if they were permanent enough to be considered a deforestation event (interpreted from the orthophoto time series) or wide enough to be considered a disturbance event (based off of road class/width). Disturbance date information was interpreted from the orthophoto time series and added into the dataset to depict the year of road construction. Minor geometry edits were performed on this selection of road and railways line features as some sections of road were not connected to each other. These selected line features were then buffered [Buffer][15] by either five or ten meters (right of ways of either ten or twenty meters) based off of the class of the right of way (Main,

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[13] The ArcGIS tool Eliminate is used to remove sliver polygons generating from overlaying two coverages that have similar but not exact geometry. Merging of slivers, in this case is based off of the longest shared boundary of an adjacent polygon.

[14] Multipart features are those polygons that spatially separate but are only described by one record in the attribute table as they have identical attribute values. The ArcGIS tool Multi-part to Single-part separates these polygons so that all polygons that are not adjacent have a unique attribute table record that applies to each polygon.

[15] The ArcGIS tool Buffer creates a new coverage of polygons around a specified feature based on a defined buffer distance.

spur road, etc.) to create polygonal features that were unioned [Union] into the disturbance dataset.

Attributes from the individual text fields were sorted into land cover, species, date of stand establishment, and site index fields for map years 1910, 1955, 1964, 1975, and 1996. Site index was not available in the 1955 data source, so these values were left empty. Requisite 1910 land cover information for areas which were disturbed between 1910 and 1955 was inferred based on adjacent mature 1955 stands, with the majority of these areas located in the Council and Lot 87 regions. Pre-disturbance forest in the Council area were assumed to be mostly Douglas-fir stands as most of the forest adjacent to the Council area was also this stand type. In addition, LiDAR-derived Digital Elevation Model data were used to delineate possible different stands separated by elevations and based on proximity to low lying, wetter areas (creeks, swamps, streams etc.) which would result in stands other than pure Douglas-fir and include other species such as western red cedar. This approach was used primarily for the Lot 87 area and used forest cover data from adjacent GVWSA lands.

2–3.5 2012 VRI Dataset Preparation

In 2011 the CRD began preparation of a new land and vegetation cover inventory for all the GVWSA lands based on the BC Vegetation Resources Inventory (VRI) standard. Because the VRI data were formatted in a relational/linked-table structure and therefore were not ideal for merging with historical data sources, a “flattening” procedure was developed in order to convert the VRI data into a useable form. Also, the preliminary nature of the attributes in VRI Phase 1 required that the 2012 VRI polygons be augmented with some of the 2006 Modified forest cover attributes through an extraction process (Appendix B). These two procedures resulted in the bulk of the processing that was required for the VRI inventory to be compiled with the historical forest cover and disturbance data. These processes along with accompanying ArcGIS 10.0 Model Builder models used, and selected attribute descriptions are documented in Appendix B.

Using the VRI leading species, stand age and height attributes in conjunction with the Ministry of Forests SiteTools version 3.3 Batch process software, site index was derived for polygons that were missing site index values (greater than 50 years age). Breast height age was also calculated in this process. In addition to these alterations, stand establishment dates, initially derived from the stand age of the leading species, were augmented using disturbance information from historical inventories in an effort to ensure original forest and disturbed forest stands were coordinated through time. The site index value that populates the SI_2012 field in the Forest cover-Disturbance geodataset was either taken directly from what was in the VRI data (ages 2-30) or was calculated using the age and height information the VRI had for the other polygons. If VRI age and height were missing the SI was copied from the 2006 inventory site index.

Due to the more coarse nature of polygon delineation in the VRI dataset relative to the 2006 forest cover inventory, some non-forest polygons had to be added. In cases where well-delineated, significant non-forest polygons were included in the 2006 forest cover data and absent in the VRI coverage, the polygons were copied and added [Update][16] into the VRI dataset. The records added were limited to only wetland and bedrock land cover polygons. These new polygons were given VRI_ID values greater than those assigned to any other GVWSA VRI polygons.

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[16] The ArcGIS tool Update combines two coverages by replacing the overlapping area with the update feature's geometry and attributes.

2–3.6 LiDAR-derived Site Index Derivation

Site index is most commonly defined as the average top height of an undamaged tree of a given species at 50 years of age (British Columbia Ministry of Forests, 1999). In forestry, site index is considered a proxy for site productivity that is heavily used in the prediction of stand growth and yield (G&Y). Reliable site indices are required in order to select G&Y equations, a critical component of CBM-CFS3 input data needed to calculate biomass pools and dynamics within the model (Kurz, et al., 2009). For those older stands that did not have a site index value in the 2012 VRI dataset, an attempt was made to recalculate site index using the heights available in VRI and the corrected ages based on polygon disturbance information (derived from the DE_2012 field). As feared, when SiteTools was rerun to calculate the new site index values from these attributes the mismatches in ages and heights produced many erroneous results (Figure 2-3).

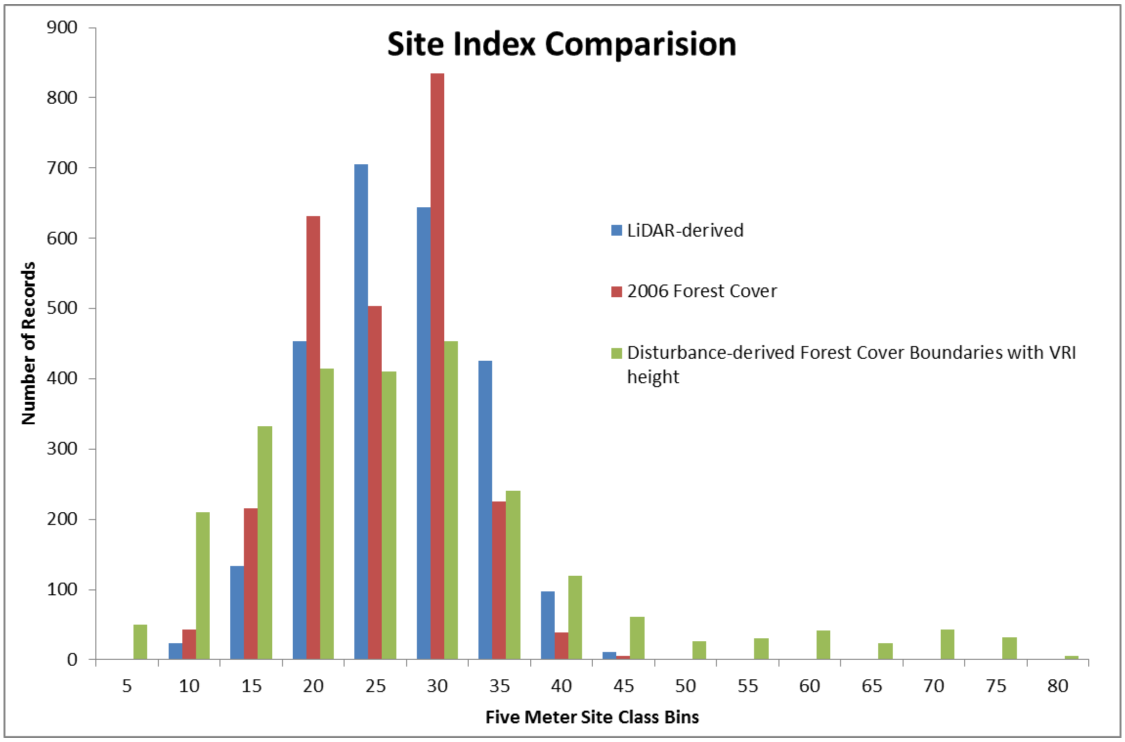

Figure 2-3 - Discrepancy between LiDAR-derived, 2006 forest cover and Vegetation Resource Inventory height-derived site indices

This is because the height data correspond to the problematic VRI polygonal boundaries while the ages correspond to the forest reestablishment dates collected from old inventories and maps. This is mainly the result of polygons in the VRI data having an older age (and thus greater height) whereas in the combined Forest cover-Disturbance geodataset the same polygons were determined to have a younger age, and vice versa. Thus the approach combining the two datasets would not produce reliable site indices.

Supplementing field-intensive and costly sampling methods of collecting forest attributes with remotely sensed data products, such as those acquired from LiDAR, can improve the efficiency of generating an accurate forest inventory, especially over a large area of interest (Andersen, et al., 2006; Wulder, et al., 2007; White, et al., 2013). Collecting forest structural attributes, including tree/stand height has proven to be reasonably accurate using LiDAR (Wulder, et al., 2010; Tompalski, et al., 2014). Species composition derived from traditional ground plot measurements and air photo interpretation can be integrated with LiDAR-derived stand height data to produce a more reliable and continuous measure of site index.

For those older stands (greater than 30 years old) that did not have site index values, a LiDAR derived site index was generated using 20 meter resolution LiDAR height metrics collected in 2006 for the Sooke Lake and Goldstream watersheds provided by Dr. Olaf Niemann. In order to generate stand-level height information the 100th height quartile was used as a measure of stand height, in accordance with common forestry practice of selecting the top height of a site tree within a 10m plot to determine stand site index (British Columbia Ministry of Forests, 1999). Though at a different resolution, this LiDAR method conforms to that of Wulder et al. (2010). Within the intervening years of LiDAR capture (2006) and VRI collection (2012), no disturbances had impacted the age or composition of stands within the study area. Stand polygons were delineated using stand age (adjusted to 2006 values), species and land cover information from 2012. Because a LiDAR-derived 20 meter cell can capture height information from multiple stands while straddling stand polygon boundaries (Figure 2-4A), only cells that had greater than or equal to 85% of their total area within a given polygon were used to generate an average stand height (Figure 2-4B).

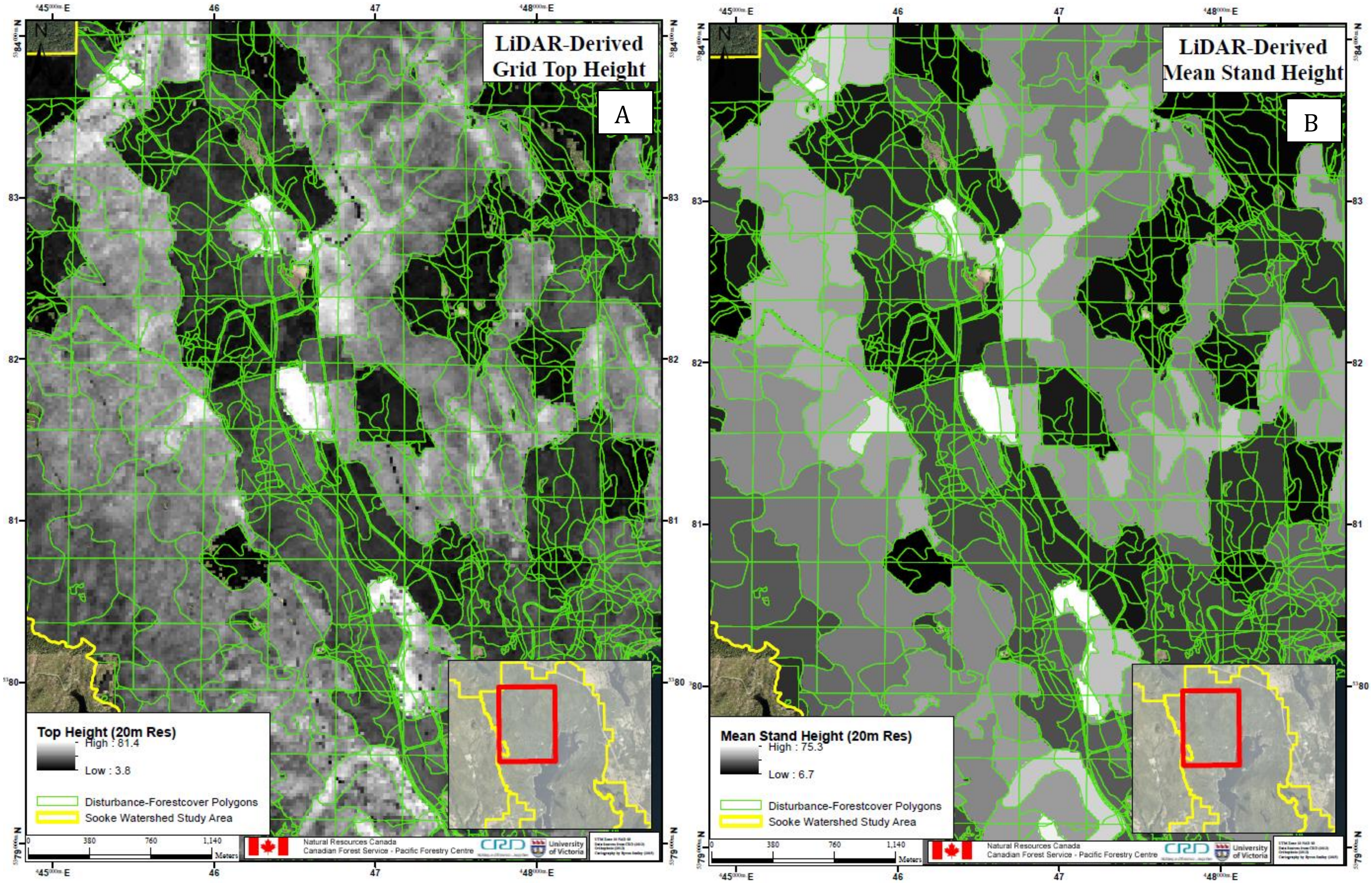

Figure 2-4 - (A) Grid-cell top height and (B) Mean stand height using 2006 LiDAR height data

Stand age (2006), species composition and LiDAR-generated stand height was input into the Province of BC Ministry of Forests tool SiteTools (Mitchell, et al., 2004) and site index values were generated using the SiteTools site index equations (Figure 2-5), comprising 78% of the CBM-CFS3-modelled area. Valley bottom forest stands (notably in Rithet Creek) and shoreline stands along Sooke Lake exhibited the highest site index values whereas upper-slope uplands stands, specifically the leeward, western ridges, had consistently low site indices.

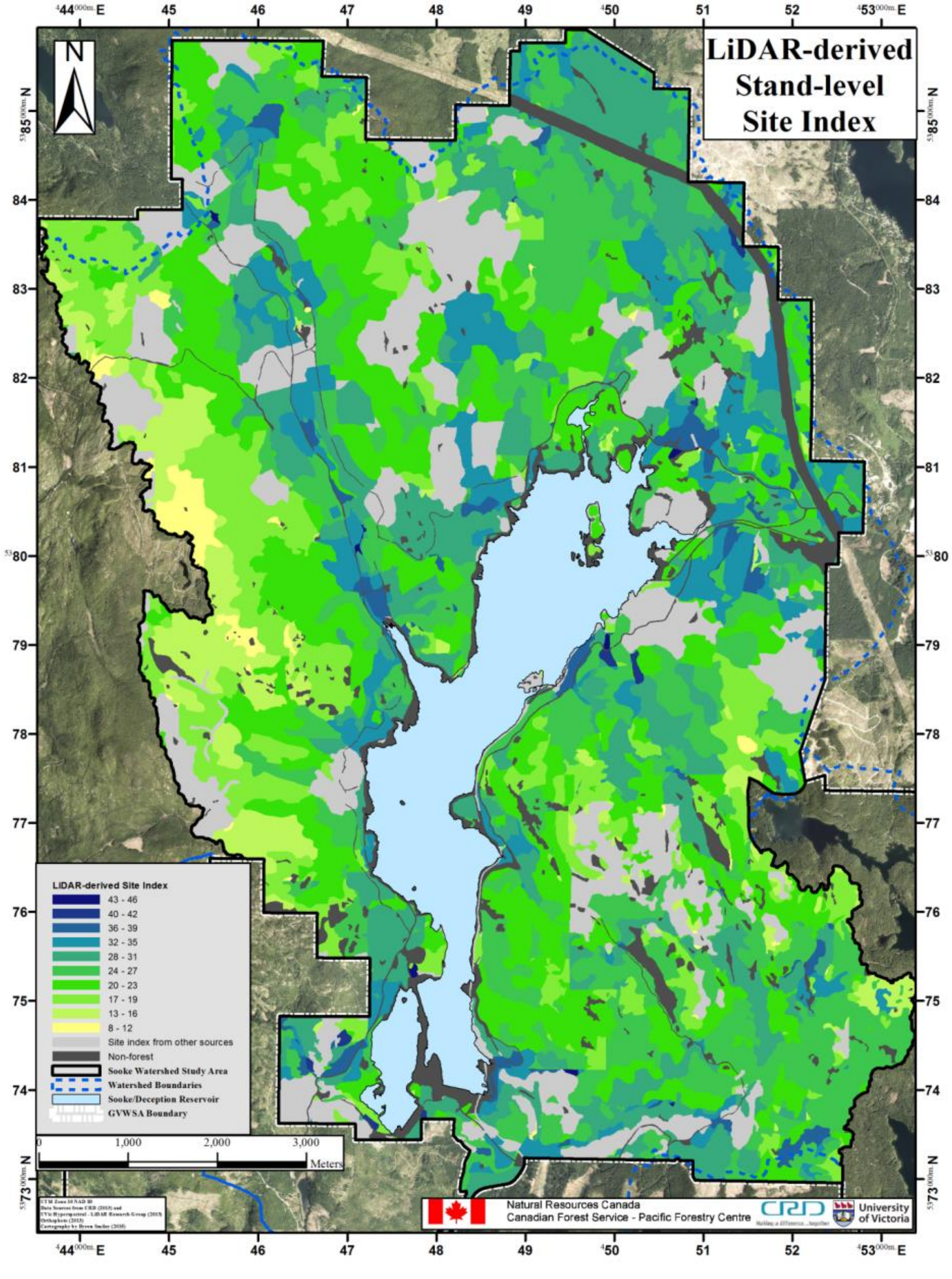

Figure 2-5 - Sooke Lake Watershed 2006 LiDAR-derived site index

As a VRI site index already existed for young stands in the SLW, no LiDAR-derived site index was needed for those stands. Also, during the generation of the canopy height model for young stands, significant portions of within-stand pixels are filtered due to the absence of a defined canopy. The remaining pixel height values can be the result of small leave patches or veteran old trees within a young stand and can substantially influence stand height when averaged across the forest stand, and consequently reduce the accuracy of any derived site index value. To this end, height (and therefore site index) values were not generated for stands 20 years old or younger (date of establishment 1986 and younger). For these stands a site index value from previous inventories was used. The detailed procedure of how the LiDAR site index was generated is given in Appendix D. The two raster datasets derived from the LiDAR biometrics include: average stand height in 2006 (Avg_stnd_ht06) and the 20 meter resolution top height (top_ht_06_20m).

2–3.7 Initial Compilation of Disturbance and Land and Forest Cover Data

Compilation of the Forest cover-Disturbance geodataset progressed in two major stages. Firstly, the disturbance dataset and pre-disturbance land and forest cover dataset were merged [Unioned] separately from the VRI dataset. Forest stand delineation and attribution for the 2012 VRI occurred largely independently of other data sources, although some information was referenced from the 2006 forest cover inventory. While the 2012 VRI did contain necessary data regarding the current status of the forest in the SLW, the historical forest cover maps proved to be a rich source of information for much of the pre-disturbance forest cover and disturbance information. The historical forest cover maps had been incrementally updated and thus maintained a fair degree of commonality between versions. By combining the historical spatial data independently of the 2012 VRI, small discrepancies pertaining to spatial registration between historical maps could be rectified prior to dealing with more serious attributional or stand delineation errors between the historical and VRI datasets. This process helped to avoid the creation of excess sliver and ‘no-data’ polygons after merging of current and historical spatial datasets.

Once the disturbance and pre-disturbance forest cover polygons were merged, it was required that every year snapshot (i.e. 1910, 1955, 1964, 1975 and 1996) had complete land cover, tree species, and site index information. To ensure that all polygons with stand destroying disturbance events did indeed have land and forest cover information prior to the disturbance, information was back-casted[17] through previous years in which the stand was undisturbed or only partially disturbed, and the entire 1925 timber cruise map was overlaid [Union] with the data set. In some cases, forest stand information was also carried forward to fill in data gaps where pre-disturbance forest cover was not available in the map source immediately prior to the date of disturbance. The 1925 species and volume fields were populated after the overlay by first calculating the metric equivalent of the imperial volumes given and then calculating a volume per ha for the net forested land area within a cruise block. The inclusion of the 1925 cruise data into the Forest cover-Disturbance geodataset adds merchantable volume per ha values (1925 merchantability standards) for the majority of the study area. These values will be used to help estimate initial C stocks for the Sooke water supply area.

Date of establishment for each disturbed stand was derived from either planting or disturbance information captured in the disturbance attributes. Stands that were planted were given the planting year as their date of establishment, while stands that were not planted and left

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[17] In this case back-casting refers to applying current (2012) attributes of a polygon to previous timeframes. This assumes that a particular attributes has not changed from past to current (i.e. no stand disturbance is evident).

to regenerate naturally were given a date of establishment based on the previous disturbance date plus one year. For stands which had no known previous disturbance date as of 1910, the date of establishment was based on the midpoint value of the 1975 forest cover map age class (see Appendix C for table). For polygons that were not within the extent of the 1975 forest cover map, the date of establishment was estimated based on that of adjacent stands.

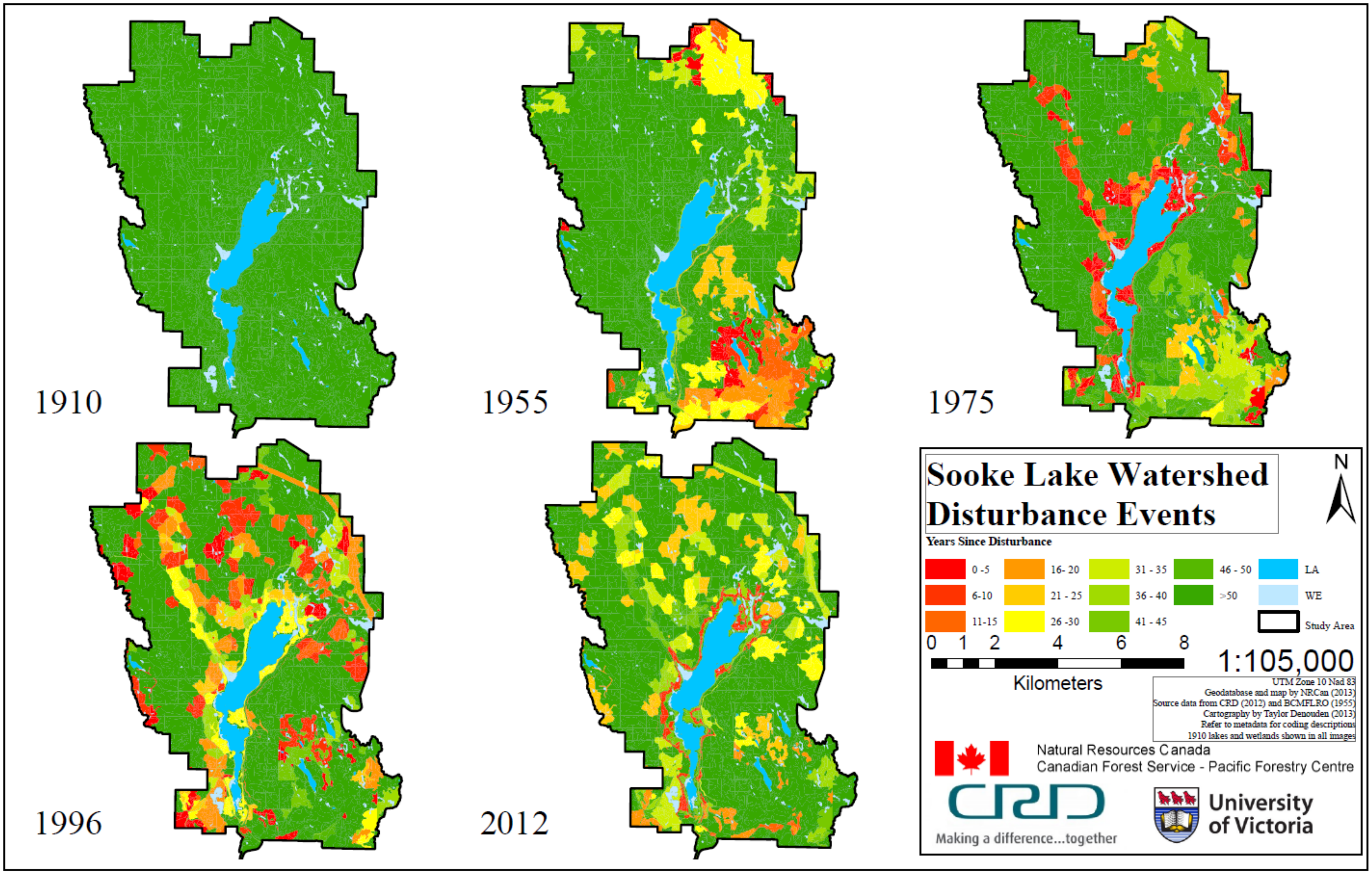
Historical non-productive areas, specifically those areas that were inundated by reservoir raising (i.e. historical wetlands and rock outcrops) were combined with current non-productive polygons. Registration issues between the current (2012) non-productive areas (including bedrock and wetlands) and that of the historic non-productive areas resulted in sliver polygons. These were eliminated using the area less than $100m^2$ and area to perimeter ratio less than four rule. After merging the non-productive areas, the resulting coverage was a single disturbance and land cover type feature class for all disturbed areas from 1910 through until the date of the most recent disturbance.

The VRI dataset was used to complete the disturbance and land cover dataset for both original forest polygons and for filling in post-disturbance forest-cover for the disturbed forest polygons. This included the current land cover, species, date of establishment, and site index fields as of 2012. As the VRI dataset's polygons and attributes did not always complement those of the historic forest cover maps for disturbed forest polygons (mismatched disturbance dates, polygon delineation issues, etc.), a method was devised to minimize the creation of sliver polygons and attribute mismatch that would have resulted from directly unioning these two datasets. The disturbance polygons, derived from the disturbance dataset were used to erase boundary areas from the VRI dataset. This erase approach ensured that line geometry between the two merged datasets remained intact after compilation. This original forest coverage was then unioned with the historic forest cover dataset and the appropriate 2012 fields were populated with the current forest cover information. Dates of establishment for these stands were available in the VRI dataset, and the values were checked using the historic aerial imagery and 2006 modified forest cover dataset.

Finally, current land cover of disturbed forest polygons was captured from the 2012 dataset by clipping the VRI to the extent of the disturbed polygons and then dissolving all attributes except for land cover, species, and date of establishment in the 2012 dataset. This reduced the number of polygons by eliminating stand age from the 2012 dataset, which was instead based off of the disturbance and stand establishment information from the disturbance dataset. The clipped and dissolved 2012 feature was overlaid with the historic disturbance and land cover feature and the appropriate 2012 fields in this coverage were populated. This information was back-casted in the same way as previous data sources, and date of establishment derived from disturbance and planting dates.

2–4.0 Data Consolidation Results

The major disturbance events throughout the history of the watershed included the three Sooke reservoir raisings, the creation of Deception reservoir and clearing for the transmission line right-of-way in 1980, the harvest of Lot 87 and Council regions in the late 1920s and early 1930s, and the sustained harvest activity the mid-1950s to the 1990s. These major events are visible as large disturbed area regions in Figure 2-6, and as spikes in area disturbed in Figure 2-7. As depicted in Figure 2-7, the area deforested for reservoir raising events was considerably less than some of the large harvesting and fire events; however, forest regeneration occurred in the latter areas but not the former.



1910

1955

1975

1996

2012

Sooke Lake Watershed Disturbance Events

UTM Zone 10 Nad 83
Geodatabase and map by NRCan (2013)
Source data from CRD (2012) and BCMFLRO (1955)
Cartography by Taylor Denouden (2013)
Refer to metadata for coding descriptions
1910 lakes and wetlands shown in all images

Figure 2-6 - Disturbances within the Sooke Lake Watershed 1910-2012

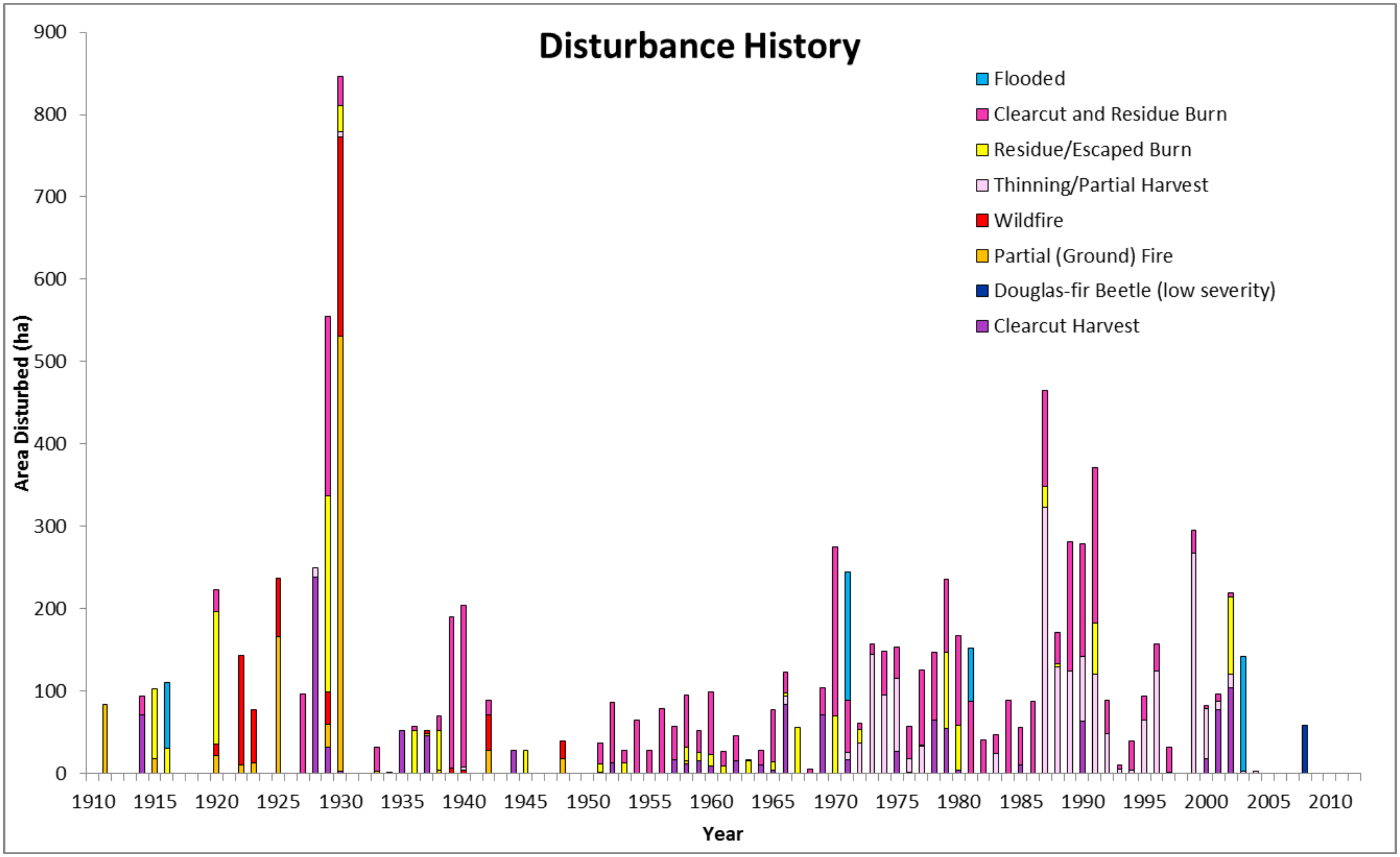


Figure 2-7 - Area (ha) Disturbed within the Sooke Lake Watershed study area: 1910 to 2012

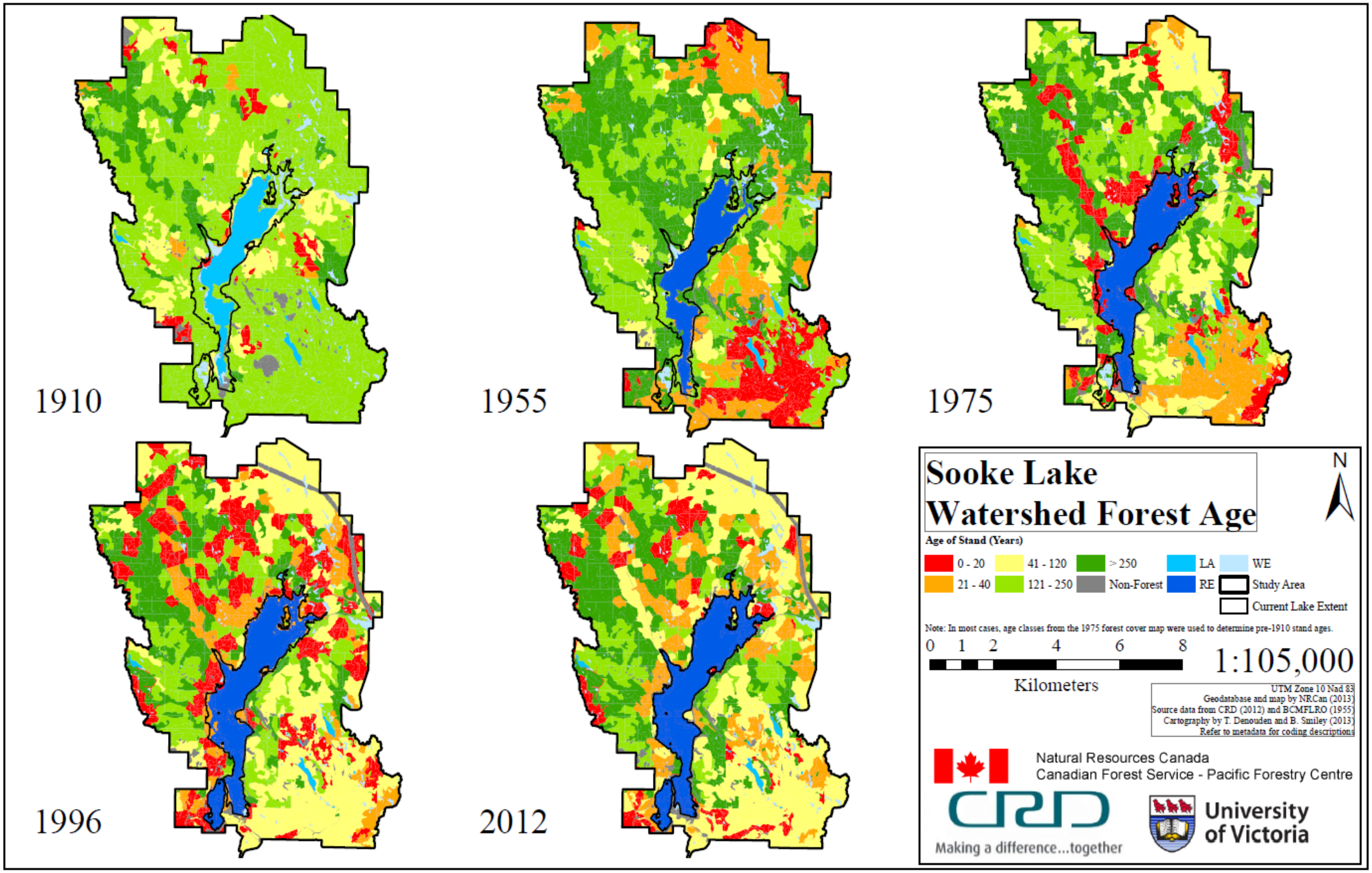


Figure 2-8 - Sooke Lake Watershed Forest Age: 1910 to 2012

Forest age is illustrated in Figure 2-8 for each snapshot date. In 1910 the forest is composed mostly of stands between 121 and 250 year old. While the 1955 forest cover map shows very tall forest stands, up to 60m in height, along some areas of Rithet Creek, the age information for much of this area was extracted from the 1975 forest cover map. It is possible that some of these areas are much older than they were recorded in the 1975 forest cover map, however, the scale of the polygons and breadth of age class did not allow for this age distribution to be captured. In the decades leading up the 1990s the average stand age of the SLW declined because of consistent disturbance events. More recently however stand ages have stabilized due to cessation of harvest activity by the late 1990s.

Land cover is shown in Figure 2-9 and enumerated in Table 2-4. Overall there is an increase in infrastructure such as roads, rail, and transmission lines throughout the study period that coincides with a rise in industrial activity in the area. Reservoir raising events have had the largest effect on the total area of forest cover as cleared and inundated forest cannot regenerate. Large cleared areas like Lot 87 and the Council area which were harvested by past logging activity (as can be seen in the 1930 and 1957 ortho-imagery), did eventually recover to productive forest status. However, this was not true for cleared areas around the Sooke Reservoir after the 2002 raising event, which was invaded by Scotch broom and attempts at forest regeneration have so far failed.

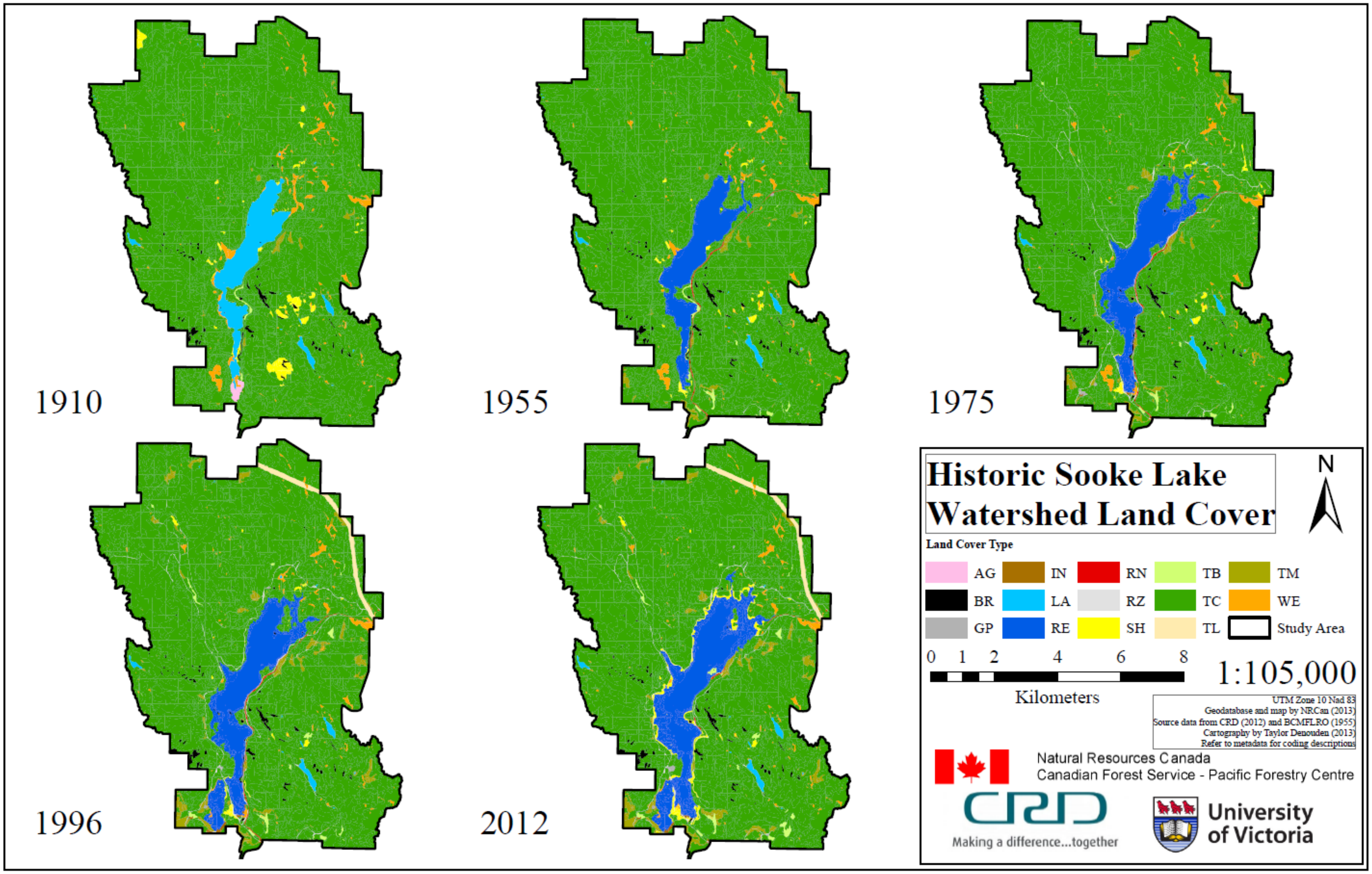


Figure 2-9 - Sooke Lake Watershed Land cover: 1910 to 2012 (see Table 2-1 for land cover code descriptions)

Table 2-4 - Percent of each Land cover type for map snapshot dates derived from the combined historic disturbance and land cover dataset.

Land cover Type	**Year**						**Δ (1910-2012)**
	1910	**1955**	**1964**	**1975**	**1996**	**2012**	
Agricultural Land	0.20	0.00	0.00	0.00	0.00	0.00	-0.20
Bedrock	0.68	0.67	0.68	0.72	0.72	0.66	-0.02
Gravel Pit	0.00	0.01	0.01	0.04	0.03	0.07	0.07
Infrastructure	0.00	0.01	0.04	0.04	0.13	0.11	0.11
Lake	4.72	0.38	0.38	0.38	0.38	0.37	-4.35
Reservoir	0.00	5.28	5.28	7.09	7.84	9.45	9.45
Railway	0.00	0.30	0.30	0.30	0.30	0.15	0.15
Road	0.00	0.02	0.60	0.83	0.96	0.91	0.91
Shrub	1.27	0.47	0.46	0.44	0.32	1.20	-0.07
Treed Broadleaf	0.10	0.30	0.33	0.23	0.38	0.54	0.44
Treed Coniferous	90.81	90.18	89.46	87.34	84.59	82.01	-8.80
Transmission Line	0.00	0.00	0.00	0.00	0.95	0.95	0.95
Treed Mixed	0.34	0.88	0.97	1.22	2.17	2.43	2.09
Wetland	1.88	1.51	1.51	1.36	1.22	1.15	-0.74

The watershed area managed through prescribed treatments such as planting and thinning is depicted in Figure 2-10. The graph shows increased management of the forest from 1958 through the 1990s. Area planted closely reflects area harvested or cleared until about 2004, with peaks in the late 1980s and early 1990s. After 2004, silviculture activity was focused on areas of unsuccessful forest regeneration (i.e. areas where Scotch broom invaded).

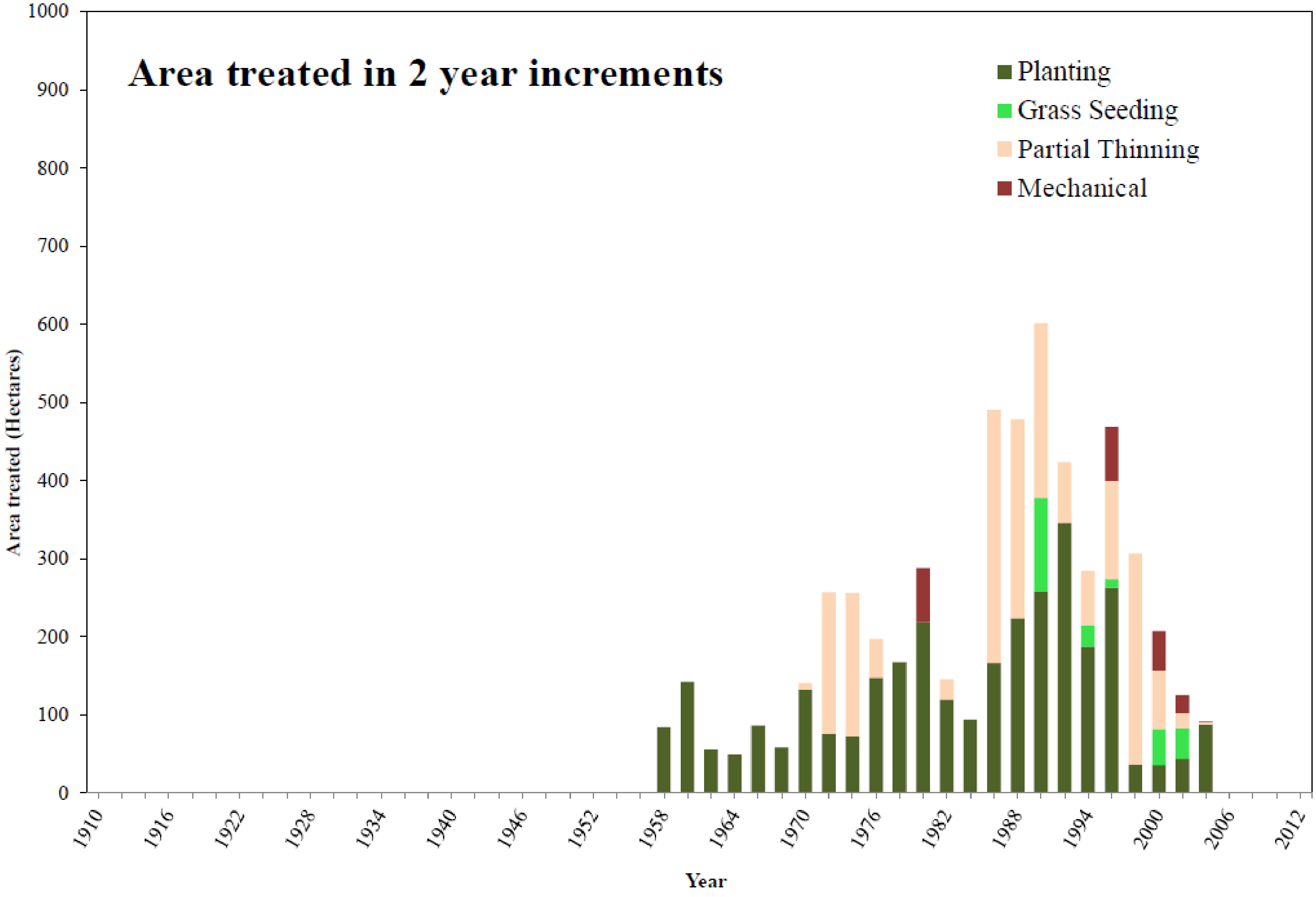


Figure 2-10 - Area (ha) within the Sooke Lake Watershed study area impacted by treatment events: 1910 to 2012

Specific types of disturbance events are represented on a per decade basis in Figure 2-11 (1910-1959) and Figure 2-12 (1960-2012). In the 1910-19 period there was minimal impact on the watershed outside of the lands adjacent to the reservoir. Starting in the 1920s on lands that were not owned by the GVWD at the time, major disturbances began to occur in the extreme southern and north portions of the SLW. Some of these disturbances (i.e. wildfire, partial fire) escaped into GVWD lands in the SLW. Forest harvesting within the SLW, specifically up the Rithet valley and along the reservoir was most prevalent between the 1960s and 1990s.

Disturbance information for the past 102 years is judged to be accurate based on verification from aerial imagery. While multiple data source maps may agree about the area disturbed they did not always agree on the year when the disturbance occurred. In these cases, the date from the data source closest to the approximate date of disturbance was considered the most accurate. These issues could have been resolved if more historical data sources were available, unfortunately efforts to find such sources were unsuccessful.

For areas such as Lot 87 and Council that were historically outside the GVWD’s ownership, older data sources would also have been useful to determine pre 1955 forest cover, which, in many cases had to be inferred from adjacent original forest polygons.

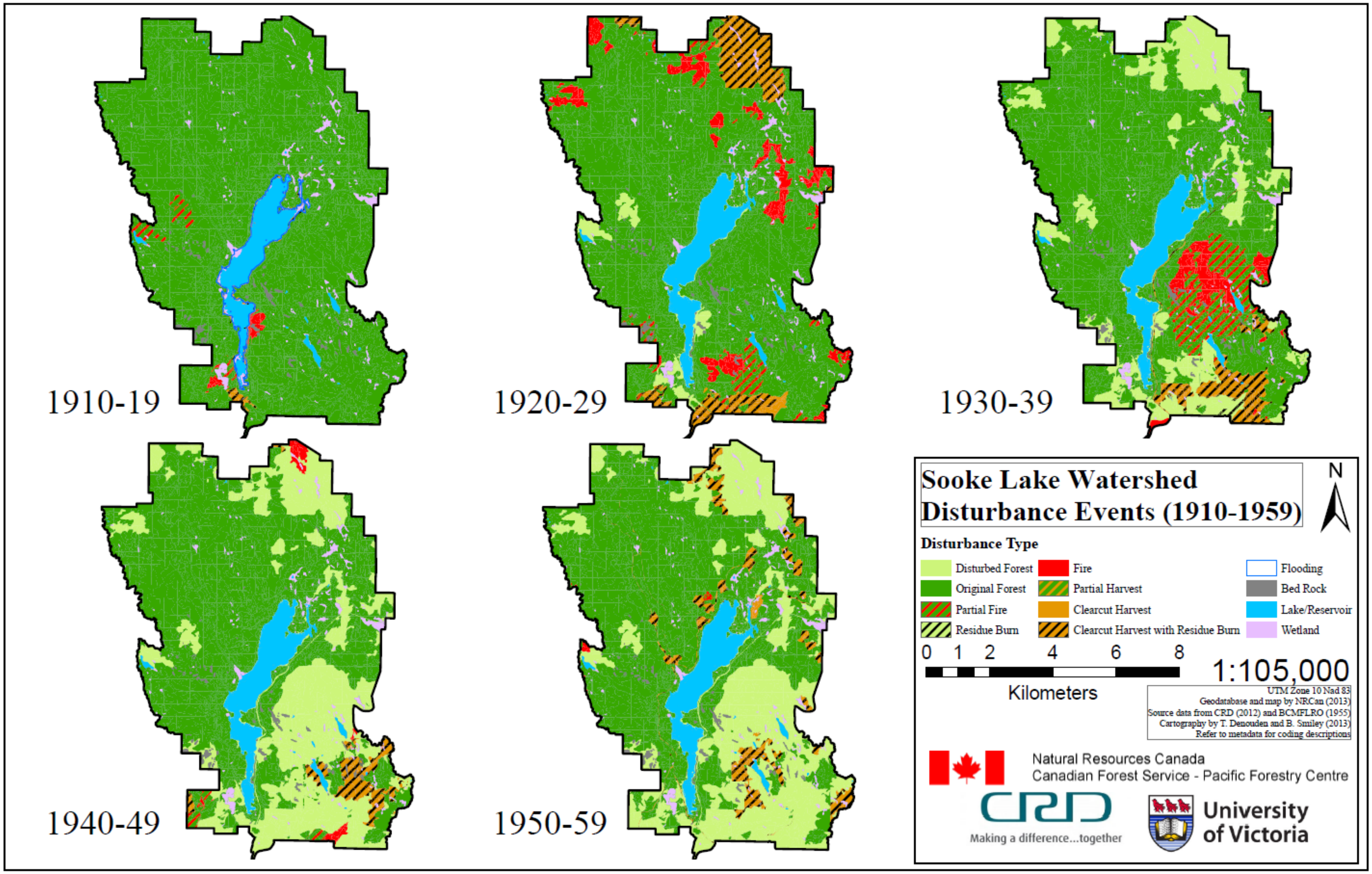


Figure 2-11 - Disturbances types on a per-decade basis within the Sooke Lake Watershed: 1910-1959

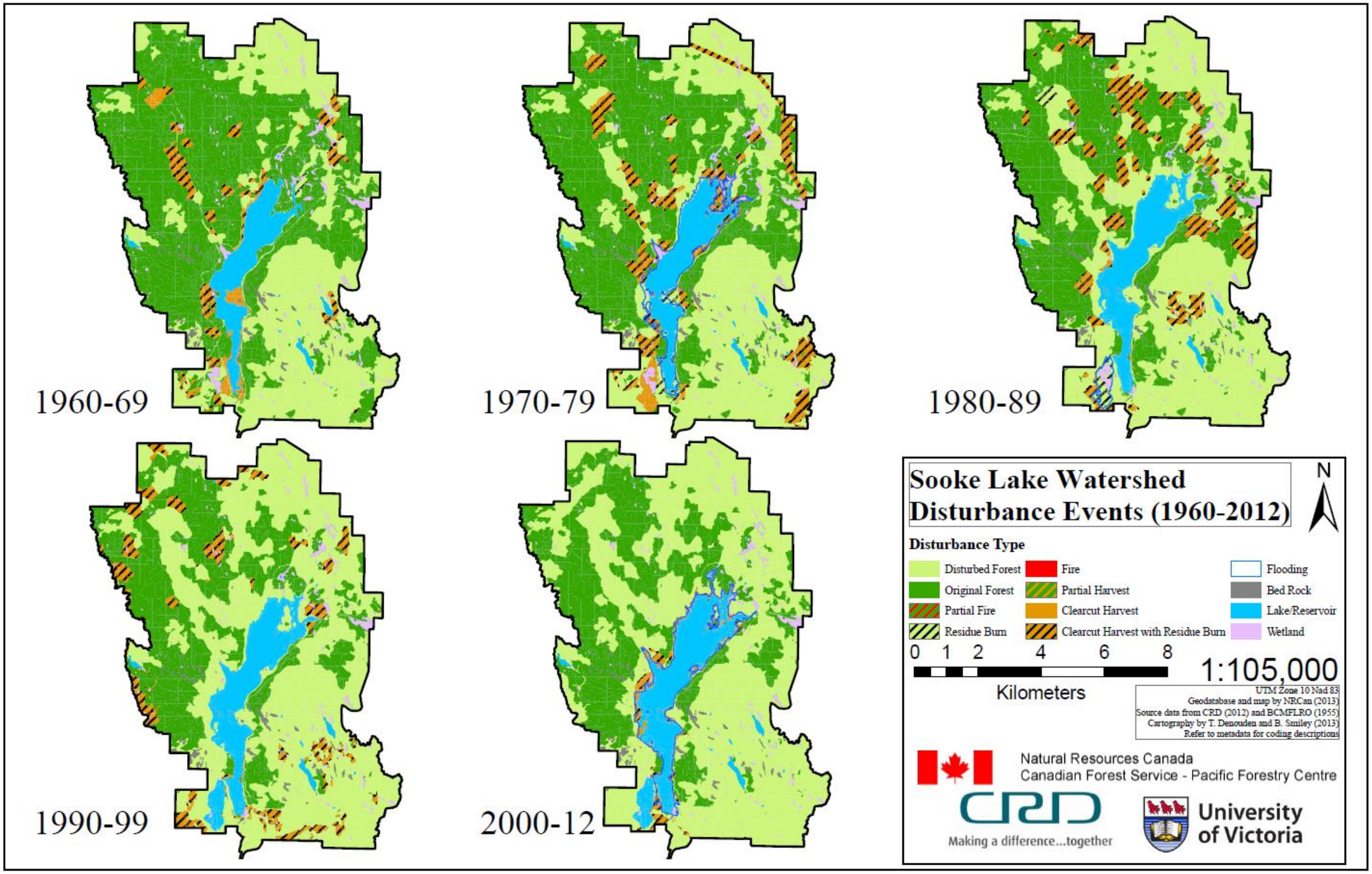


Figure 2-12 - Disturbances types on a per-decade basis within the Sooke Lake Watershed: 1960-2012

The final version of the combined Land cover/Forest cover-Disturbance geodataset for the SLW encompasses all recorded post-European settlement disturbance events, both anthropogenic and natural, from 1910 to 2012 (Denouden & Trofymow, 2013). This coverage has a total of 8524 polygons and 75 attributes that include disturbance year and type, stand treatment year and type, stand establishment year, current and historical land and forest cover, derived current and historical site index values, ArcMap generated ID, area, and perimeter, as well as several other fields relating to land cover class and 1925 cruise information (see Appendix E) A metadata text file that follows Fluxnet documentation standards (Oak Ridge National Laboratory, 2010) was also prepared and is located in Appendix C.

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Chapter 3 - Baseline CBM-CFS3 Model Runs

3–1.0 Introduction

The forest ecosystems and natural and anthropogenic disturbances that have existed within the SLW since 1910 have resulted in a unique forest C history. Retrospective C budgets help to improve the understanding of how past forest changes, and the forest management practices that lead to those changes, impact current C stocks. The Forest cover-Disturbance geodataset assembled for the SLW and described in Chapter 2 defines the temporal and spatial characteristics of the forest structure and what disturbance and deforestation events have influenced the forest structure. Absent at this point and required for CBM-CFS3 input are mechanisms to define the growth, decay and disturbance dynamics of the various forest C pools, including the DOM pools that are rarely included in forest inventories. These C dynamics determine how C moves into, out of and through a forest ecosystem.

CBM-CFS3 requires specific data inputs to define the growth, disturbance and decay dynamics of the forest to be modelled. To describe forest growth, G&Y curves are used; these data express the annual volume increment of each unique forest stand through time. As different forest types grow at different rates, these curves must be matched to the specific site productivity, species composition and management type (managed or unmanaged) of each unique stand type. For disturbance events, the transfer of C between pools and out of the forest ecosystem is defined using disturbance matrices (DMs). DMs, specific to each disturbance type, map how much and to what pool C is transferred after a disturbance event. Default decay dynamics specific to each ecozone (Kull, et al., 2011) and based on scientific analysis and calibration (Kurz & Apps, 1999) are built into CBM-CFS3. Also, prior to commencing model simulation, a spin-up procedure is run to populate the DOM stocks using a historical ecozone-default disturbance type (wildfire) and disturbance return interval (300 years). While a sensitivity analysis was performed on the default disturbance return interval (see Chapter 6), the default parameters both for decay dynamics and DOM stock spin-up were used in this study.

As CBM-CFS3 does not simulate C dynamics for non-forest areas, certain areas were masked out of the simulation as they had remained non-forested for the length of the study period. These polygons totalled 652 ha of the 8595 ha study area and included non-forest areas such as lakes (including the original Sooke Lake), unchanged wetland and brush areas, and bedrock outcrops. Other areas that became forested (either naturally or through silvicultural activities) or were deforested were included in the simulation. These areas varied from a low of 95 ha from 1925-27 to a high of 654 ha from 2002-07. In total, 7943 ha of the 8595 study area (92.4%) were included in model runs.

The Baseline model runs for the SLW described in this chapter characterize the historic changes in C stocks and fluxes from 1910 to 2012. This period encompasses three reservoir raising events, large wildfires and clear-cut harvests, sustained yield logging, and the recent (last 15 years) migration to a strictly water supply management regime in the watershed. The growth, disturbance and decay dynamic inputs described are linked to the spatial Forest cover-Disturbance geodataset through a new spatially-explicit CBM-CFS3 data entry tool called 'Recliner'. Using this tool for model input and output, annual spatial and aspatial results were exported for C stocks, stock changes and fluxes.

3–2.0 Growth and Yield Curve Selection and Validation

3–2.1 Overview

Growth and yield (i.e. volume-age) curves are a required input into the CBM-CFS3 (Kurz, et al., 2009) as they define forest stand growth dynamics. Using biomass conversion factors (Boudewyn, et al., 2007), net merchantable volume yields derived from growth and yield curves are converted to aboveground biomass components such as stemwood, foliage, branches, tops and sub-merchantable-size trees. Within CBM-CFS3, belowground biomass is estimated as a function of aboveground biomass and species group (Li, et al., 2003).

The study period for the Retrospective C Project for the SLW spans over 100 years. Depending on the type of disturbance that occurred, or the forest management regime of the period, forest stands were considered to be either managed (e.g. planting occurred), or unmanaged. As forests that are managed grow at different rates and densities than unmanaged forests, unique growth curves were required for both management types. Unmanaged stands include both current stands (e.g. old forest, naturally disturbed forest or anthropogenically disturbed forest but naturally regenerated) and historic stands that were previously unmanaged but were subsequently harvested and planted during the study period. The Variable Density Yield Prediction 7 (VDYP7) program (BC MFLNRO, 2013a) was used to generate growth and yield curves for the unmanaged stands and the Table Interpolation for Stand Yields (TIPSY) program (BC MFLNRO, 2013b) was used for the managed stands.

The forest type attributes that are required inputs into TIPSY and VDYP7 are species composition and site index. These stand attributes for all forest polygons within the SLW are contained in the Sooke Forest cover-Disturbance geodataset (Smiley, et al., 2013). Tree species combinations from the Sooke combined Forest cover-Disturbance geodataset were grouped into 10 analysis units (AU) in order to select growth and yield curves. The AUs were similar to the qualitative descriptions of the AUs used by TimberWest for the Oyster River Retrospective C budget on east Vancouver Island that dealt with similar stand types (Trofymow, et al., 2008). The AUs are defined as a combination of one or two species and the compositions of those species for a forest stand (Table 3-1).

Table 3-1 - Growth and yield equation Analysis Unit (AU) and species composition used to define growth and yield equations (Coastal Douglas-fir=FD; Western Red cedar=CW; Western hemlock=HW; Red alder=DR)

Analysis Unit	Description	Simplified Species Mix for G&Y Curve Input			
		Sp1	Comp1	Sp2	Comp2
1	Fir	FD	100		
2	Fir-Cedar	FD	67	CW	33
3	Fir-Hemlock/Grand fir/Sitka Spruce	FD	67	HW	33
4	Fir-Alder/maple/poplar/arbutus	FD	67	DR	33
5	Cedar leading with conifer mix	CW	67	FD	33
6	Hemlock	HW	100		
7	Hemlock-Fir	HW	67	FD	33
8	Hemlock-Cedar	HW	67	CW	33
9	broadleaf greater than 75% composition	DR	100		
10	Alder-Conifer Mix	DR	67	FD	33
-1	Non-forest				
-2	Deforested				

Because of the limitations of VDYP7 and TIPSY and to minimize the number of growth curves required for the Sooke Lake C budget project, all species combinations present within the Sooke Forest cover-Disturbance geodataset were aggregated into 10 AU classes (see Table 3-2 for detailed grouping query). Site index values were binned into 5 meter site classes (10 - 45) to minimize the total number of growth curves needed. The combination of AU and site class required a total of 58 growth and yield curves to be generated from each of VDYP7 and TIPSY programs. CBM-CFS3 requires a separate growth curve for each unique combination of classifiers (management status, AU, site class and leading species). For 141 polygons, the leading species of the stand did not match an existing AU. For these cases, growth curves were duplicated using curves of comparable leading species (e.g. Red alder for Big leaf maple). With the inclusion of null growth curves for non-productive/deforested stands and unique leading species, the total number of growth curves was expanded from 116 to 173.

Table 3-2 - Analysis Unit descriptions and selection statement used to group species combinations in the Sooke Lake watershed Forest cover-Disturbance geodataset (SP1=leading species SP2=second leading species, etc.; CMP=species composition in percent. See Table 2-1 for species code descriptions)

Type Group	AU	Selection statement	Description
1	1	SP1 = 'FD' AND "CMP1" > 75 OR ("SP1" = 'FD' AND "CMP1" <= 75 AND "SP2" = 'PL') OR ("SP1" = 'FD' AND "CMP1" <= 75 AND "SP2" = 'PW') OR ("SP1" = 'PL' AND "SP2" = 'FD') OR ("SP1" = 'PW' AND "SP2" = 'FD')	Fir
2	2	SP1 = 'FD' AND "CMP1" <= 75 AND "SP2" = 'CW'	Fir-Cedar
3	3	(SP1 = 'FD' AND "CMP1" <= 75 AND "SP2" = 'HW') OR ("SP1" = 'FD' AND "CMP1" <= 75 AND "SP2" = 'BG') OR ("SP1" = 'FD' AND "CMP1" <= 75 AND "SP2" = 'SS')	Fir-Hemlock/Grand fir/Sitka Spruce
8	4	SP1 = 'FD' AND "CMP1" <= 75 AND ("SP2" = 'DR' OR "SP2" = 'MB' OR "SP2" = 'RA' OR "SP2" = 'AC')	Fir-Alder/maple/poplar/arbutus
9	5	("SP1" = 'CW' AND "CMP1" <= 75 AND ("SP2" = 'FD' OR "SP2" = 'HW' OR "SP2" = 'BG' OR "SP2" = 'PL' OR "SP2" = 'DR')) OR ("SP1" = 'CW' AND "CMP1" > 75) OR ("SP1" = 'CW' AND "CMP1" <= 75 AND ("SP3" = 'FD' AND "CMP3" >= 25))	Cedar leading with conifer mix includes
12	6	("SP1" = 'HW' AND "CMP1" > 75) OR (SP1 = 'BG' AND "CMP1" > 75) OR (SP1 = 'BG' AND "CMP1" > 75)	Hemlock
13	7	SP1 = 'HW' AND "CMP1" <= 75 AND "SP2" = 'FD'	Hemlock-Fir
14	8	SP1 = 'HW' AND "CMP1" <= 75 AND "SP2" = 'CW'	Hemlock-Cedar
38	9	("SP1" = 'DR' OR "SP1" = 'MB' OR "SP1" = 'RA' OR "SP1" = 'AC') AND "CMP1" >75	broadleaf greater than 75% composition
17	10	(("SP1" = 'DR' OR "SP1" = 'MB' OR "SP1" = 'RA' OR "SP1" = 'AC') AND "CMP1" <= 75) OR ("SP1" = 'HW' AND "CMP1" <= 75 AND ("SP2" = 'DR' OR "SP2" = 'MB' OR "SP2" = 'RA' OR "SP2" = 'AC'))	Alder-Conifer Mix

The suitability of the VDYP7 and TIPSY curves for the SLW was examined by comparison of growth and yield model gross volume predictions against measured volumes for eight Coastal Forest Chronosequence plots (Trofymow, et al., 1997) within and adjacent to the SLW.

3–2.2 Variable Density Yield Prediction 7 (VDYP7)

VDYP is a growth model that provides stand yield prediction for unmanaged (natural) forest stands. All unique combinations of AU and site class were input into VDYP7. The percent stockable area parameter was considered to be synonymous with the Operational Adjustment factor 1 (OAF1) parameter in TIPSY. Although relatively high, a stockable area/OAF value of

0.95 (95%) was considered reasonable as non-productive areas in the Sooke Forest cover-Disturbance geodataset were delineated at a finer resolution compared to other forest cover inventories; therefore, unstocked areas had been adjusted for at the stand level. Because of the lack of historic stand density information, default values were used for all other parameters.

CBM-CFS3 simulations in British Columbia require net merchantable volumes, which are then used to generate the aboveground biomass pools. Net merchantable volume is defined as the wood volume inside bark minus the volume of tops and stumps and includes reductions for decay, waste and breakage (Figure 3-1). Net merchantable volume was exported from VDYP7 for an age range of 0-365 years[18] using a 17.5 cm (centimeter) utilization level. A total of 58 growth curves were generated from VDYP7.

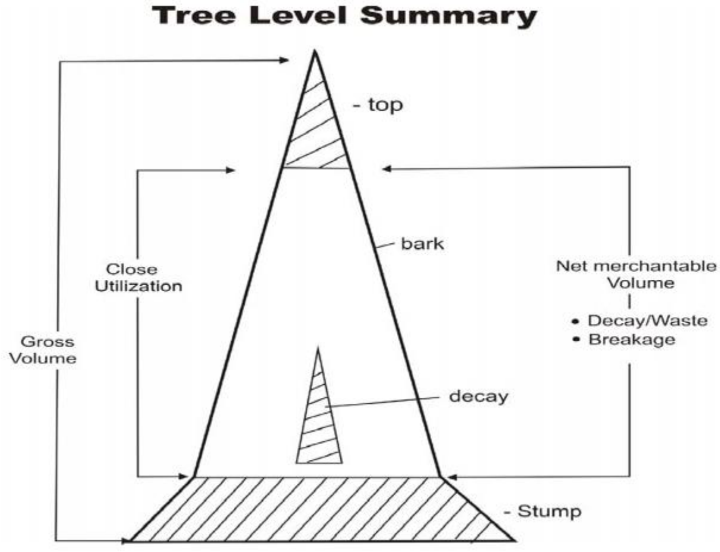

Figure 3-1 - Coastal BC volume reporting summary (MFLNRO, 2012)

3–2.3 Table Interpolation for Stand Yields (Batch TIPSY v4.3)

TIPSY is a growth and yield program for managed species that retrieves and interpolates yield tables in databases generated from TASS and SYLVER models (BC MFLNRO, 2013b).

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[18] 365 years was the oldest stand age over the course of the 102 year study period.

The ‘Batch’ process in TIPSY allows for yield table generation to occur simultaneously for all combinations of AU, site class and other stand parameters. Unlike VDYP7, TIPSY requires an initial stand density value for growth and yield curve generation. A value of 1200 trees per ha was chosen for initial density as it was believed to be the nominal planting density used within the GVWSA (J. Ussery, pers. comm.) and it was consistent with common silvicultural practices for the Arrowsmith Timber Supply Area (TSA). The default OAF1 value is 0.85. A value of 0.95 was input because non-productive areas were delineated at a finer resolution than other forest cover inventories and therefore were adjusted for at the stand level.

Because TIPSY is derived from models of stand development on an individual tree basis, crown structure is an essential parameter. Modelling Red alder stands at this scale has proven challenging and therefore TIPSY does not generate growth and yield curve data for mixed Red alder stands or Red alder stands with site index values less than 20 or greater than 32. When either of these conditions occurred within the SLW, growth and yield curves were supplemented with those of similar curves[19].

Corresponding to the 17.5cm merchantability limits for coastal BC used in CBM-CFS3 (Kull, et al., 2011), net merchantable volume was exported from TIPSY using the 17.5cm utilization level. Depending on the site quality and stand age, growth curves from TIPSY reach an asymptote at a certain age, ending any net volume increase, while VDYP7 curves continue to add volume but at extremely low rates. TIPSY does not report growth and yield volumes for stands over 350 years. In order to have a consistent age range with VDYP7 output, volumes from 350 to 365 years were populated with the volumes reported for the years 336-350, assuming zero

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[19] Pure Alder stands with site classes less than 20 or greater than 32 were given pure alder curves (AU 9) of the next closest site class. AU 10 was copied from VDYP7 generated AU as it was assumed that the Alder component was most likely natural infill that overtook the coniferous component. AU3 was used to supplement AU4 which follows the procedure TimberWest used for growth curves in the Oyster River study (Trofymow, et al., 2008).

net growth after 350 years. A total of 58 growth curves were generated from TIPSY. The difference between managed and unmanaged growth and yield equations is most evident in the first 100 years of the curve (see Figure 3-2 for AU 1 managed and unmanaged growth curves).

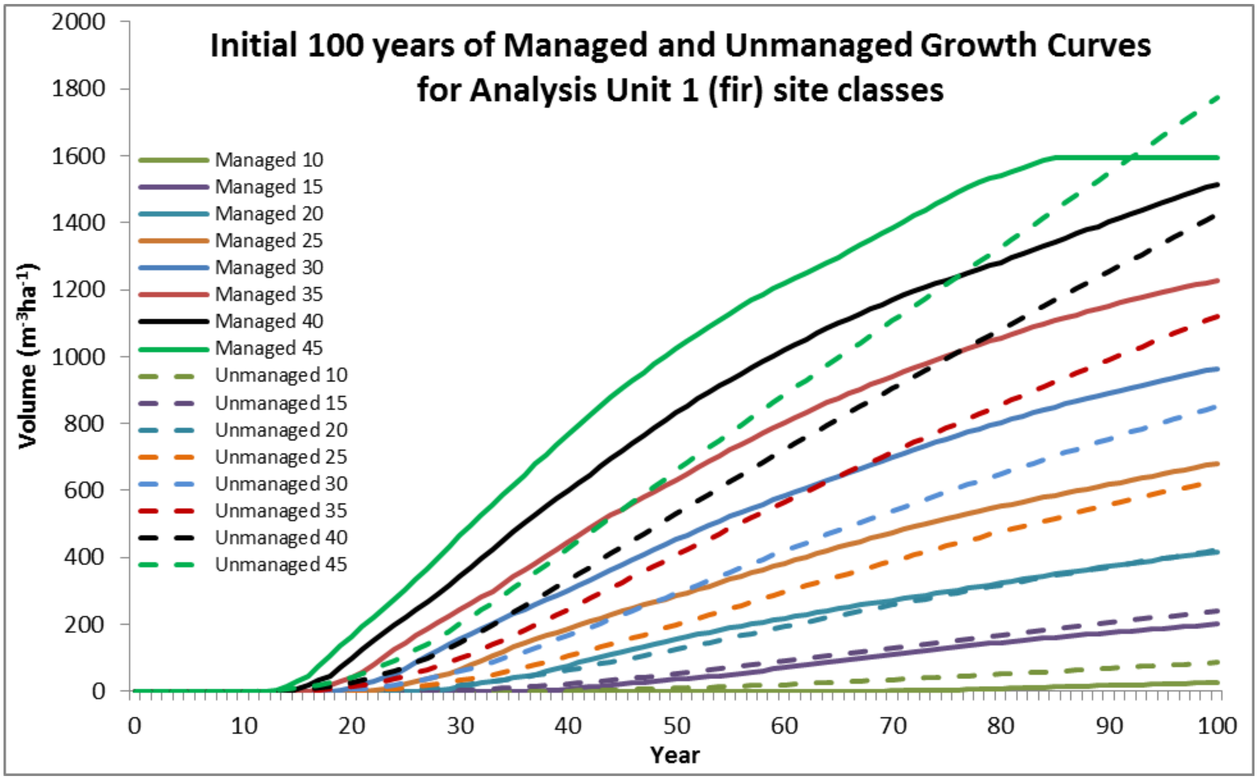
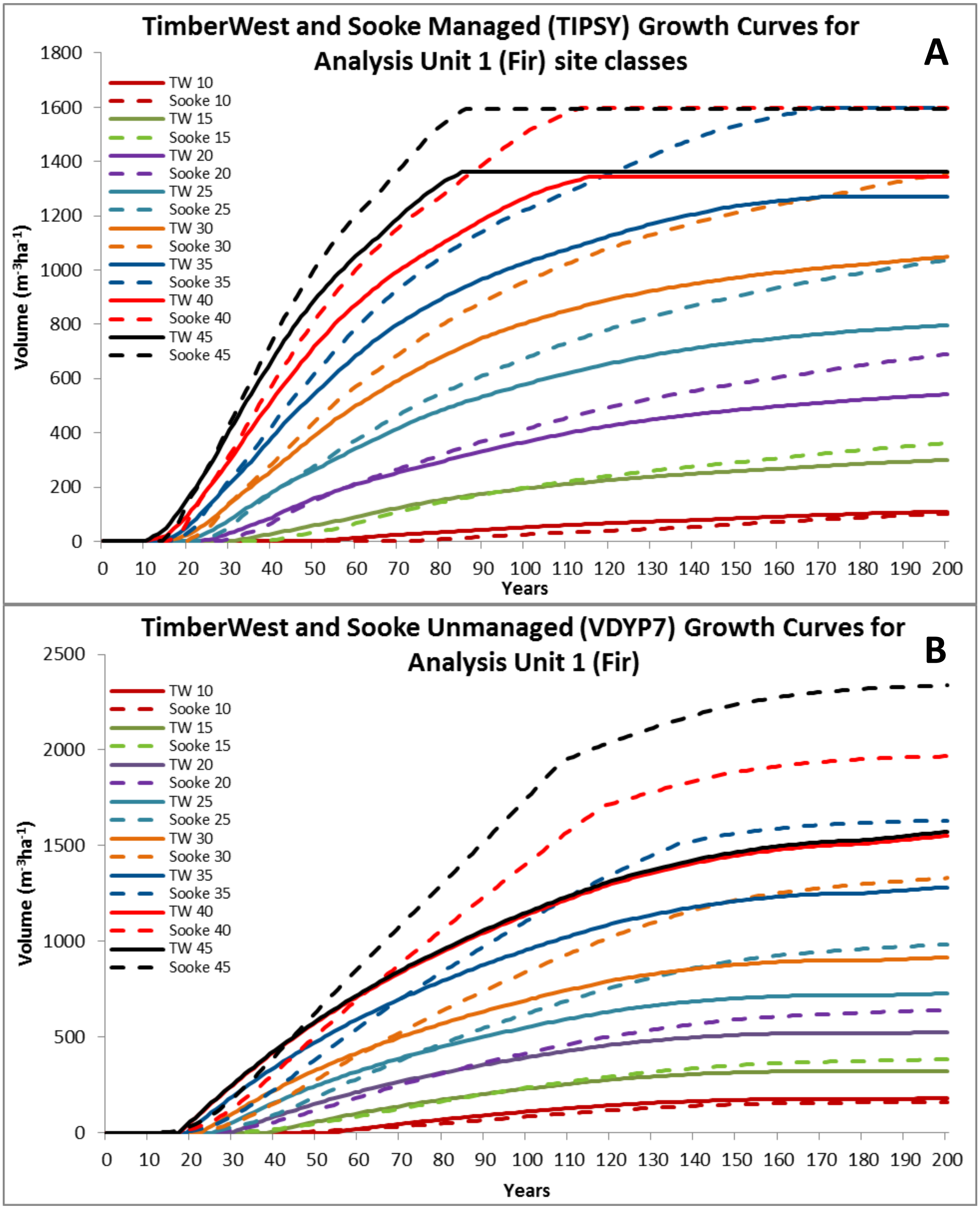


Figure 3-2 - Growth curves for the first 100 years for Analysis Unit 1 (fir) generated for Sooke using the Variable Density Yield Prediction 7 (VDYP7) program and the Table Interpolation Program for Stand Yields (TIPSY) for unmanaged and managed stands, respectively.

3–2.4 Validation of Growth and Yield Curves using Coastal Forest Chronosequence (CFC) Ground plot data

VDYP7 and TIPSY growth and yield curves for the SLW were compared to curves used in the 86-year retrospective C budget study (Trofymow, et al., 2008) near the Oyster River on eastern Vancouver Island. The Oyster River curves, supplied by the study area tenure owner (TimberWest Forest Corporation), were significantly different from the curves generated from VDYP7 and TIPSY for the SLW (Figure 3-3).


TimberWest and Sooke Managed (TIPSY) Growth Curves for Analysis Unit 1 (Fir) site classes

TimberWest and Sooke Unmanaged (VDYP7) Growth Curves for Analysis Unit 1 (Fir)

Figure 3-3 - Unmanaged (A) and managed (B) growth curves for Analysis Unit 1 (fir) received from TimberWest and generated for Sooke Lake watershed using VDYP7 and TIPSY

As a result, CFC ground plot data from within and adjacent to the SLW were used to examine the suitability of TIPSY and VDYP7 growth curves by comparing growth and yield model gross volume predictions against measured CFC ground plot volumes. As only basic stand attributes are available in the Sooke Forest cover-Disturbance geodataset, two sets of VDYP7 and TIPSY growth curves were generated for the six CFC stands used in the comparison. One set of curves was based solely on stand information (species type, site index) while the other set used stand and more detailed information for each CFC plot including height, stems per ha, and basal area.

Evaluation of the growth curves generated for the SLW C project and those used for the Oyster River C project showed stark differences. Maximum values of all curves are significantly higher for the Sooke curves, especially in later years and for higher site classes (Figure 3-3). However, for very low site classes (10 and 15) and prior to approximately 60 years for other site classes the TimberWest curves show higher volume than the Sooke curves. No metadata was provided by TimberWest regarding the parameters used to generate the curves or for the species composition of the analysis units. Possible causes might be the differences in assumptions used in the TimberWest curves for percent stockable area or OAF1 used in VDYP7 and TIPSY, respectively. A lower OAF1 and percent stockable area can be used to adjust for stand gaps and other non-productive areas that are not delineated in a finer resolution inventory.

Output from VDYP7 and TIPSY growth and yield models for the SLW was compared to the measured volumes reported for the CFC Victoria Watershed South (VWS) and Victoria Watershed North (VWN) ground plots. These plots were measured in 1992 (Trofymow, et al., 1997) and 2002 (Blackwell, 2003) for C and nutrient content in standing biomass, coarse woody debris, forest floor and soils. The TIPSY model is best suited to generate growth and yield curves for managed stands and was therefore used to generate curves for the clear-cut and immature plot stand types (plots: 2200014, 2200024, 2200114 and 2200124). The VDYP7 model is best suited to generate growth and yield curves for unmanaged stands and was used to generate curves for the mature and old growth plot stand types (plots: 2200054, 2200064, 2200134 and 2200154).

National Forest Inventory (NFI) generated whole stem volume from the 1992 CFC establishment measurement and 2002 re-measurement were compared to the growth curve model output for the same age and stand types found in the CFC ground plots. The measured plot volume was taken as the average of the three NFI-style sub-plots in each CFC ground plot. These data were retrieved from “PLOTVOL_STANDLIVE” variable in the NFI SITE_INFO table. “PLOTVOL_STANDLIVE” includes volume inside bark of the main stem, stump and top of large trees. TIPSY's volume variable "VOL TOTAL +7.5" (Gross Volume in Figure 3-1) was most similar to the NFI’s “PLOTVOL_STANDLIVE” volume variable. VDYP7's reported "Whole Stem" volume variable (Gross Volume in Figure 3-1) with a minimum DBH limit of +7.5 was most similar to NFI's “PLOTVOL_STANDLIVE” for large trees (i.e. >9.0cm diameter at breast height (DBH)). As the CFC NFI data does not report volume for small trees, the +7.5cm DBH limit in the VDYP7 and TIPSY curves excluded the majority of what would be considered small trees in NFI. Thus, the CFC NFI compiled volume variable “PLOTVOL_STANDLIVE” was considered synonymous with the TIPSY “VOL TOTAL +7.5” and VDYP7 “Whole Stem” volume variables for all comparisons.

Two different types of input parameters were used in VDYP7 and TIPSY to compare to the measured volumes: **1) Stand Only information** (species, species composition and site index), and **2) Plot information** (species, species composition, site index, age and height of stand, basal area and trees per ha), see Table 3-3. Results and comparison are given for growth curves generated using these two input types. The stand and plot input attributes elucidated the sensitivity of TIPSY-and VDYP7-generated volumes to different levels of forest cover information.

Table 3-3 - Stand Only and Plot attributes used for input parameters into TIPSY and VDYP7 programs to generate predicted growth and yield volume curves for the CFC plots (see Table 2-1 for species codes)

			TIPSY Runs				VDYP7 runs			
		Stage	**clearcut**	**immature**	**clearcut**	**immature**	**mature**	**oldgrowth**	**mature**	**oldgrowth**
		ID	2200014	2200024	2200114	2200124	2200054	2200064	2200134	2200154
Plot Attributes	**Stand Only Attributes**	**Species 1**	PW	FDC	CW	FDC	FDC	FDC	FDC	FDC
		Composition Percent 1	36	77	78	100	95	89	99	91
		Species 2	FDC	HW	FDC		CW	HW	CW	CW
		Composition Percent 2	29	23	23		4	6	1	6
		Species 3	CW				DR	CW		HW
		Composition Percent 3	25				1	4		3
		Species 1	DR					DR		
		Composition Percent 3	11					1		
		Forest Inventory Zone	C (coastal)	C (coastal)	C (coastal)	C (coastal)	C (coastal)	C (coastal)	C (coastal)	C (coastal)
		Site index (stand)	27	31	27	25	32	24	21	14
		Management status	P (planted)	P (planted)	P (planted)	P (planted)	N (non-managed)	N (non-managed)	N (non-managed)	N (non-managed)
		Util	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
		Operational Adjustment Factor 1	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
		Operational Adjustment Factor 2	1	1	1	1	1	1	1	1
		Biogeoclimatic zone	CWH	CWH	CWH	CWH	CWH	CWH	CWH	CWH
		Height	0	17.7	0	19.6	43.1	51.5	32	35.6
		Stand Age	4	32	6	42	99	245	93	316
		Site index (plot)	27	30	27	26	32	28	24	19
		Basal Area	0.3	27.9	0.5	47.5	89.6	86.4	78.9	93.9
		Stem density	1443	802	1019	1899	751	389	995	500

Predicted VDYP7 curve volumes differed when stand only and plot attributes were used (Figure 3-4). For the mature stands, the predicted VDYP7 volumes for Plot 5 (2200054), both with stand and plot attributes, fell within the range of Plot 5 measured volumes[20] for that stand age. Predicted Plot 13 (2200134) volumes were considerably lower than those measured in 1992 and 2002. Predicted old growth volumes for Plot 6 (2200064) were slightly higher than the mean but fell within the broad range of sub-plot volumes[21]. The mean measured volumes for Plot 15 (2200154) were higher than the predicted values for both the stand and plot level VDYP7 curves, although the plot level curve was within the lower range of the measured volume. Predicted TIPSY volume showed very little variation between stand only or plot attribute curves for either the clear-cut or immature plots (Figure 3-5).

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[20] The measured plot volumes are the average of three sub-plots and the range is the sub-plots with the maximum and minimum measured volumes.

[21] No 2002 measured exists for plot 6 because the stand was logged prior to 2002.

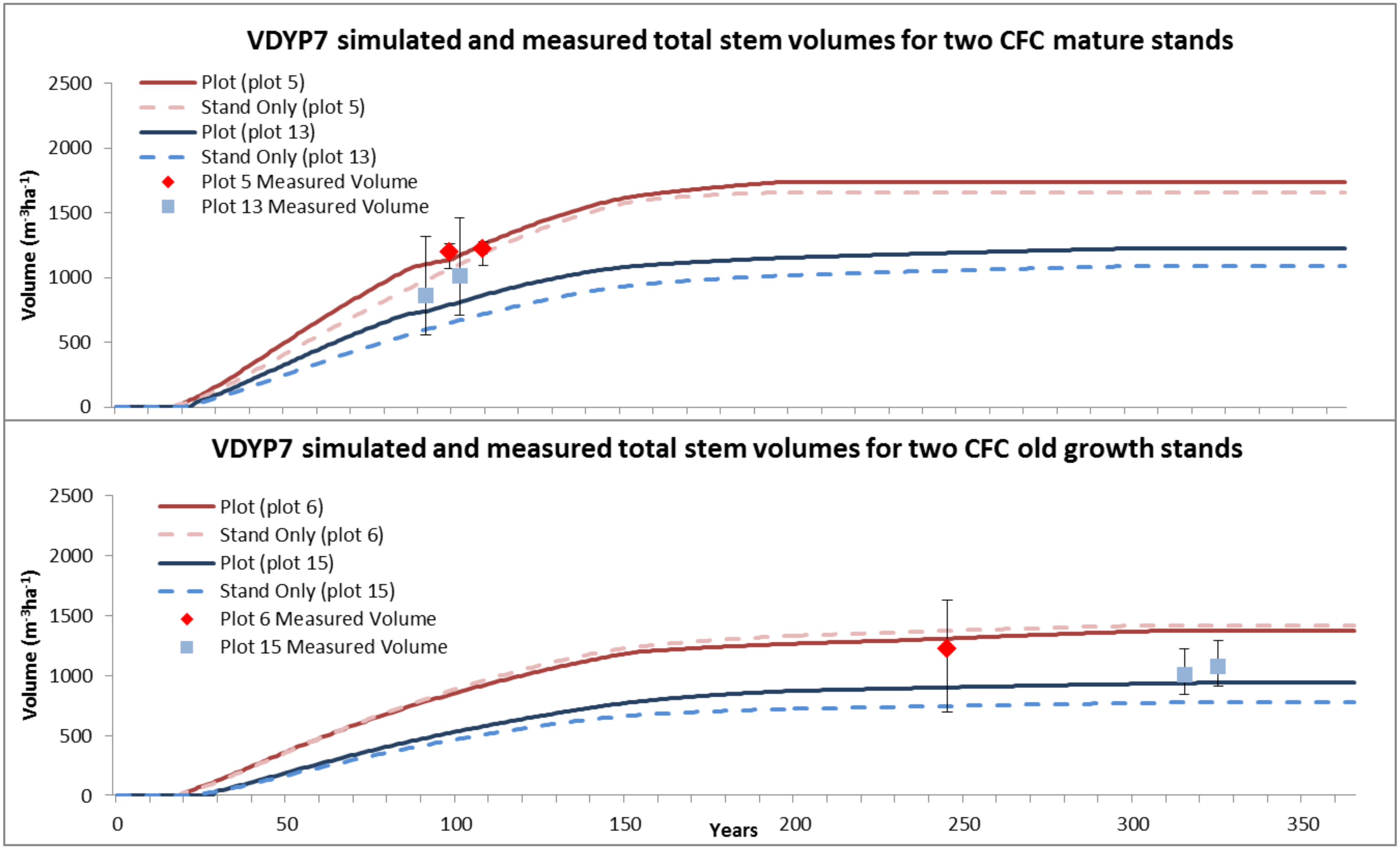

Figure 3-4 - VDYP7-generated and National Forest Inventory (NFI)-style Coastal Forest Chronosequence (CFC) ground plot full stem volumes using stand only and plot attributes. CFC plots were measured in 1992 and 2002. NFI CFC volumes are the average of three sub-plots and error bars indicate the upper and lower ranges of sub-plot volumes

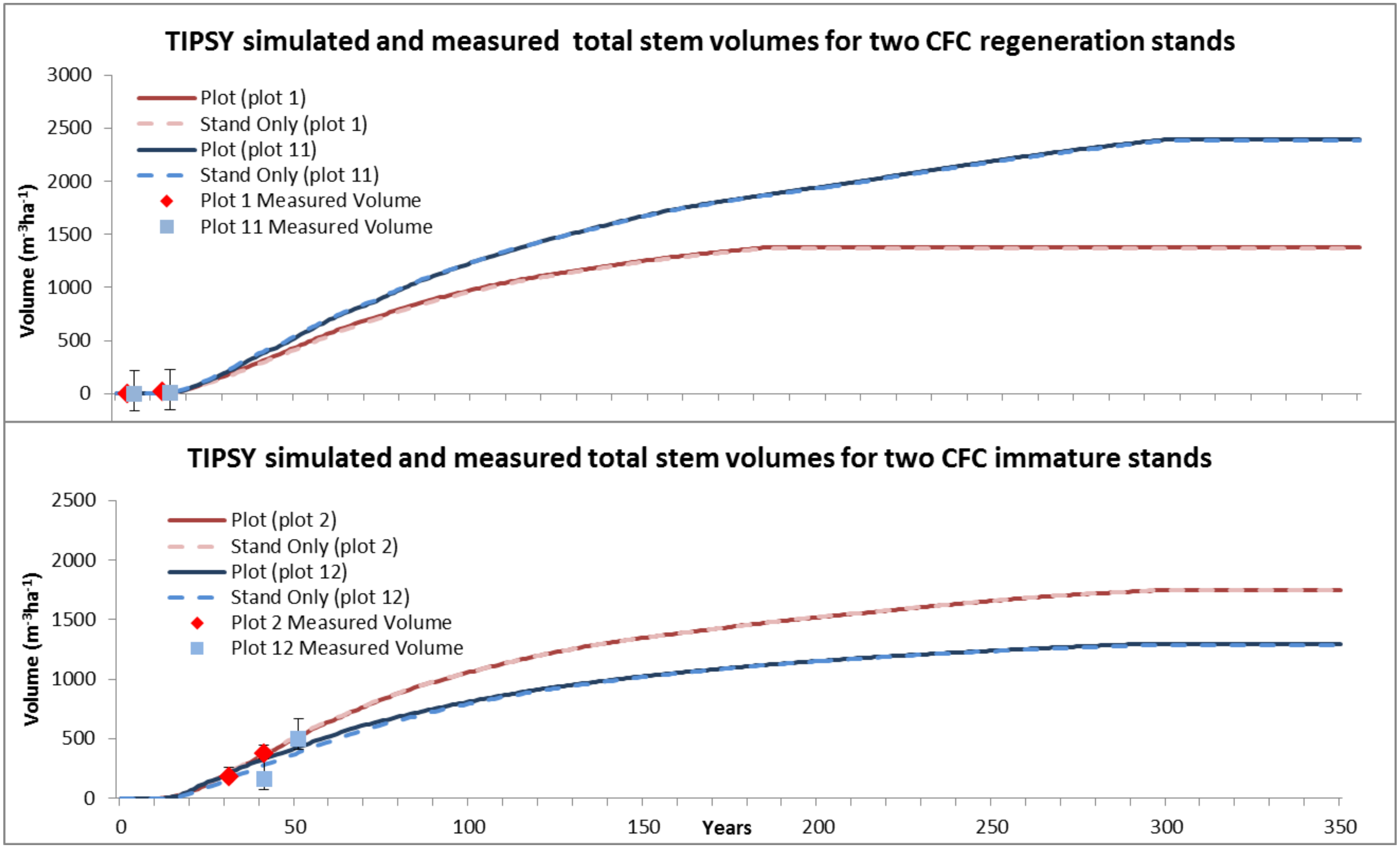

Figure 3-5 - TIPSY-generated and National Forest Inventory (NFI)-style Coastal Forest Chronosequence (CFC) ground plot full stem volumes using stand only and plot attributes. CFC plots were measured in 1992 and 2002. NFI CFC volumes are the average of three sub-plots and error bars indicate the upper and lower ranges of sub-plot volumes

Comparison of measured vs predicted volumes showed predicted volumes were correlated with measured volumes, though regression analysis of the measured versus predicted showed some bias. Using stand only attribute curves produced an R-squared value of 0.90 (Figure 3-6a). This bias was reduced when plot attribute curves were used (R-squared value of 0.96) (Figure 3-6b) and was smallest for those mature and old stands (unmanaged stands) using VDYP7.

This comparison represents a fraction of the forest stand types that exists in the SLW; however, Douglas-fir-leading stands are the most extensive, and thus the comparison is valid for the majority of forest types. Because of this work, the use of VDYP7 and TIPSY growth curve equations was considered valid for the SLW C project (Figure 3-6). The use of curves generated from stand information, while less accurate than curves from plot data, were still deemed suitable for SLW forest stand types. Future work to validate SLW-specific growth and yield equations should rely on data from ground plots in stands of less prevalent forest types. Investigating stands with site indices other than those featured in this analysis or stands without a substantial component of Douglas-fir would be an appropriate starting point for validating G&Y model predictions.

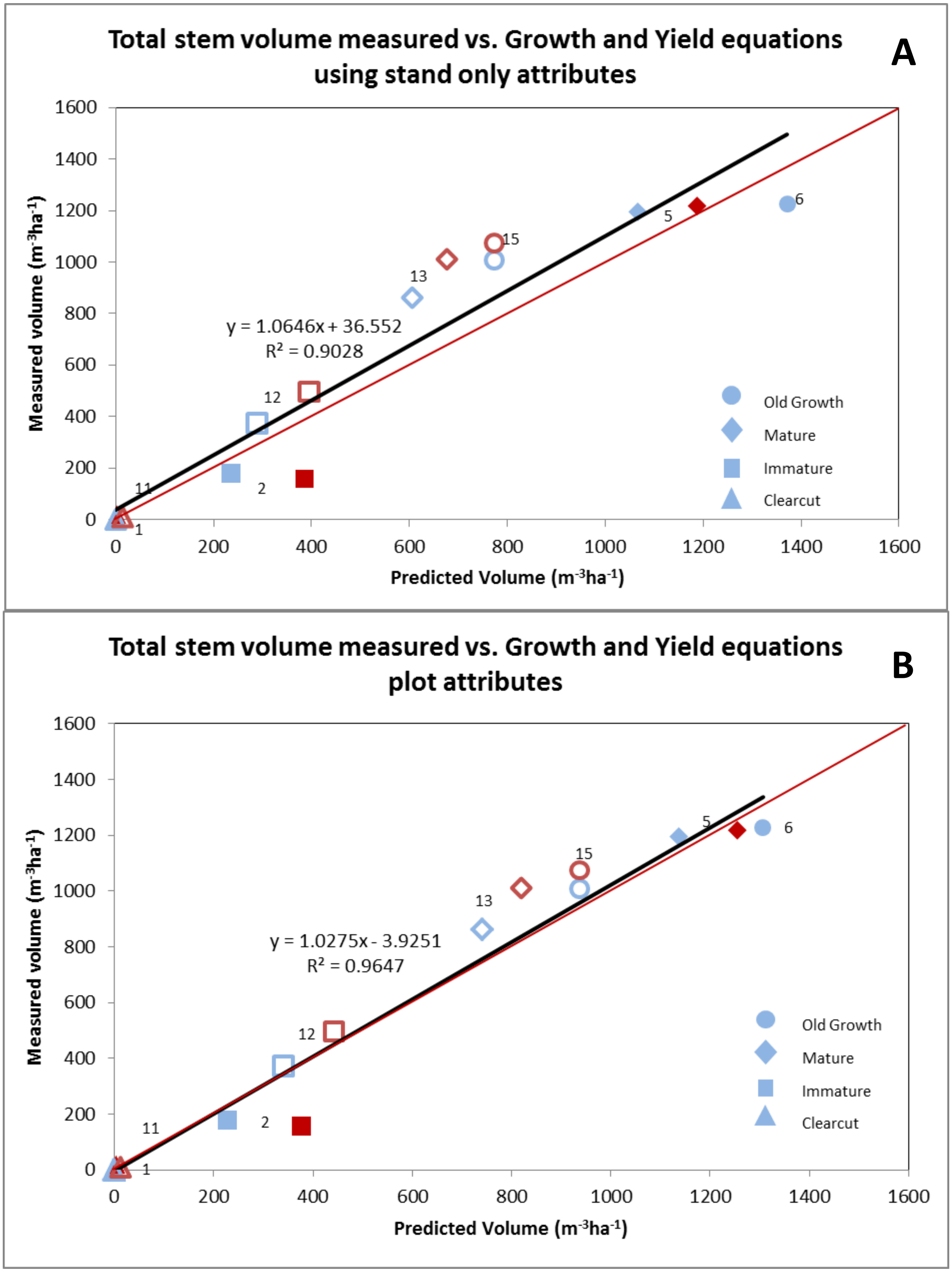

Figure 3-6 – Coastal Forest Chronosequence (CFC) Measured vs. TIPSY/VDYP7-predicted volume using stand only (A) and plot (B) attributes. Light blue shades denote 1992 year of measurement, dark red denotes 2002 year of measurement. Open symbols represent Sooke (Victoria) Watershed North (VWN) plots and closed symbols represent Sooke (Victoria) Watershed South (VWS) plots

3–3.0 Preparation of Disturbance Matrices

In CBM-CFS3, Disturbance Matrices (DMs) are an efficient means for indicating how, following a disturbance, C is redistributed amongst the large number of ecosystem pools (Kurz, et al., 2009). Each unique disturbance type uses a DM that is customized to what C pools are affected and to what degree. Within the DM for each disturbance type, all source (donating) and sink (receiving) pools are identified as well as the fraction of the source pool that is transferred to the sink pool. The source pool represents where the C resided pre-disturbance (e.g. softwood or hardwood merchantable stemwood), while the sink pool denotes where the C is transferred to post-disturbance (e.g. harvested wood products, CO_2 to atmosphere, or medium DOM (coarse woody debris, etc.)). Different disturbances affect the redistribution of C among the C pools and each of these disturbance types are coded as a specific DM.

CBM-CFS3 default DMs were selected and customized based on disturbance types that have occurred over the last century in the SLW. The disturbance types were derived from reports and maps of forest harvest, road construction and wild- and human-caused fire events (Smiley, et al., 2013). Discussions were held with current (Joel Ussery, Cal Webb) and former (Art Walker) GVWSA land management staff that had intimate knowledge of land clearing and harvest practices conducted on the land base. Some revised DMs from Trofymow et al. (2008) were also used as the Sooke disturbance types matched those observed in the Oyster River study area. In total, 18 unique DMs were developed to describe the redistribution of C that occurred as a result of forest disturbance (Table 3-4).

Table 3-4 - Disturbance types recorded for the Sooke Lake watershed (1910-2012) and assigned CBM-CFS3 disturbance matrix ID (CBM_ID)

CBM_ID	Disturbance Dataset Code	Description
1010	Wildfire	Wildfire
1011	Fh/Fsb	Broadcast/escaped burn
1012	Fpb	Partial Burn
1013	Frp/Fto	Residue pile burn
1014	Frt	Transmission line residue burn
1020	Lc/Lct	Transmission line/Clearcut harvest
1021	Lch	Historical clearcut logging
1022	La	Partial harvest (50% remains)
1023	Ll	Land-clearing logging
1024	Llb	Land-clearing logging with biomass export
1025	Lr	Logging for road right-of-way
1030	Lsb	Logging with broadcast (slash) burn
1031	Lrp	Logging with residue pile burn
1032	Lls	Land-clearing logging with broadcast (slash) burn
1033	Llp	Land-clearing logging with pile burn
1034	Llr	Land-clearing logging for road right-of-way
1040	IBD	Douglas-fir Beetle (Trace or low severity)
1051	Tp	Thinning (85% remains)

One example of a customized disturbance matrix was that of ‘land-clearing logging with biofuel export’ (‘Llb’). This disturbance type occurred during the 2002 reservoir raising and only around certain parts of the shoreline that were cleared. As with other logging and land clearing disturbance events, merchantable stemwood was exported as HWP. However, the major difference between ‘Llb’ and contemporary forest harvesting or land clearing (e.g. clear-cut logging and broadcast burning (‘Lsb’)) was the export of all merchantable wood as well as stump and snag biomass to HWP. As stumps are part of the softwood and hardwood “Other” pool, which also includes live branches and small trees including bark, a fraction of 0.86 of the pool was considered to be stump biomass and thus exported to forest products. This biomass was ground or chipped at roadside and trucked to a local pulp mill for pulp and bioenergy production (pers. comm. C. Webb, J. Ussery). ‘Llb’ is unique compared to other logging disturbance types as there was no *in situ* release of C to the atmosphere via residue burning. Other wood biomass (live branches and small trees) were transferred to the aboveground fast DOM pools (0.14) and foliage moved to the aboveground very fast DOM pool. Root biomass was partitioned into the above and below ground DOM pools, fine roots going to the very fast pool and coarse roots to the fast pool. The DM used in this example is located in Appendix F.

3–4.0 Baseline CBM-CFS3 Model runs of the Sooke Lake Watershed (1910-2012)

3–4.1 Methods

3–4.1.1 CBM-CFS3

The C Budget Model of the Canadian Forest Service 3 (CBM-CFS3) is an annual time-step model that uses growth and yield curves and forest cover inventory attributes to estimate stand- and landscape-level biomass C dynamics (Kull, et al., 2011). Using forest management and disturbance information the model can assess past changes in C stocks as well as evaluate future changes that might result from modified management schemes or altered disturbances patterns (Kull, et al., 2011). The model integrates a series of C pools that have varying decay rates based on the specific properties of each pool (Figure 1-1). Initial stand conditions are determined by forest inventory information input by the user. DOM pools, which are typically not included in forest inventory, are generated through an initialization 'spin-up' process. CBM-CFS3 uses a series of successive disturbance events based on the historical natural disturbance type and disturbance return interval for the region of interest (e.g. ecozone) to generate initial values for DOM pools (Kull, et al., 2011). Using this pool structure, the model accounts for C stocks and stock changes in tree biomass and DOM (Kull, et al., 2011). For all turnover and decay parameters as well as DOM initialization procedures, default values for the ecozone (Pacific Maritime) were used during the SLW Baseline CBM runs.

3–4.1.2 Recliner

Through discussions with the C Accounting Team regarding data entry into CBM-CFS3, the use of ‘Recliner’, a newly developed data entry tool for submission of spatially-explicit raster and vector formatted datasets, was seen as a more preferable option for importing the Sooke Lake Forest cover-Disturbance geodataset into CBM-CFS3, compared to the existing Standard Import Tool (SIT). As the dataset consists of multiple disturbances and forest cover changes over the 100-year time period, the import of raster data simplified model setup. A configuration file is used to read the attributes of one or more spatial layers in order to generate the rasterized parameter groups for input into CBM-CFS3. A parameter group is a collection of pixels which share all of the same attribute values throughout the whole study period. A configuration file was developed to read the Sooke Forest cover-Disturbance geodataset from an ArcGIS format. All required Recliner inputs including a landscape raster which describes the study area extent and resolution, lookup tables for growth and yield curves, species and disturbance codes and the archive index that contains all DMs, are referenced in the configuration file. For a further description of Recliner inputs and run procedures, as well as spatially explicit CBM-CFS3 map export refer to Appendix G. Once the data are successfully run through Recliner, two outputs exist: 1) a rasterized ‘parameter groups’ file that represents the spatial identifier for the CBM-CFS3 input and output and; 2) a Microsoft Access database containing all CBM-CFS3-required input data in the necessary format.

3–4.1.2 Data formatting

Spatially explicit forest cover attributes, including species composition and site index as well as disturbance information from 1910 to 2012 for the SLW was compiled and merged into a combined Forest cover-Disturbance geodataset (Smiley, et al., 2013). These data were the basis from which the SLW retrospective C budget runs were conducted. As mentioned in Section 2.0, AUs were assigned to specific species compositions and site index values were rounded to the nearest 5 meters. Also, a management status attribute was added to denote if and when a forest stand became managed (e.g. planted). In addition to leading species, the unique combination of these three attributes was the basis by which growth curves were assigned to forest cover polygons. In CBM-CFS3 parlance, these three attributes (Management status, AU and site class) are denoted as ‘Classifiers’ that allow CBM-CFS3 results to be partitioned and summarized based on the unique values of these classifiers.

CBM-CFS3 models C stock and stock changes on an annual basis. C pool dynamics are driven by a set of supplied growth and yield curves until a disturbance event occurs which consequently alters the growth trajectory of the above and belowground pools. This requires that input data describe the initial forest cover attributes of a stand, the disturbance event that impacts the stand, and the new, post-disturbance forest cover attributes of the stand. In contrast, the Sooke Forest cover-Disturbance geodataset was compiled and developed based on a series of forest cover inventory ‘snapshots’ after major watershed disturbance events. This provided the essential data for model runs but not in the necessary format for CBM-CFS3 input. Therefore the Sooke Forest cover-Disturbance geodataset was reorganized to correspond to a pre-disturbance status, disturbance event, post-disturbance status format. For example, the attribute which described the year a forest stand was considered re-established (Date of Establishment) was transformed to the number of years after disturbance the stand was established (Regeneration Delay). Instead of corresponding to a particular snapshot year, species composition, AU, management status and site class were transformed to characterize the forest cover attributes that existed post-disturbance.

3–4.2 Results

Between 1910 and 2012 disturbances across the watershed resulted in significant changes in forest age structure (Figure 3-7) and species composition changes (as demonstrated by the change in AU areas – Table 3-5). The 100-year disturbance history (Smiley, et al., 2013) is denoted by three distinct stages of management practices. Until the early 1950s the disturbance regime varied between years of no disturbance and years of intense, large scale disturbance (Figure 2-7). The 1950 to mid-1990 period is characterized by sustained yield forestry practices whereby harvesting occurred each year but over a less extensive area than in the 1930s and 1940s. The transition to the third stage of SLW management occurred in the mid-1990s. This transformation was precipitated by the end of forest harvest and the transition to managing the watershed for water quality and supply – reducing anthropogenic disturbances to small scale thinning and reservoir raising activities. Over the 100-year study period, of the 7943 of forest modelled, 2430 ha was cut and replanted and 640 ha deforested.

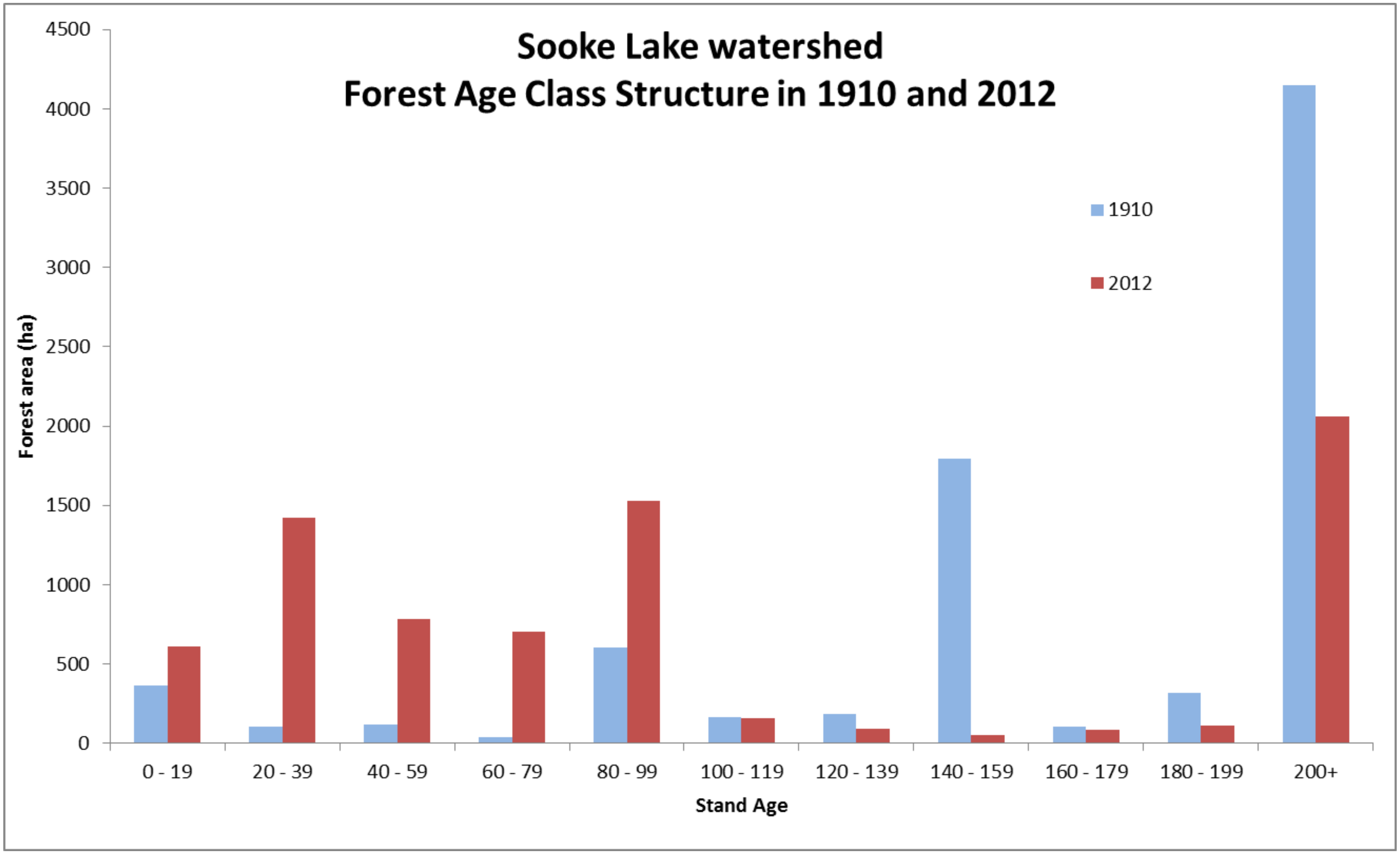

Figure 3-7 - Sooke Lake watershed forest age class structure in 1910 and 2012

Table 3-5 - Area of forested Analysis Units and non-forest in the Sooke Lake watershed in 1910 and 2012

Analysis Unit	Description	Area in 1910 (ha)	Area in 2012 (ha)
Productive Forest land			
1	Fir	5371	4326
2	Fir-Cedar	1048	760
3	Fir-Hemlock/Grand fir/Sitka Spruce	1097	1479
4	Fir-Alder/maple/poplar/arbutus	9	357
5	Cedar leading with conifer mix	35	48
6	Hemlock	5	6
7	Hemlock-Fir	217	247
8	Hemlock-Cedar	33	34
9	Broadleaf greater than 75% composition	8	20
10	Alder-Conifer Mix	18	13
	Total	**7841**	**7290**
Non-forest land			
	Sooke Lake/Reservoir	373 (49%)	813 (62%)
	Other Non-forest	382 (51%)	492 (38%)
	Total	**754**	**1305***
* 80% of the change in non-forest land is due to reservoir creation, the remainder is from road/railway creation, etc.			

In 1910 the watershed was dominated by mature/old Douglas-fir forests with aboveground biomass[22] C of 258 tC ha^{-1} (metric tonnes of C per ha) on average across the watershed (Figure 3-8). Deforestation occurred as a result of reservoir inundation between 1911 and 1915. The effect of deforestation as well as fires and localized, intensive harvest from 1920 to 1940 on what were private forest lands in the north and south east of the study area, reduced aboveground biomass C to an average of 189 tC ha^{-1}. The greatest pools of belowground biomass existed prior to any extensive disturbance in the watershed (58 tC ha^{-1} in 1913). In contrast, the deadwood and

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[22] See Table 3-6 for a detailed description of CBM-CFS3 C pools and fluxes.

litter pools received their highest input after the extensive disturbances of mature and old forests during the late 1920s and early 1930s. On average across the watershed, in 1928 the litter pool reached 99.8 tC ha^{-1} and in 1930 the deadwood pool was 92.4 tC ha^{-1}. The soil C pool reached a maximum of 211.3 tC ha^{-1} in 1930. Distributed harvesting between 1954 and 1998 resulted in a minimum aboveground biomass C value of 148.7 tC ha^{-1} in 1991. By 2012 aboveground biomass had begun to recover (177.9 tC ha^{-1}); however, soil C, while relatively stable, continued to decline (207.1 tC ha^{-1}). Over the study period, changes in spatial distribution of aboveground biomass were characterized by large, concentrated disturbances until the 1950s. Disturbance became dispersed across the watershed thereafter (Figure 3-9).

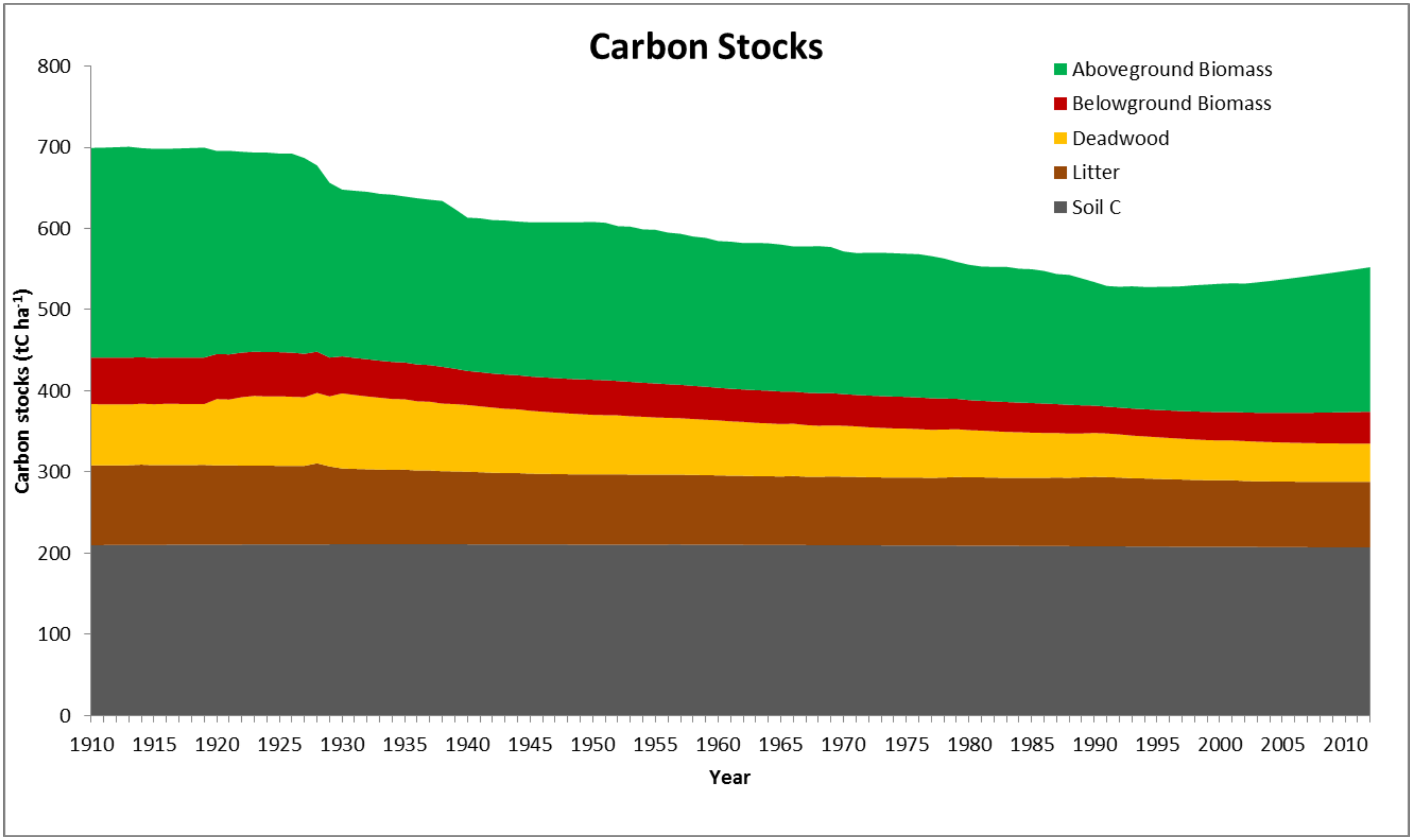
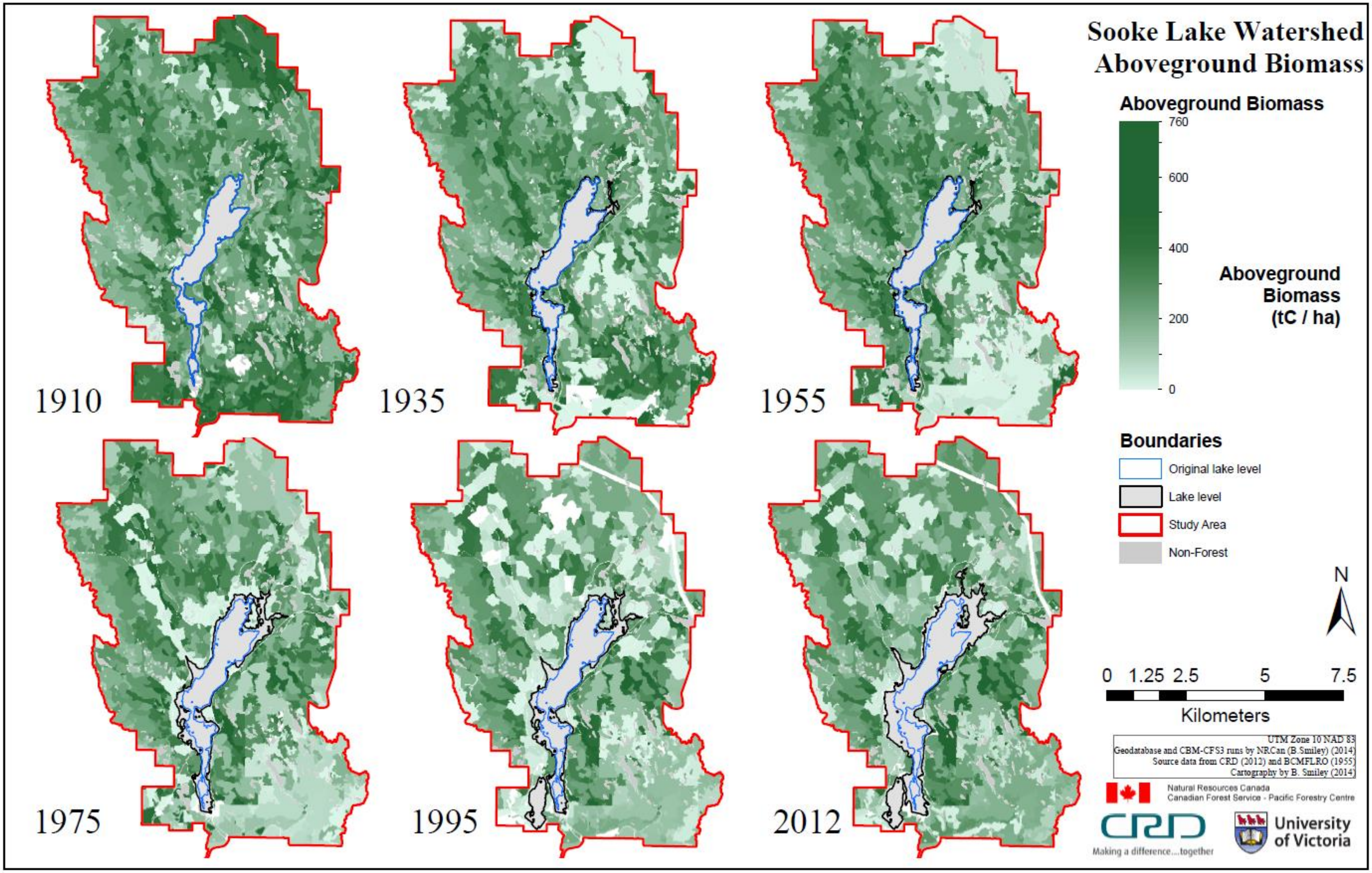


Figure 3-8 - CBM-CFS3-generated carbon stocks per ha for the Sooke Lake watershed 1910-2012



UTM Zone 10 NAD 83
Geodatabase and CBM-CFS3 runs by NRCan (B.Smiley) (2014)
Source data from CRD (2012) and BCMFLRO (1955)
Cartography by B. Smiley (2014)

Figure 3-9 - Sooke Lake watershed aboveground biomass 1910-2012 and lake level change due to reservoir raising

Table 3-6 - CBM-CFS3 carbon pools and fluxes and descriptions

Type	Carbon Pool/Flux	Description	Calculation
Carbon Pool	Aboveground Biomass	Stemwood branches, tops, submerchantable-sized trees, and foliage	Sum of softwood and hardwood foliage, merchantable wood, submerchantable wood, and other wood pools
	Belowground Biomass	Live coarse and fine roots	Sum of coarse and fine root pools
	Deadwood	Dead coarse roots, coarse woody debris and standing dead (snag) trees	Sum of fast belowground, medium DOM, softwood and hardwood stem and branch snag pools
	Litter	All biomass inputs to DOM pools through litterfall, turnover and mortality but does not include transfers from disturbances	Sum of fast aboveground, very fast aboveground and slow aboveground pools
	Soil Carbon	Carbon in soil, including various forms of organic and inorganic soil carbon and charcoal but excluding soil biomass, such as roots and living organisms	Sum of very fast belowground, slow belowground and black carbon pools
Carbon Flux	Net Primary Productivity (NPP)	Sum of all biomass production (i.e. growth that results in positive increment) and growth that replaces material lost to biomass turnover during the year	Sum of all biomass increments minus all losses due to litterfall, biomass turnover, disturbances, and harvesting
	Decomposition Releases	Sum of all decomposition releases, not counting direct losses due to disturbances	Sum of all dead organic matter pool decay
	Net Ecosystem Productivity (NEP)	Biomass production minus decomposition	NPP minus all decomposition losses
	Net Biome Productivity (NBP)	Total ecosystem carbon stock change (includes releases due to disturbance)	NEP minus losses from harvesting and disturbances
(Kurz, et al., 2009; Kull, et al., 2011)			

Prior to any large-scale disturbance (1911), the SLW was a small C sink with NEP of 0.6 tC ha^{-1} yr^{-1} (Figure 3-10). NEP decreased during the high intensity disturbances between 1920 and 1940, varying from -1.7 to 0.0 tC ha^{-1} yr^{-1}, resulting in the SLW as a whole being a net C source for the majority of these decades. The concentration of disturbances in the northeast and southeast of the watershed during this time had a significant influence on the watershed's average NEP (Figure 3-11). Over the period of sustained logging NEP remained positive within 1.0 tC ha^{-1} yr^{-1} of neutral. After forest harvest activity ceased in the mid-1990s NEP began a steady increase to a study period maximum of 2.3 tC ha^{-1} yr^{-1} in 2012. Net biome production (NBP) includes C flux changes due to disturbance (Kurz, et al., 2009) and depicts how reservoir creation, fire and forest harvest impact C emissions across the watershed (Figure 3-12). The contrasting logging methods between the 1920-40s and the 1950-96 are clearly evident based on the NBP fluxes that occurred (Figure 3-10). Also, NBP demonstrates the impact on landscape-level C fluxes that result from the concentrated disturbances that occur during reservoir expansion.

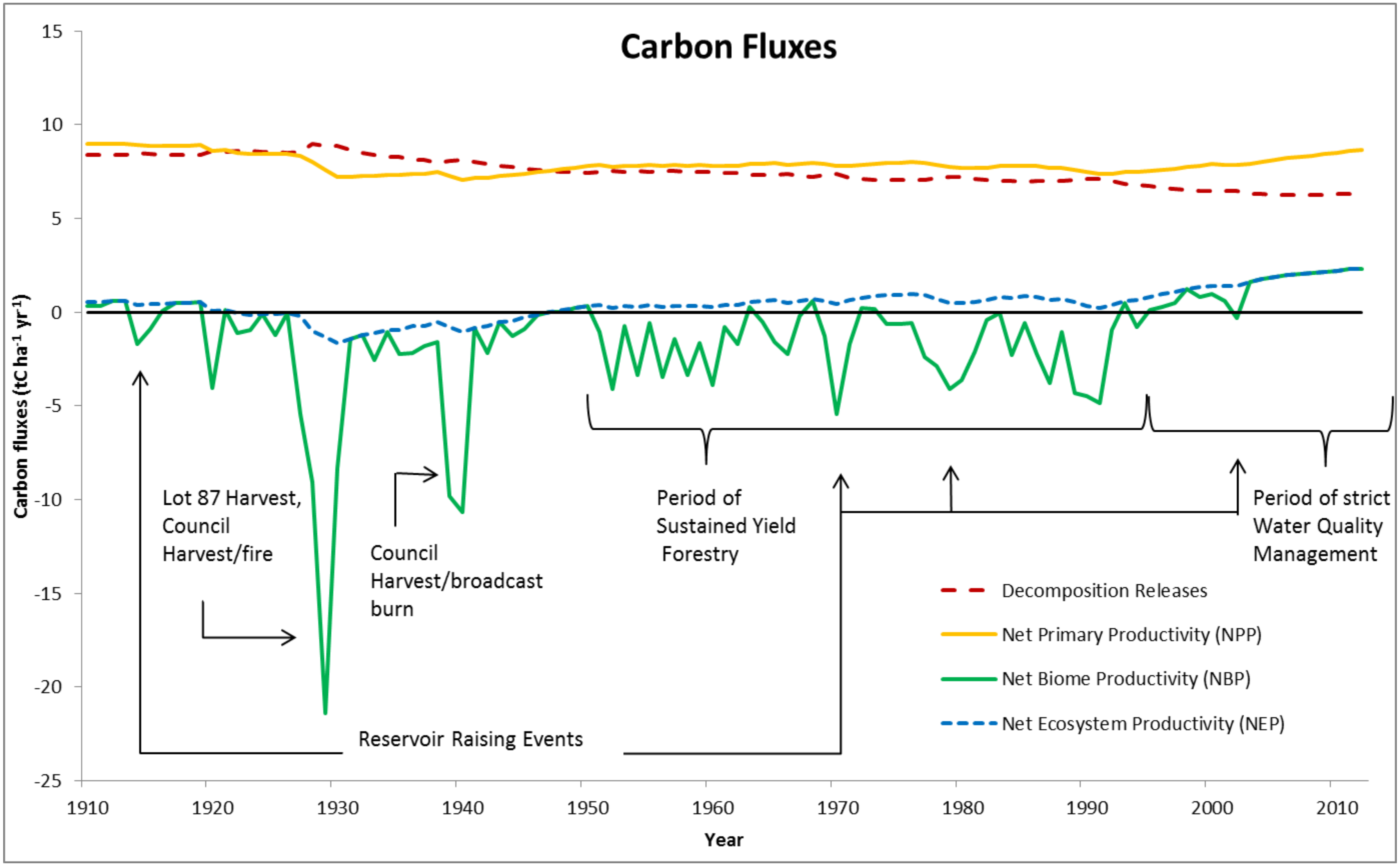


Figure 3-10 - CBM-CFS3-generated carbon fluxes per ha for the Sooke Lake watershed 1910-2012

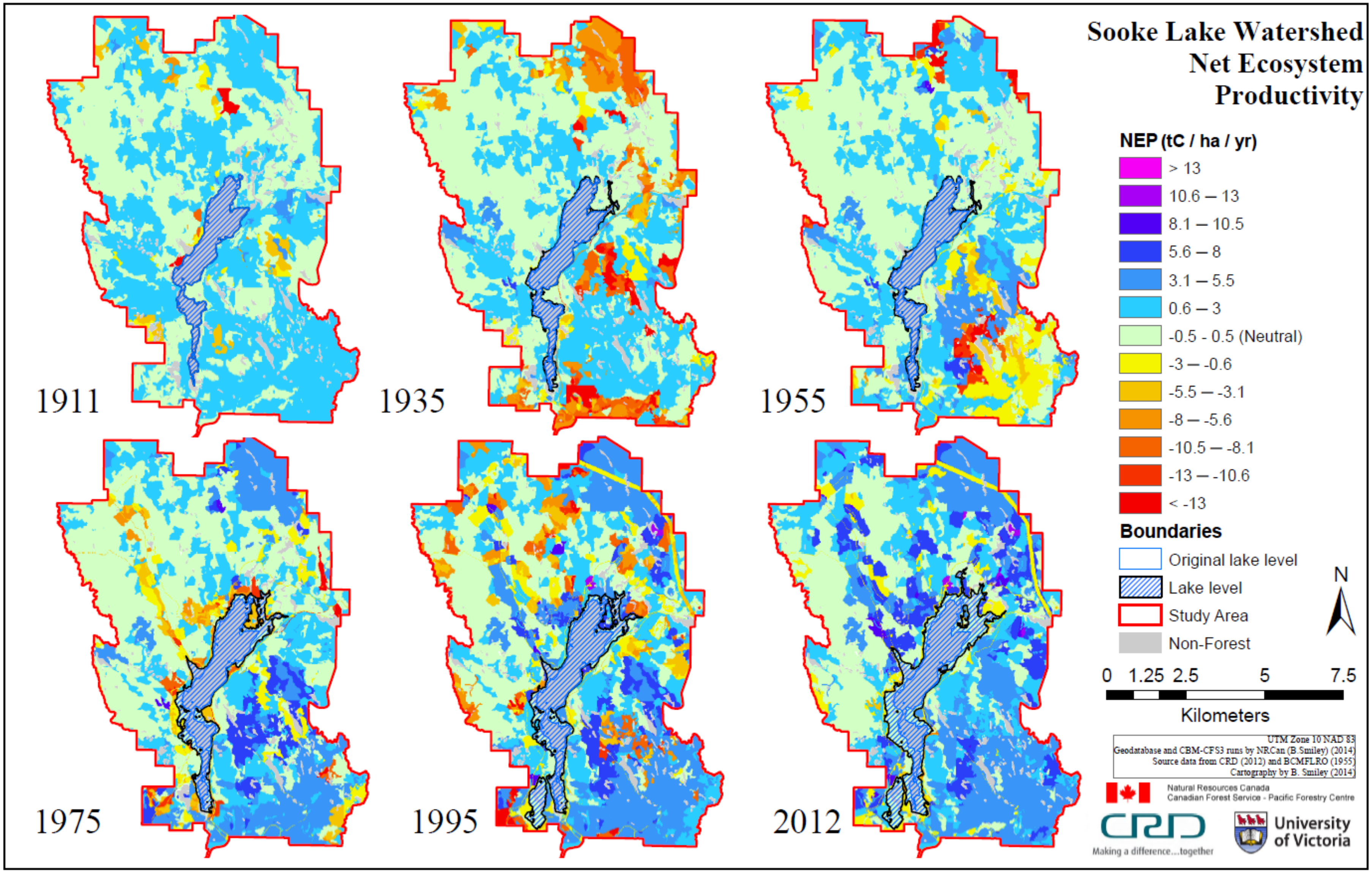


Figure 3-11 - Sooke Lake watershed Net Ecosystem Productivity (NEP) 1910-2012 and lake level change due to reservoir raising

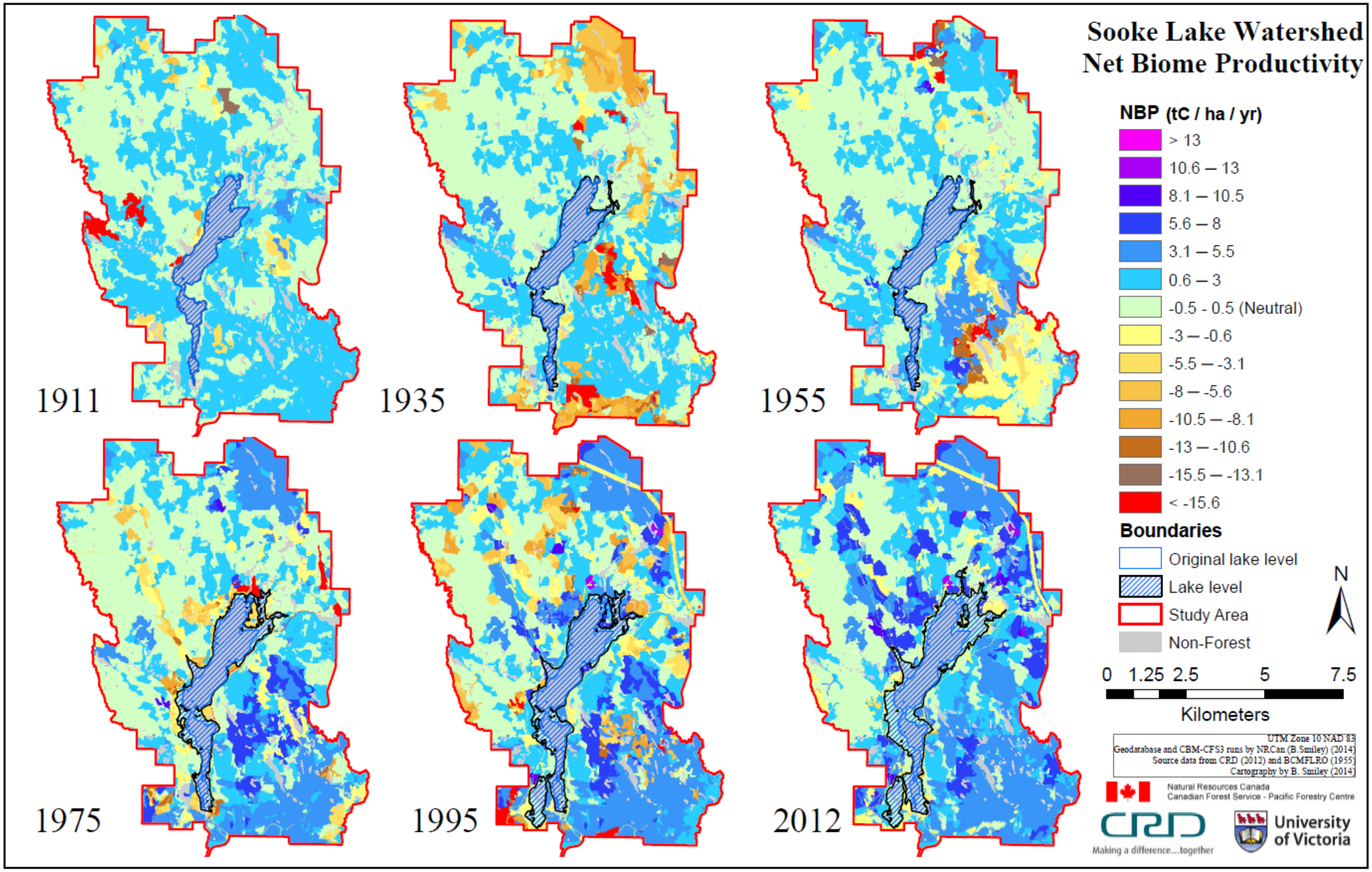


Figure 3-12 - Sooke Lake watershed Net Biome Productivity (NBP) 1910-2012 and lake level change due to reservoir raising

3–4.3 Discussion

Growth and yield curves and DMs are the two major model inputs that drive C stock and C stock changes. Growth and yield curves determine the rate at which C increment accrues in the live biomass pools while DMs impact the amount of C that is removed from live biomass pools and transferred to the atmosphere and DOM pools[23].

Shifting species composition (and therefore AU) resulted in the use of different growth and yield curves over the study period. The vast majority of stands within the SLW remained either pure Douglas-fir or Douglas-fir-leading (Table 3-5). Being a climax tree species for unmanaged stands at the ages found in 1910 and given the forest disturbance, temperature and moisture regime present, Douglas-fir would be expected to dominate the study area. However, after 1910, many stands were recorded in the forest inventories as having transitioned post-disturbance to a hardwood tree species-leading stand. This could be a result of preferential growth of hardwood species during early stand development. Yet, the impression of more hardwood-leading forest stands could also be due to limitations in the historic forest cover maps and inventories in coastal BC as they did not always record hardwood stand components because they were considered non-merchantable. The presence of more hardwood-leading forest stands with higher litterfall rates relative to softwood-leading stands could impact the rate at which the litter pool recovers post disturbance (Kurz, et al., 2009).

The key influence on growth curve selection was the change from the use of unmanaged to managed yield curves due to planting. In contrast to other areas of the province where forest management practices did not mandate post-harvest planting until the late 1970s, the GVWD

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[23] Decay transfer functions from biomass pools also affect the annual amount of C assigned to DOM pools.

(now CRD) began planting within the GVWSA in the 1950s[24]. Also, in the case of managed stands, Douglas-fir was the leading planted species on the coast as it was the most valuable coastal species and had the highest survival rate (90-95%) in the SLW (Walker, 2014). The newly managed stands also signify the changing age class structure that has occurred due to logging of old forest within the watershed. Due to silvicultural practices that include genetic selection of seedlings, fertilization and brush clearing[25], managed growth curves predict biomass accumulation faster and earlier in stand development compared to unmanaged stands. Consequently, the large aboveground biomass C stocks that were removed when mature and old forest were logged and burned have recovered considerably. The observed changes in aboveground biomass C were either amplified or curtailed depending on if the recorded site class for the managed stand had increased or decreased, relative to the pre-disturbance site class. While the site productivity of a stand should not change drastically after a fire or harvest, the estimated site index may change as it is dependent on the assessed growth potential of individual trees in the stand and the stand as a whole, both of which can change post-disturbance (Nigh & Love, 1997). The inappropriate selection of site trees (from which site index is calculated), be they diseased, suppressed, or damaged can negatively impact the accuracy of stand site index, resulting in different pre- and post-disturbance site class.

Over the last century forest management practices have changed significantly in response to changing public perceptions of what constitutes forest values (Kamp, 2013). The GVWD pre-emptively instituted some progressive management practices due to the sensitivity (both ecological and perceptual) of disturbance within water supply lands. However, some logging,

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[24] Areas within the Sooke Lake watershed but outside GVWD jurisdiction until recently, such as Lot 87 and Council watershed only began planting activities after they were mandated by the Province of BC in the late 1970s.

[25] The silvicultural practices of genetic selection and fertilization were not conducted on GVWSA lands. Silvicultural practices that did occur in the Sooke Lake watershed included planting of seedlings from the GVWD nursery at Cabin Pond and fencing of planted areas to minimize deer browsing (Walker, 2014).

land clearing or wildfire/burning practices over the study period were either outside of GVWD jurisdiction, or were a result of technological or economic limitations of the era. Merchantability standards are a prime example of changing economic conditions that impact the amount of stemwood left onsite. In 1960 the rough utilization minimum merchantable top was 20cm (Walker, 2014) and would have been significantly larger prior to 1950. Over the 20th century, both merchantability standards and technological limitations impacted stump height. Current utilization standards on the BC coast, while dependent on market conditions, typically range between 10cm and 15cm tops (Trofymow, et al., 2014), thus impacting the amount of stemwood that is removed from a forest stand as HWP. The differences between contemporary and historic logging practices were parameterized within the DMs that relate to those disturbance types. For example, with historic logging, 80% of merchantable stemwood was exported as HWP, exemplifying lower utilization standards. The remaining stemwood would either be broadcast slash burned, left as medium DOM or decayed post-harvest. Consequently, a higher proportion of C was transferred to DOM pools (left as coarse woody debris) or emitted to the atmosphere[26]. In contrast, contemporary harvesting within the watershed has been more efficient, represented by a higher proportion (88% to 95%) of stemwood biomass removed as HWP, consistent with other areas of the BC coast (Trofymow, et al., 2008).

Merchantable logs (stemwood) harvested from SLW lands over the last 100 years accounts for a significant fraction of the change in forest C stocks (Figure 3-13) and NBP flux. Harvesting occurred for commercial purposes on lands outside of GVWSA tenure and within the GVWSA to fund water infrastructure projects and to clear land for reservoir raising (Smiley, et al., 2013). The various HWP that are derived from the harvested stemwood are not considered to be a C

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[26] The DOM pool was burned the following year if logging and residual burning occurred in different years.

sink; instead, under current Intergovernmental Panel on Climate Change (IPCC) rules (IPCC, 1996), the C is deemed to be immediately emitted to the atmosphere. However, in actuality approximately 40% of HWP could potentially be manufactured into long-lived forest products (Government of British Columbia, 2010), storing that C in a manufactured C sink.

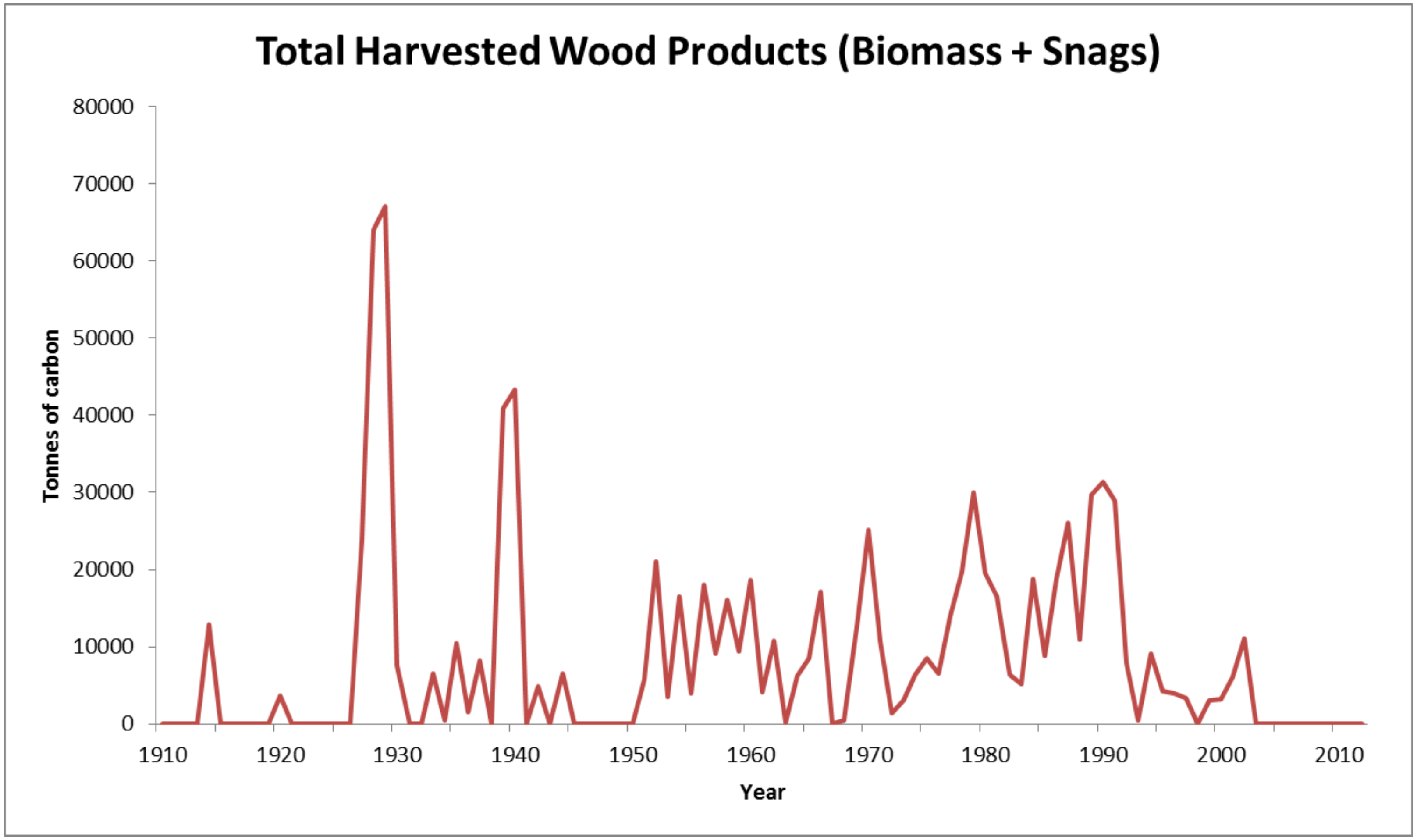

Figure 3-13 - Total harvested wood product carbon exported from the Sooke Lake watershed (1910-2012)

In this Baseline run, the impact of residence time in manufactured goods of HWP resulting from logging and land-clearing disturbances are not included in modelling efforts. As per IPCC guidelines, the current assumption within CBM-CFS3 regarding HWP is that C exported as wood products is immediately released to the atmosphere as CO_2 at the time of harvest (IPCC, 1996). While emitting all HWP C as CO_2 does alter the gas composition compared to other pool transfers and disturbance types[27], it does not take into account the life cycle of the wood product or its C storage potential. Work has been done to incorporate the storage and emissions from HWP into a more comprehensive C budget for BC that includes North American HWP consumption and use (Dymond, 2012).

Biomass residues left over from harvesting activities, including C from the hardwood and softwood sub-merchantable, snag and other pools as well as C existing or transferred to DOM pools are also impacted by changing disturbance types over the study period. Broadcast burning of residues was common practice until the 1980s. In this case, 48-62% of the C from the snag, medium DOM and aboveground DOM pools is emitted to the atmosphere as CO_2, CH_4 and CO. Also, fine roots and foliage are impacted by broadcast burning. Current forest management policy prescribes forest residues left over from harvesting to be piled and burned as to avoid large scale forest floor disturbance that results from broadcast burns. Contemporary silvicultural practices like this also help to reduce forest fire risk from large amounts of dispersed residues and improve access and area available for planting (Kamp, 2013). This disturbance type maintains the majority of the C in DOM pools (although transfers between DOM pools do occur). Only 27% of the medium DOM and 6% of the other aboveground DOM pool C is emitted to the atmosphere (Trofymow, et al., 2008; Kurz, et al., 2009). Less coarse woody debris

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[27] 100% of C removed through HWP is emitted to the atmosphere as CO_2 at the time of harvest whereas gas emission composition for other pool transfers is 90% CO_2, 9% Carbon monoxide (CO) and 1% Methane (CH_4).

(medium DOM) is gathered into piles and burnt (27%) than would have been broadcast burned (48%). C in forest floor (other aboveground DOM pools) is only impacted within the footprint of the residue burn piles which is estimated to average 6% of the area of a logging block (Trofymow, et al., 2014) compared to between 48% and 62% of the forest floor C emitted to the atmosphere during broadcast burning. Reflected in 18 unique DMs, the different disturbance types that have occurred within the SLW have influenced the C stock changes markedly over the last 100 years and in so doing shaped the current forest C stocks.

Construction of the Sooke Lake Reservoir and subsequent raising events are defining features in the disturbance history of the watershed. The land-clearing that occurred prior to the reservoir raising events (Figure 2-7) resulted in noticeable changes in NBP (Figure 3-10). Also, deforestation due to inundation reduced the ability of the SLW as a whole to re-establish the aboveground biomass C stocks that existed prior to disturbance. Some areas that were cleared during earlier raising events did not become inundated. Due to the reestablishment of young stands these areas recovered some of the aboveground biomass C post-disturbance. However, in subsequent reservoir expansions most of these areas were cleared again and eventually became flooded. In CBM-CFS3, flooded areas are considered in transition to a ‘forest becoming wetland’ land cover class, and by default these areas (and any C stocks remaining) are no longer included in the C budget for the watershed. After 20 years these areas convert to a ‘wetland remaining wetland’ land cover class in accordance with United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol rules (Kurz, et al., 2009). However, in order to fully account for and compare the C budget effect of deforestation events (see Chapter 5), the flooded areas were retained to preserve a consistent study area value and the DOM stocks were frozen in the year they were deforested and those areas preserved for the remainder of the study period. Decomposition releases (Rh) from these DOM stocks were removed from the C budget as CBM-

CFS3 does not incorporate decay dynamics of submerged DOM pools (Kurz, et al., 2009). In the future the effect of inundation should be taken into account by adjusting the rate of DOM decay for these deforested areas.

While the SLW has a unique disturbance history relative to other areas of Vancouver Island, many parallels can be drawn between initial, pre-disturbance conditions and those of similar studies in BC. Trofymow, et al. (2008) conducted an 86-year retrospective C budget study near the Oyster River on the east coast of Vancouver Island. The initial study area conditions, including stand age, species composition, NEP, and average ha^{-1} aboveground biomass stocks were comparable to the SLW in 1910. Oyster River NEP was very near zero (net C neutral) in 1920, similar to the SLW (0.57 tC ha^{-1} yr^{-1}). Average aboveground biomass C in Oyster River (292 tC ha^{-1}) was similar to Sooke (258 tC ha^{-1}). The lower value for Sooke is most likely due to the higher proportion of immature and mature stands relative to old growth stands in the SLW as compared to Oyster River area. While the age class structure in the Oyster River study in 1920 was generally similar to the SLW in 1910, the subsequent differences in disturbance history led to divergent age class distributions. Study area-wide disturbances that occurred in the Oyster River resulted in the forested land base becoming a stronger C source (~ -10 tC ha^{-1} yr^{-1}) in the mid-1930s whereas the large areas left undisturbed in Sooke buffered the effect of disturbance on average NEP for the watershed, limiting it to ~ -1 tC ha^{-1} yr^{-1}). Similarly, cumulative NBP remained higher in Sooke (-146 tC ha^{-1} between 1910 and 2012) than in Oyster (-211 tC ha^{-1} yr^{-1} to -277 tC ha^{-1} yr^{-1} between 1920 and 2005).

The response of forest ecosystem C dynamics to forest management would differ depending on if the management regime prescribes HWP or conservation as the primary objective. During different periods over the last 100 years, the SLW has been managed for both of these values, presenting a unique case of how management strategies impact C stocks and stock changes.

While forest management for conservation can have immediate C storage (and climate change mitigation) benefits (Sharma, et al., 2013), exclusion of all disturbances, both natural and anthropogenic, can lead to greater risk of catastrophic disturbance in the future (Kurz, et al., 2008). Forests managed for conservation increase DOM C stocks whereas the aboveground biomass plateaus or decreases (Sharma, et al., 2013). Conversely, forest lands managed for HWP show a steady decline in deadwood, litter and soil stocks due to the absence of C transferred from large aboveground biomass pools (Trofymow, et al., 2008). Evaluating the impact of other forest management regimes on GVWSA lands could elucidate how to optimize C storage in the watershed while also minimizing the risk of large scale forest disturbance in the future.

3–5.0 References

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Chapter 4 - Derivation of Annual Dissolved Organic Carbon (DOC) flux into a water supply reservoir: Implications for watershed-scale terrestrial carbon budgets

4–1.0 Introduction

The high value placed on the SLW as the primary source of water for the region requires that possible consequences of forest management and climate change on the forest and aquatic ecosystem be investigated thoroughly. Because of the relatively high prevalence of inland aquatic systems (lakes and streams) within the SLW, considering only the terrestrial land base in ecosystem modelling efforts becomes problematic as it does not integrate the interactions between the terrestrial and aquatic components. The movement of C from the forested land base into the aquatic system is a subtle feature of the C cycle that has not been widely included in modelling efforts, dissolved organic C (DOC) being a primary vector for C transport between these components. The current C pool structure of CBM-CFS3 assumes that any C exiting the forest ecosystem via DOC is respired to the atmosphere. However, the potential exists for some of this DOC to be sequestered in inland aquatic systems, specifically in lake sediment and wetlands. This chapter will provide a background on mechanisms that lead to C transport between the terrestrial and aquatic systems. Using [DOC] data and stream discharge, annual DOC load will be reconstructed for the years 1996-2012 and used to quantify and parameterize within CBM-CFS3 the export of terrestrially-sourced C, via DOC, to the inland aquatic system (Figure 4-1). This study will address a gap in current forest C budget research relating to the relative importance of including DOC as a dynamic C export mechanism from the terrestrial ecosystem.

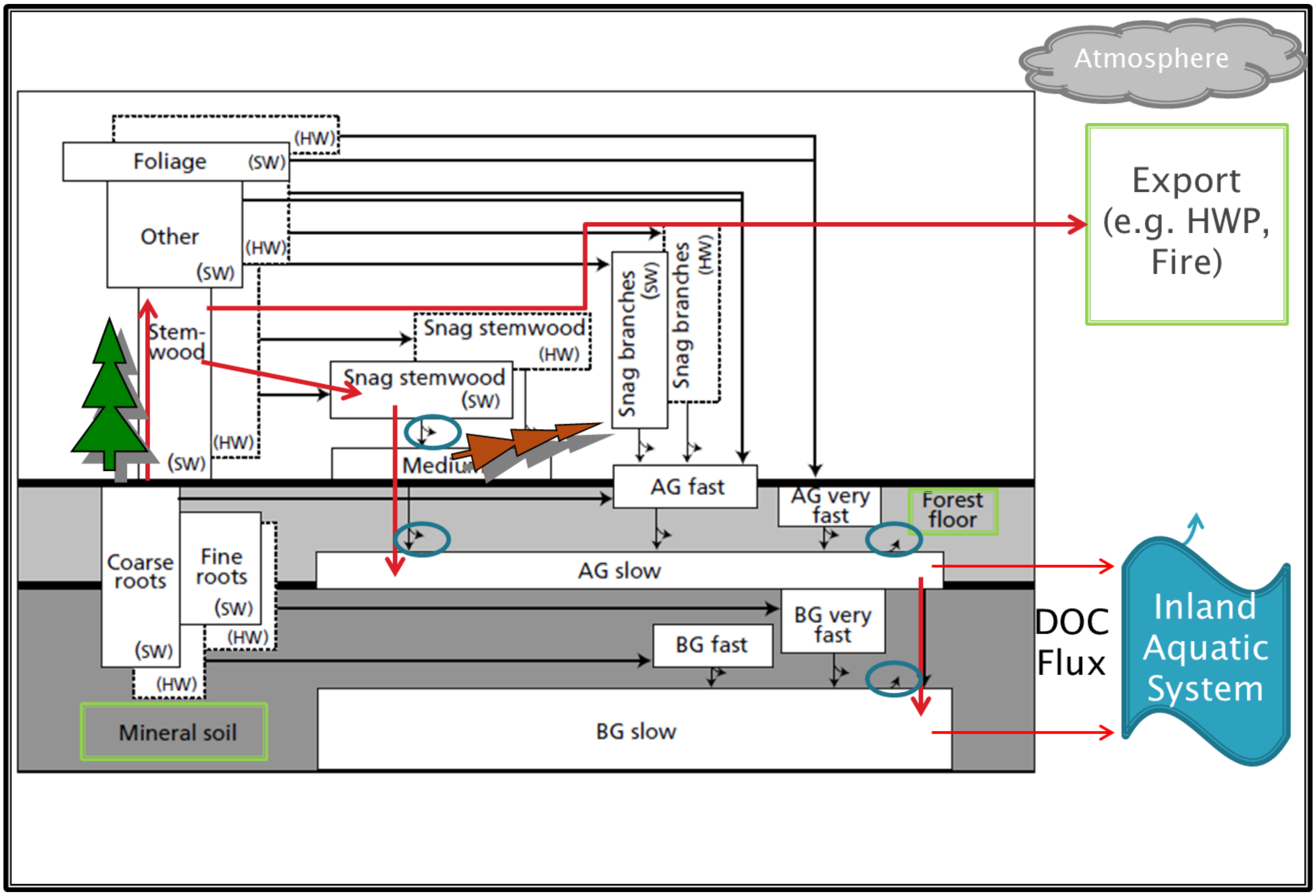

Figure 4-1 - CBM-CFS3 carbon pool structure augmented to include transfers of C from the aboveground slow and belowground slow pools to the inland aquatic system via dissolved organic C (DOC) Adapted from (Kull, et al., 2011).

4–1.1 Background

Change in precipitation patterns, intensity and duration as well as potentially more extreme and prolonged drought periods are forecast to impact both water quality and quantity over the next century in the US Pacific Northwest and British Columbia, Canada (IPCC, 2014). Consequently, the form and magnitude of C being transported into lakes and rivers will likely be altered and have ecological consequences.

Through its constituent acids, DOC has an effect on the pH of aquatic systems, it imparts color, it attenuates both visible and UV light, thus acting as a sunscreen for aquatic micro-organisms. DOC also binds metals, affecting their toxicity and bioaccumulation, and

> nutrients such as N, P, Fe, Cu, and Se, thus controlling their bioavailability and mobility (Porcal, et al., 2009, p. 715).

Research by Creed, et al., (2014) indicates that in North America, both environmental factors (summer precipitation, summer length, water residence time) and environmental factors (forest type and age) will need to be considered when attempting to increase resilience of forested water supply watersheds against future climate warming. Considering the area of inland river systems in the form of reservoirs has increased by approximately 700% (Vorosmarty, et al., 1997), the lateral transport of C from terrestrial systems to inland aquatic environments represents a significant C flux that may be altered by future climate change through increased sudden rainfall events and longer periods of summer drought (IPCC, 2014).

While the link between major hydrological events within a watershed and C being discharged in fluvial systems from that watershed are highly correlated, other watershed characteristics that may impact the concentration of C fluxes have not been well studied (Raymond & Saiers, 2010). Dissolved organic matter, or dissolved organic carbon (DOC) as it commonly measured, is sourced from leached plant material and mineral soil layers (Hillman, et al., 2004). The fraction of lakes and wetlands within a catchment has been known to be an important regulator of DOC export (Alvarez-Cobelas, et al., 2012). While the presence of bogs or wetlands within a catchment is a major source of DOC (Hillman, et al., 2004), natural or anthropogenic disturbance to forest cover and other land use classes (Oni, et al., 2011) can also greatly influence the type and amount of C being exported from the terrestrial component of a watershed (Hope et al. 1994; Raymond & Saiers 2010; Hillman et al. 2004). Forest cover disturbance affect both the short term discharge of DOC to the aquatic system due to factors such as amplified overland water flow (Hornberger, et al., 1994) and rapid accumulation of organic matter (Schlesinger & Bernhardt, 2013), but also long term DOC discharge resulting from slow redevelopment of soil and forest floor C pools.

Aboveground litter deposition and belowground root turnover are the main contributors of C to detritus that, through decomposition dynamics, are transformed by the soil community into soil organic matter. The decomposition dynamics of micro fauna, bacteria and fungi occur in two stages: 1) labile - surface processes that lead to the rapid turnover of the majority of litter and; 2) resistant - processes at depth that result in the slower production, accumulation and turnover of highly resistant organic compounds known as humus. The accumulation of soil organic matter is due largely to decomposition rates that are driven by differences in regional temperature and moisture regimes; Net Primary Productivity (NPP) seems to be less of a factor controlling soil organic matter development compared to decomposition processes (Schlesinger & Bernhardt, 2013). Residence time for C in detritus is also mainly dependent on the decomposition rate of the material. The composition of the litter in question has a significant impact on this rate (Schlesinger & Bernhardt, 2013).

The majority of CO_2 production from soil organic matter originates in surface litter due to the rapidity of decomposition and the large proportion of fine root biomass (Bowden, et al., 1993). In fact, Edwards & Sollins (1973) found that in a temperate forest, soils below 15cm only contributed 17% of the annual CO_2 production, presumably from the decomposition of humus substances. This CO_2 can accumulate in the soil and soil water in high concentrations relative to the atmospheric and is the primary component in carbonation weathering (Schlesinger & Bernhardt, 2013). Also, nitrogen availability is a significant factor in C decomposition (Cleveland, et al., 2004).

During soil development, humus accumulation occurs at rates between 1-12g of C m^2yr^{-1} (Schlesinger & Bernhardt, 2013). Eventually soils reach a steady state of organic material and therefore the production of humic compounds is balanced by their export out of the system via heterotrophic respiration as well as by leaching and erosion (Schlesinger & Bernhardt, 2013). The export of C from the soil organic matter pool via fluvial systems represents a significant gap in many C budget analyses, especially over long temporal scales (Lugo & Brown, 1986).

In a watershed, the transport of C from the terrestrial to an inland aquatic ecosystem, such as a reservoir, mainly occurs through groundwater and stream mechanisms. Many previous investigations of atmosphere-biosphere C dynamics have been conducted at diurnal or seasonal temporal scales and therefore did not include C export from the terrestrial system via inland aquatic systems which impacts C dynamics more at the inter-annual and decadal time scales (Randerson, et al., 2002). This transport of C into streams is often divided into dissolved C and particulate C, although a nutrient atom can cycle between a particulate and dissolved state numerous times over the course of its downstream movement (Schlesinger & Bernhardt, 2013). While dependent on the pH of the water body, dissolved inorganic carbon (DIC) (Schlesinger & Bernhardt, 2013) can also precipitate from carbonate minerals in the sediment, as well as oxidize from organic material (Brunet, et al., 2009). Allochthonous C (i.e. C from outside the aquatic environment - the terrestrial environment) is the primary source of C for most small streams (Schlesinger & Bernhardt, 2013). Depending on the presence of clay materials[28] in the surrounding soils (Nelson, et al., 1993) the ratio of dissolved C (i.e. DOC[29]) to particulate C (i.e.

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[28] The absence of clay materials allow organic compounds to move freely from soils to stream water (Nelson, et al., 1993)

[29] DOC includes soluble carbohydrates and amino acids from decomposing leaves and plant roots and humic and fulvic acids from soil organic matter (Schlesinger & Bernhardt, 2013) that can pass through a 0.45 ɥm

particulate organic C (POC)) can be approximately 3:2 respectively. Small stream NPP from benthic algae and mosses may only supply 0.2% of available organic C (Fisher & Likens, 1973). The presence of clay materials in the surrounding soil may determine the initial input ratio of dissolved to particulate C; however, as downstream movement occurs, the particulate component degrades into dissolved C (Fisher, 1977). Also, increased stream flow can heighten the concentration of overall DOC and POC as a higher proportion of stream volume is derived from organic material-laden overland flow (Hornberger, et al., 1994). Estimates suggest that between 1 and 5 grams of C m^2yr^{-1} are removed from a forested watershed by small stream flow (Hope, et al., 1994); this is less than 1.0% of forest NPP (Mantoura & Woodward, 1983).

While lakes are commonly net sources of CO_2 to the atmosphere (Cole, et al., 2007), organic C that is buried in lake sediments is an important global C storage mechanism as it removes C from the more active C pools (Sobek, et al., 2009). The flooding and soil saturation that occurs in lakes, wetlands and reservoir systems impedes the decomposition process and thus large accumulations of organic matter result (Schlesinger & Bernhardt, 2013). Anthropogenic disturbance can also have a considerable impact on the transport of suspended sediments, 90% of which do not make it to the ocean and deposit in lake and floodplain sediments (Lal, 1995). Cole, et al. (2007) used a simple mass balance equation to explain the integrated terrestrial-aquatic C budget:

Equation 1

$$I=G+S+E$$

“Where carbon imported into the aquatic system (I) can be estimated as the net carbon gas balance of the aquatic system with the atmosphere (G), plus storage (S) and export in drainage waters (E)”. In the case of allochthonous C, the storage efficiency in lake sediments is more efficient than autochthonous C (NPP from within the lake); consequently autochthonous C is the dominant fuel for microbial respiration within a lake (Sobek, et al., 2009). Also, the amount of DOC that is lost from rooted plants and hence input into the lake is dependent on the nature of the lake's depth as shallower lakes will have more rooted plants than steep, deep lakes (Schlesinger & Bernhardt, 2013). In the case of the relatively shallow Lawrence Lake, only 7.8% of the organic C deposited in the lake is permanently stored (Rich & Wetzel, 1978). In addition, atmospheric C can directly dissolve into lakes, but is dependent on pH. "At pH levels less than 4.3, most [CO_2] is found as a dissolved gas, between 4.3 and 8.3 as a bicarbonate and greater than 8.3 as a carbonate... together these forms are known as dissolved inorganic carbon (DIC)" (Schlesinger & Bernhardt, 2013, p. 277).

An important consideration in both terrestrial and aquatic C cycling is the significance of methane (CH_4) because of its role as a potent greenhouse gas which can affect the intensity of global climate change. As a greenhouse gas CH_4 is 25 times more potent than CO_2; this fact coupled with the speed at which it is accumulating in the atmosphere relative to CO_2, averaging 1% per year over the last few decades (Schlesinger & Bernhardt, 2013), makes it an important component to study in terrestrial-inland aquatic ecosystems. The major natural source of CH_4 stems from methanogenisis which mainly occurs in wetlands and wet lowland areas where C is released from wetland and lakebed sediments (Schlesinger & Bernhardt, 2013). In upland regions, a small amount of CH_4 is absorbed into the soil by methanotrophic bacteria, although this is only a fraction of what is released from lowland areas (Schlesinger & Bernhardt, 2013). Other detriments to CH_4 sequestration in forest ecosystems include many forestry practices such as land clearing (for quarries, roads, etc.) and nitrogen fertilization which have been found to produce nitrite that persistently inhibit methanotrophic bacteria (King & Schnell, 1994).

The increased inland water volume and aquatic sediment deposition resulting from reservoir creation could, over time, offset the sudden release of C that occurs during reservoir creation. The biogeochemical reactions in lowland lakes and wetlands are intensely interrelated to the reactions occurring in the upland terrestrial environment and the river and groundwater runoff systems that link the ecosystem components together (Schlesinger & Bernhardt, 2013). Integrating and modelling the two systems requires an in-depth understanding of these complexities and how they interact.

4–1.2 Study area Hydroclimatology

The three gauged and largest catchments within the Sooke reservoir are the focus of this chapter. Rithet is the largest catchment in the SLW (Table 4-1) and is the only catchment that has perennial stream flow; consequently it is the largest contributor of water volume to the Sooke Reservoir.

Table 4-1 - Individual catchment (Rithet, Council, Judge) and combined catchments (Rithet+Rithet-Like, Council+Council-Like, Judge+Judge-Like) sharing similar physiographic and hydrologic characteristics (Werner, 2007) for scaling up to SLW level of analysis

Catchment	Area (ha)	% of SLW
Rithet	1824.9	21.2
Council	1189.4	13.8
Judge	765.1	8.9
Rithet + Rithet-Like	3926.4	45.7
Council + Council-Like	1473.2	17.1
Judge + Judge-Like	2822.5	32.8
Not modelled (non-forest)	373.1	4.3
SLW	**8595.1**	

Because of the absence of snowpack, glaciers or significant lakes as a contributing factor to summer discharge, Rithet summer stream flow is thought to be sourced from a small bedrock aquifer (Kenny, 2004; Werner, 2007). Groundwater can also be a source of high DOC (Striegl, et al., 2007). While Kenny (2004) investigated aquifer extent across the CRD, little is known about the geological formations and their porosity and permeability within the SLW. Therefore, groundwater DOC input into the reservoir was not considered.

On average, Rithet catchment is the steepest at 17 degrees and has the largest range of elevation from 188 meters (m) at lakeside to 840 m (average elevation is 450m). Sustained yield forestry occurred in the Rithet valley between 1954 and 1996, harvesting high quality old growth Coastal Douglas-fir stands, however, the majority of the Rithet catchment remains undisturbed. Of the three gauged catchments, Rithet has the highest proportion of forest considered to be mature or old growth at 67% (> 80 years old) (Table 4-2) and has the least extensive disturbances over the last 100 years (Smiley, et al., 2013). Due to the low proportion of both lakes and wetlands, Rithet catchment has limited capability to buffer stream discharge or alter constituent loading once the runoff enters Rithet Creek.

Table 4-2 - Individual catchment (Rithet, Council, Judge) and combined catchments (Rithet+Rithet-Like, Council+Council-Like, Judge+Judge-Like) characteristics in 2012 including areas of forest seral stage, wetlands and lakes (total area and percent of catchment)

Catchment		Rithet	Council	Judge	Rithet + Rithet-like	Council + Council-like	Judge + Judge-like
Immature Forest*	**Area (ha)**	601.8	899.2	322.6	1353.8	1007.2	1150.3
	% of catchment	33.2	78.7	43.5	36.6	71.4	46.5
Mature and Old Forest*	**Area (ha)**	1210.8	243.0	418.6	2347.2	403.3	1325.4
	% of catchment	66.8	21.3	56.5	63.4	28.6	53.5
Wetlands	**Area (ha)**	7.8	15.3	23.5	22.5	16.3	59.8
	% of catchment	0.4	1.3	3.1	0.6	1.1	2.1
Lakes	**Area (ha)**	0.8	16.1	0.0	14.6	16.1	1.0
	% of catchment	0.0	1.4	0.0	0.4	1.1	0.0

* Immature forests are considered to be stands less than 80 years old while mature/old forest are 80 years old or greater

Council Creek is regularly diverted into Sooke Reservoir via Trestle Creek (see history below); for the purpose of this study the Council and Trestle systems are considered to be the same catchment. In contrast to Rithet, the Council-Trestle (Council) catchment (Figure 1-3) has had an intense and distributed disturbance history, spanning from 1930s through the 1990s and has the highest proportion of juvenile and immature forest (<80 years old) at 79% (Table 4-2) (Smiley, et al., 2013). Council has roughly the same mean slope (16.5 degrees) and elevation (450 m) as Rithet however; Council has a much lower peak elevation (630 m). While the proportion of wetlands area in Council is similar to Rithet, Council catchment contains a 14 ha lake into which the majority of the catchment drains before exiting into Council Creek. This hydrologic feature has important implications for constituent flux from the terrestrial land base of Council to Sooke Reservoir.

Judge Creek is the third and smallest catchment (Table 4-1) and is the most northern of the three gauged creeks. The disturbance history of Judge is characterized by a short period of intense clear-cut logging and broadcast burning during the late 1920s. Other areas of Judge were harvested from the early 1950s until the mid-1980s and by 2012 56% of the catchment was considered to be mature or old growth and only 44% was immature forest (Table 4-2) (Smiley, et al., 2013). The most pronounced physiographic and hydrologic difference between Judge and the other catchments is the prevalence of large wetland areas. Judge catchment has the lowest proportion of area covered by lakes, however, over 3% of Judge land cover is considered wetlands compared to Rithet's 0.5% and Council's 1.3%. The flow path of Judge Creek directly connects the largest wetlands and therefore has a significant impact on the load of dissolved stream constituents into Sooke Reservoir.

4–1.3 Objectives

The objectives of this chapter were first to reconstruct annual per ha DOC loading (flux) from 1996 to 2012 using available DOC measurements and regular stream discharge measurements from the Rithet, Council and Judge catchments within the SLW. Second, the different per ha values of DOC flux generated for the Rithet, Judge and Council catchments were used to parameterize the transfer of C within CBM-CFS3 slow aboveground and slow belowground dead organic matter (DOM) C pools to DOC. The parameters, referred to the DOC fraction parameters (see Glossary), were initially applied to the three catchments of interest and then scaled up to the SLW level. The simulated and aboveground biomass pools for the years 1996-2012 used in this analysis were derived from the Baseline model runs described in Chapter 3. The DOC transfer parameters serve as a basis for the amount of C being exported from the land base via fluvial processes as opposed to *in situ* respiration to the atmosphere. The CRD's 2012 strategic mandate to improve the understanding of the potential effects that climate change may have on forest ecosystems and water quality/hydrology, as well as how forest management plans could amplify or reduce these impacts will be partly addressed by this research (Capital Regional District, 2012).

4–2.0 Software

4–2.1 R (The R Project for Statistical Computing)

'R' is an open source program for statistical computing and graphical display designed with its own language and environment (R Core Team, 2014). Numerous packages are available that enable application-specific modelling, statistical testing, time series analysis and graphing ability. For the purposes of this DOC flux analysis, the 'R' environment and related time series packages (i.e. zoo package) were used to merge the stream flow and DOC measurement data files received from the CRD into a LOADEST-acceptable form and reformat them to daily values for processing.

4–2.2 LOADESTimator (LOADEST, rLOADEST) (United States Geological Survey)

The FORTRAN Load Estimator (LOADEST) program is designed for estimating loads and concentrations of stream and river constituents. Using a stream flow time series dataset, measured constituent concentrations and other optional variables, LOADEST can support the development of a regression model for constituent load (Runkel, et al., 2004). While three statistical estimation methods are available in LOADEST, for the purposes of this study Adjusted Maximum Likelihood Estimation (AMLE) was used. “Estimates of instantaneous load are developed for all of the observations in the estimation data set using:

Equation 2

$$\hat{L}_{AMLE} = exp\left(a_0 + \sum_{j=1}^{M} a_j X_j \right) H(a, b, s^2, \alpha, \kappa)$$

where $\hat{L}_{AMLE}$ is the AMLE estimation of instantaneous load, a and b are functions of explanatory variables, α and κ are parameters of the gamma distribution and s^2 is the residual variance” (Cohn, 1988; Cohn, et al., 1992; Runkel, et al., 2004, pp. 5-6). AMLE allows for a “nearly unbiased” estimation of instantaneous dissolved stream constituent load (Cohn, 1988).

rLOADEST is based on the LOADEST FORTRAN program and was converted to an R-usable package (Lorenz, et al., 2013). rLOADEST provides both a collection of predefined models that can be selected based on the ‘best fit’ with the data, and the ability for the user to define a unique model form. In this case, ‘best fit’ is defined as the lowest Akaike Information Criterion (AIC). AIC employs the log-likelihood of a given model and balances it against the number of estimated parameters used.

Using AIC information criterion to select a best fit model enables the selected model to have as few variables as possible which increases precision but maintains enough variables to avoid bias (Runkel, et al., 2004). An alternative stepwise approach of forward analysis using R^2 to select the best fit model has been found to over-fit models (Whittingham, et al., 2006). Instead, AIC uses information theoretic analysis to compare models and is seen as a better approach to model selection (Burnham & Anderson, 2002; Alvarez-Cobelas, et al., 2012). Information theoretic approaches are an alternative to the traditional method of testing a null hypothesis. Instead, information theory is based on Kullback-Leibler information, comparing the information lost between multiple hypothesized realities (e.g. a set of models) and actual reality (Burnham, et al., 2011). AICc (c for correction) is an extension of AIC that corrects for small sample size by including an 'effective sample size' variable (n). Model coefficients are developed using ordinary least squares (OLS) regression. This regression equation is then used to calculate estimates of log- load for each observation in the time series. The full form of AICc is:

Equation 3

$$\mathrm{AICc} = -2(\log - \text{likelihood}) + 2\mathrm{K} + \frac{2K(K+1)}{(n-K-1)}$$

Where K is the number of estimated parameters included in the model and *n* is the effective sample size.

4–2.3 Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3)

CBM-CFS3 is an annual time-step model that uses growth and yield curves and forest cover inventory attributes to estimate stand- and landscape-level biomass C dynamics (Kull, et al., 2011). Using management and disturbance information the model can assess past changes in C stocks as well as evaluate future changes that might result from modified management schemes or altered disturbances patterns (Kull, et al., 2011). The model integrates a series of C pools that have varying decay rates based on the specific properties of each pool. Using this pool structure, the model accounts for C stocks and stock changes in tree biomass and dead organic matter (Kull, et al., 2011).

While the aspatial CBM-CFS3 is extremely useful in estimating historic C stocks and projecting future stocks based on altered management scenarios, both at the stand and landscape scale, it does have some basic limitations. The model is based on annual time steps and therefore does not possess the temporal resolution to describe seasonal variations in C stocks and stock changes (Kull, et al., 2011). While it can simulate changes in temperature on decomposition rates, the model does not explicitly integrate changes in precipitation on decomposition, or the impact of climate change on forest growth (i.e. CO_2 fertilization, changes in annual increment due to temperature) (Kull, et al., 2011). As a forest-centric model, CBM-CFS3 only simulates C pools for the forested areas of a landscape. Gaseous C fluxes occur between the terrestrial system and the atmosphere while forest harvesting results in a C export to ‘harvested wood products’ which are currently considered to be immediately released to the atmosphere[30]. The only parameter currently available in CBM-CFS3 to integrate a terrestrial-to- aquatic C flux is the fraction of the slow aboveground and slow belowground dead organic matter (DOM) pools that respire to the atmosphere. Respiration is dependent on the annual base decay rate for these pools which is 1.5% per year for the aboveground slow DOM pool and 0.33% per year for the belowground slow DOM pool (Kurz, et al., 2009). The path by which the respired C exits the terrestrial system is determined by the “proportion to atmosphere” parameters for these pools, (the DOC fraction parameters), the default of which is 1. Consequently by default, 100% of the C fluxed from the slow DOM pools is respired to the atmosphere. Adjusting this value to less than 1 enables a fraction of the C lost from these pools to be exported from the forest system as DOC.

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[30] Depending on how carbon is fluxed from the land base (i.e. harvested wood products vs. direct release of carbon to the atmosphere via decay or wildfire) the gas composition (i.e. carbon dioxide, carbon monoxide, and methane) is altered

4–3.0 Methods

4–3.1 Datasets

Stream discharge measurements between late 1994 and the end of 2012 were supplied by the CRD for the Rithet, Judge and Council catchments; this constituted the entire record of stream flow for these three catchments. Flow measurement for the three catchments did not begin at the same time and large spans of data were missing during the period leading up to the end of 1995 so the dataset was truncated to January 1st 1996 to December 31st 2012. Stream flow for the three catchments was measured hourly until the last few months of 1996 and then every fifteen minutes thereafter. For the Council catchment diversion that makes up 90% of the flow for the combined Council-Trestle discharge, stream flow is measured using a mechanical totalizer (Werner, 2007). Both Rithet and Judge catchments use a concrete weir and water level recording device to determine stream discharge (Werner, 2007; F. Hall, pers. comm. 2014).

DOC concentration (mg/L) was taken intermittently between 1997 and 2008 at the Rithet, Judge and Council outflow points into Sooke Reservoir. These data, as well as DOC concentration for the south basin of Sooke reservoir, Council Lake and pre-treated raw drinking water were collected by the CRD. Fifty millilitre water samples were collected using either a Sutek sampler or sampling rod close to the water surface and transported to the lab in a cooler (Blaney, 2014). The CRD lab uses a Shimadzu TOC analyzer to separate the fraction of DOC (<0.45 ɥm) in the sample.

Other data requirements included the necessary CBM-CFS3 input to generate biomass and DOM pools. These were derived from a spatially explicit historical forest cover and disturbance dataset for the SLW 1910-2012 (Smiley, et al., 2013). Using these data, Baseline model runs with default DOC fraction parameter values were conducted (Chapter 3) and DOC parameters adjusted for this study.

4–3.2 Empirical DOC Flux Estimation

Chemical concentration data are often scarce compared to measurements of stream flow. However, through a regression relationship, missing concentration data can be interpolated using available site-specific concentration data and consistent stream discharge measurements. In this study, annual DOC flux reconstruction was performed for the Rithet, Judge and Council catchments for the period 1996 to 2012. These years were used as they were inclusive of all DOC measurements made by the CRD and had the most comprehensive flow measurements for all three catchments.

Daily stream flow values for days where DOC concentrations were measured were loaded into R for each separate catchment dataset. These data were used to initially test the ‘select best model’ function (selBestModel) in rLOADEST, and produce AIC and AICc statistics for the nine different default models. This function automatically selects the best fit model based on the AIC statistic; however, because of the small sample sizes the AICc values were used. For Rithet and Judge, model #4 had the lowest AICc while in Council, model #4 had the second lowest AICc. The default selection process (using AIC) selected model #4 for Rithet and Council but selected model #8 for Judge. Because of the prevalence of model #4 in the selection results (see Appendix H) model #4 was used to predict DOC load values for the three catchments. The model form used was:

Equation 4

$$Instantaneous\ Load = a_0 + a_1 \ln Q \;\; a_2 \sin(2\pi dtime) + \; a_3 \cos(2\pi dtime)$$

Where ln$Q$ = ln(stream flow) - center of ln(stream flow); $dtime$ = decimal time – center of decimal time and a_0 to a_3 are model coefficients. Summary statistics and bias diagnostics for the three catchments using model #4 can be found in Appendix I. Also, several diagnostic plots are available in rLOADEST and were generated for each catchment. These plots help describe the fit of the selected model (Appendix J). The suitability of the models was in some cases marginal due to the minimal sample size of DOC concentrations for the three catchments over the sampling period.

Once the regression model form was defined, various temporal scales of DOC load and concentration were predicted to interrogate the output data. Daily DOC concentration and flow values for the three catchments were examined in relation to measured DOC concentrations in order to gauge the model's ability to interpolate concentration at the daily temporal scale (Figure 4-2). For CBM-CFS3 parameterization, annual DOC load values were required, therefore calendar year DOC load in tC per day was the final output from rLOADEST. These figures were then annualized to tC in a given year and converted to a per unit area value given the area of each catchment of interest. These values are considered to be the 'observed' values..

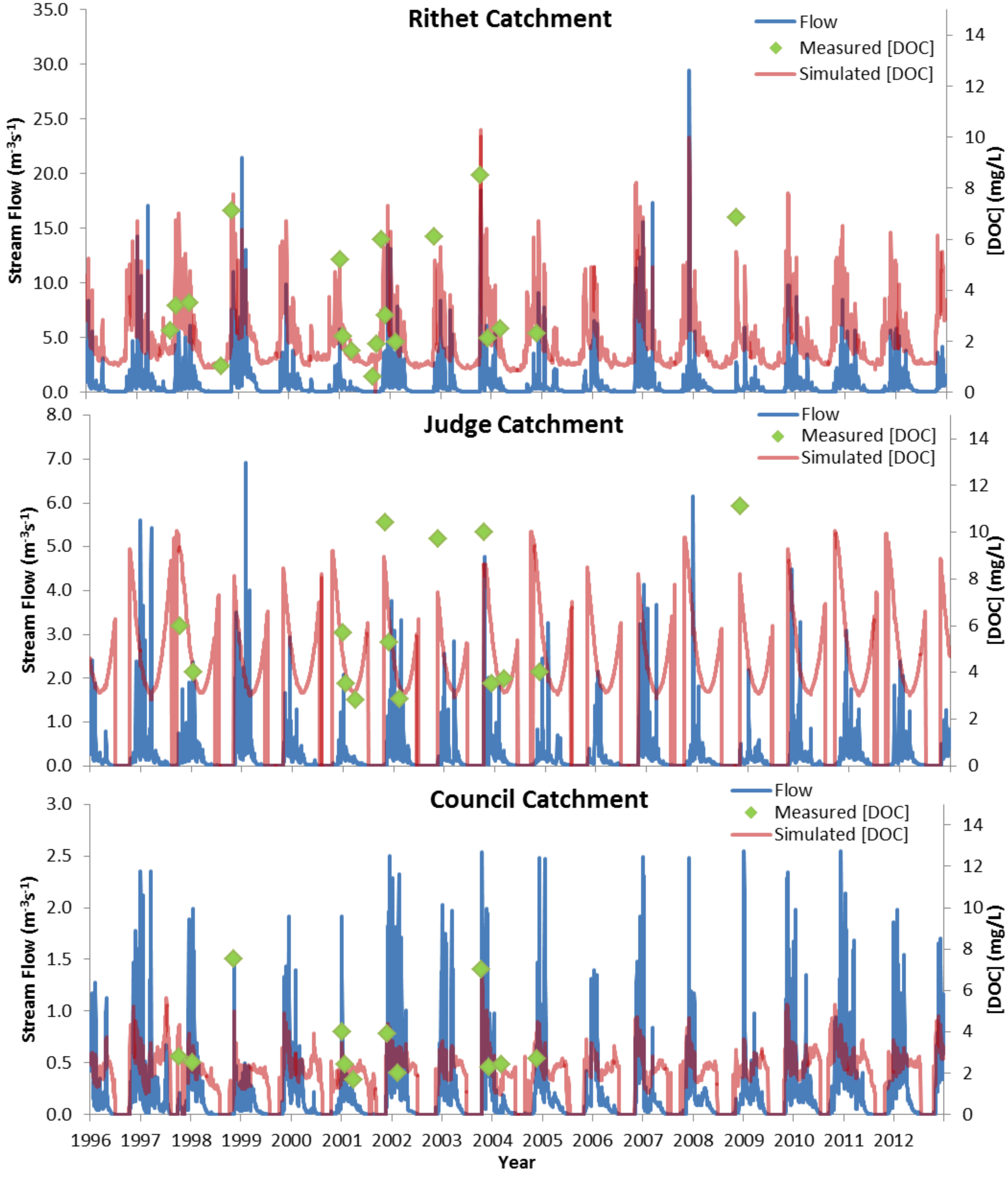

Figure 4-2 - Daily stream flow and dissolved organic carbon (DOC) concentration, measured and simulated, for Rithet, Judge and Council catchments 1996-2012

4–3.3 CBM-CFS3 DOC Fraction Parameterization and Watershed Scale Modelling

Currently in CBM-CFS3, the only C pools from which terrestrial C can be transferred to DOC are the aboveground slow Dead Organic Matter (DOM) and belowground slow DOM pools. The aboveground slow DOM pool includes the F, H, and O soil horizons (Kurz, et al., 2009) and roughly corresponds to the 'Litter' pool in the IPCC Good Practice Guidance (GPG) (IPCC, 2003). These horizons include organic material that develop from the decomposition of mosses, rushes, woody material, and litter (Soil Classification Working Group, 1998). The belowground slow DOM corresponds to a segment of the "soil organic matter" GPG pool and specifically includes humified organic matter in the mineral soil layer (Kurz, et al., 2009). The aboveground very fast DOM pool contains other probable DOC sources including the foliar litter and dead fine roots but currently there exists no mechanism in the model to include a transfer of DOC from this pool.

Through multiple runs, the DOC fraction parameter was tuned so that modelled DOC flux matched the annual per ha DOC loads observed for the three catchments. Because of the variance in observed annual DOC values, most likely resulting from higher or lower stream flow years, the mean per ha DOC load for each catchment for the 1996-2012 study period was used for CBM-CFS3 DOC fraction parameterization. The aboveground and belowground slow DOM to DOC fraction parameters were adjusted prior to running a CBM-CFS3 simulation; post-simulation, the DOC fluxes for the time steps that correspond to the study period (1996-2012) were compared to the observed annual values. As each gauged catchment had a different mean per ha DOC load, multiple model runs were required to tune the DOC fraction parameter. DOC fraction parameter values were tuned until CBM-CFS3 output DOC flux ha^{-1} for each catchment was within one thousandth of a tC ha^{-1} of the observed DOC fluxes; at which point the remaining

SLW catchments were assigned a DOC fraction parameter. Assignment of ungauged to gauged catchments was based on the work of Werner (2007) who used physiographic and hydrologic similarities of the catchments to scale up to the watershed level of analysis (e.g. The DOC fraction parameter derived for the Rithet catchment was assigned to a grouping of ‘Rithet-like’ catchments) (Table 4-1). The end result was CBM-CFS3-modelled DOC flux for the whole of the terrestrial SLW.

4–4.0 Results

4–4.1 Catchment Scale

Over the course of the study period the mean DOC load from the Rithet catchment was approximately 72.5 tC yr^{-1}. The mean DOC load from Judge was 29.1 tC yr^{-1} which is high relative to the size of the catchment. Council exported an average of 18.3 tC yr^{-1} to DOC (Figure 4-3a). While the overall export of C in Rithet is high relative to the other two catchments, the unit area value was very similar to that of Judge (Figure 4-3b) (0.0397 tC ha^{-1} yr^{-1} for Rithet vs. 0.0381 tC ha^{-1} yr^{-1} for Judge). Both the total and unit area (0.0154 tC ha^{-1} yr^{-1}) values for Council catchment are significantly lower than the other two catchments despite it being the second largest by area. In all three catchments the variability in DOC load is closely tied to the annual flow (Figure 4-3). This is most likely due to the higher positive correlation between DOC load and stream flow as opposed to DOC concentration. Over the course of the study period Council was the only catchment that showed an upward trend in DOC flux. While Judge and Rithet trended downward slightly, the change between 1996 and 2012 was not significant.

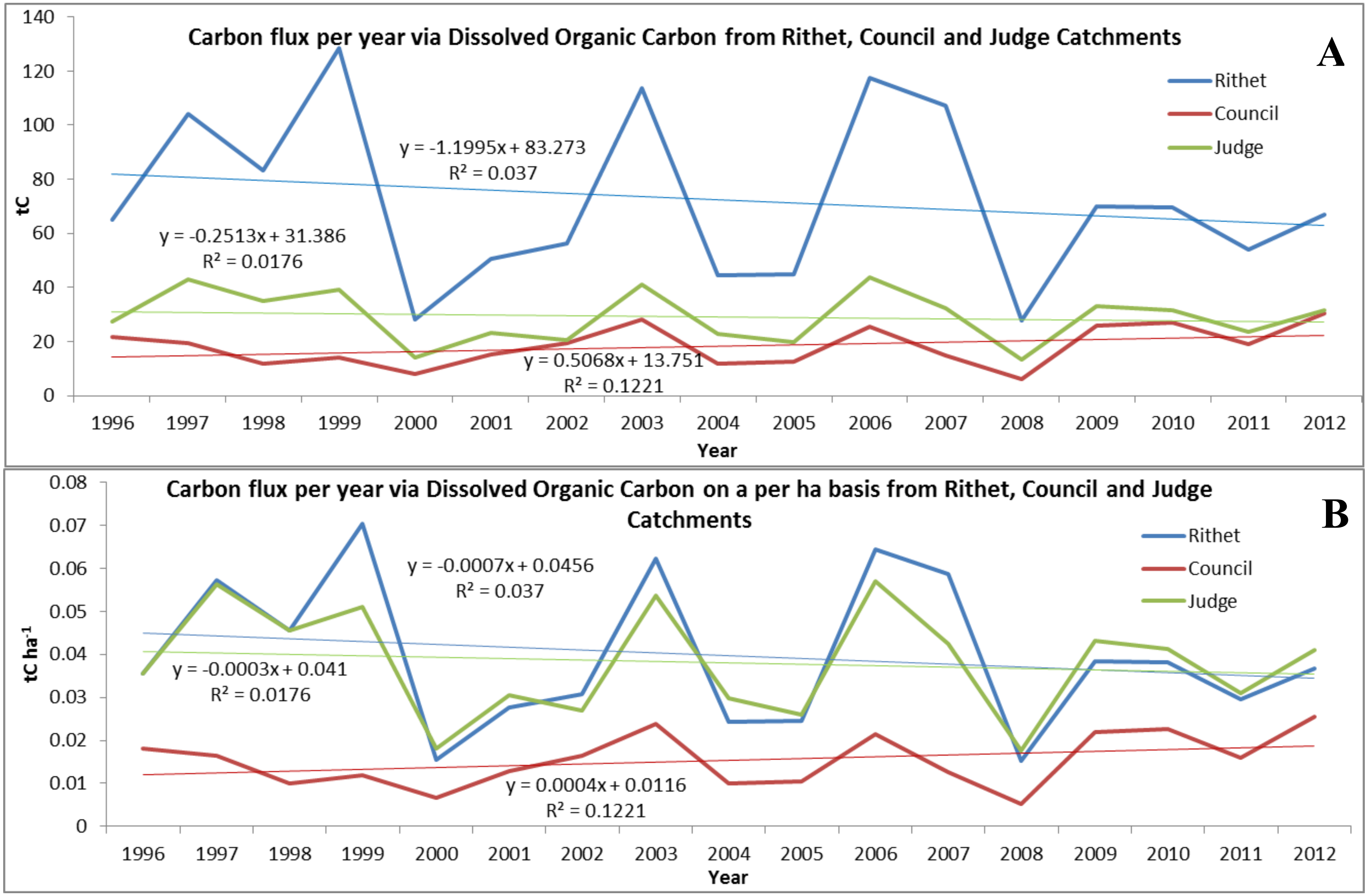

Figure 4-3 – Dissolved Organic Carbon (DOC) load and trendlines from 1996-2012 on a (A) total DOC flux per year and (B) DOC flux per year per ha basis

As the observed DOC load magnitudes varied among the three catchments, the CBM-CFS3-modelled transfer of C to DOC from the slow aboveground and belowground DOM pools required different DOC fraction parameters. Because the belowground pools were significantly larger relative to the aboveground pools (Table 4-3) the belowground DOM pool DOC fraction parameter was maintained at 0.99 for all three catchments representing a 1% flux to DOC.

Table 4-3 - CBM-CFS3 Dissolved Organic Carbon (DOC) parameterization of slow aboveground DOM pool (AG) and slow belowground DOM pool (BG) – mean and mean per ha tonnes of carbon 1996-2012 for Rithet, Judge and Council catchments (Modelled and observed values)

Catchment	Slow DOM Pool	Parameter (% to atmosphere)	Modelled Value		Observed Value	
			16 yr mean (tC yr^{-1})	16 yr mean (tC ha^{-1} yr^{-1})	16 yr mean (tC yr^{-1})	16 yr mean (tC ha^{-1} yr^{-1})
Rithet	AG	94.5	60.4	0.0331		
	BG	99	11.9	0.0065		
	Total		**72.4**	**0.0397**	**72.5**	**0.0397**
Council	AG	97.5	11.4	0.0096		
	BG	99	7.4	0.0062		
	Total		**18.7**	**0.0157**	**18.3**	**0.0154**
Judge	AG	93.5	23.4	0.0306		
	BG	99	5.6	0.0073		
	Total		**29.0**	**0.0379**	**29.1**	**0.0381**

While the C in the slow aboveground DOM pool is more labile owing to the constituents that are represented within it (Schlesinger & Bernhardt, 2013), it was also considered to have a greater fraction of that labile C exported as DOC. This supposition was based on a higher probability of aboveground DOM in overland flow, presenting a greater chance of that DOC source reaching a watercourse; although some of that C is transferred to the slow belowground pool, and is represented in the model as a 0.6% annual transfer. In contrast, DOC sources in the humic belowground DOM component are considerably more immobile as microbes consume more than 90% before it can enter a watercourse (Cleveland, et al., 2004). As a result, a 1% DOC fraction parameter was appropriate for the slow belowground DOM pool. Judge catchment had high ha^{-1} DOC flux relative to the size of the aboveground DOM pool, consequently resulting in the largest DOC fraction parameter from the slow aboveground DOM pool at 6.5%. The slow aboveground DOM parameter was 5.5% for Rithet and 2.5% for Council (Table 4-3). The relative size of the modelled slow aboveground DOM pools over the course of the study period (Rithet (63 tC ha^{-1} +/- 1) > Judge (49 tC ha^{-1} +/- 1) > Council (41 tC ha^{-1} +/- 2) ranked similarly to the observed DOC flux for all three catchments, suggesting the slow aboveground DOM pool as a possible driving force behind long term DOC fluxes.

4–4.2 Watershed Scale

DOC fraction parameters for the gauged catchments were scaled up to the entire SLW. Combined Rithet and Rithet-like catchments made up the largest proportion of the entire modelled watershed (Table 4-1); while, the area of the combined Judge and Judge-like catchments was greater than the Council and Council-like catchments. Stands with high DOC fluxes in 2012 had higher soil C stocks and tended to be older (Figure 4-4). Areas west and south of Sooke Lake typically had lower DOC fluxes compared to forests east and northeast of the lake. The non-gauged catchments have differing amounts of C in the slow above and belowground DOM pools compared to the gauged catchments. As the ungauged catchments were assigned DOC parameters based on their hydrologic and physiographic characteristics (Werner, 2007) and not on similar DOM pool sizes, the ha^{-1} DOC flux values differed slightly from those of the gauged catchments (Table 4-4). Significantly higher DOC fluxes were observed from polygons that recently had old growth forests (> 300 years) on high site index stands.

Table 4-4 - CBM-CFS3 Dissolved Organic Carbon (DOC) flux from slow aboveground (AG) and belowground (BG) DOM pools from 1996 to 2012 for -gauged and ungauged catchments and Sooke Lake watershed totals. All totals in tonnes of carbon or tonnes of carbon per ha

Catchment	Value	MEAN	MAX	MIN	TOTAL
Rithet+Rithet-like	**AG**	123.2	124.6	122.0	2094.3
	BG	24.7	24.9	24.5	419.5
	TOTAL	147.9	149.6	146.5	**2513.8**
	ha^{-1}	0.0377	0.0381	0.0373	X
Council+Council-like	**AG**	14.5	14.8	14.2	246.2
	BG	9.3	9.4	9.2	158.2
	TOTAL	23.8	24.0	23.6	**404.4**
	ha^{-1}	0.0168	0.0169	0.0166	X
Judge+Judge-like	**AG**	89.1	90.6	88.0	1515.4
	BG	18.1	18.4	17.8	307.2
	TOTAL	107.2	109.0	105.8	**1822.6**
	ha^{-1}	0.0380	0.0386	0.0375	X
Sooke Lake Watershed	**AG**	75.6	124.6	14.2	3855.8
	BG	17.4	24.9	9.2	884.9
	TOTAL	93.0	149.6	23.6	**4740.7**
	ha^{-1}	0.0308	0.0386	0.0166	X

The average DOC flux from the terrestrial area of the SLW was 93.0 tC yr^{-1} (0.0308 tC ha^{-1} yr^{-1}) with 81% of that coming from the slow aboveground DOM pool. Assuming no C is respired to the atmosphere from within the lake, 4740.7 tC of terrestrially-sourced C was sequestered in lake sediment for the period 1996-2012.

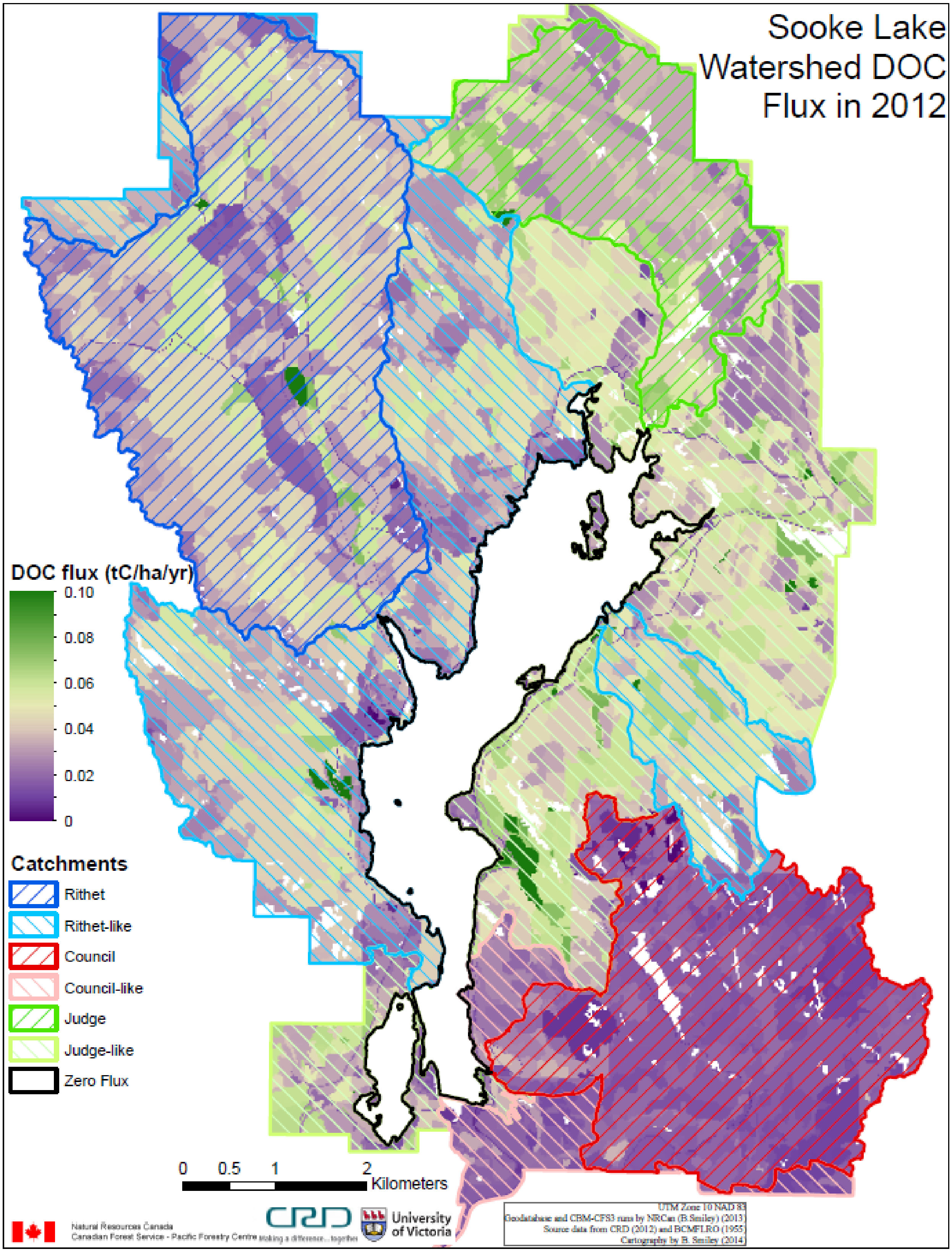

Figure 4-4 - Sooke Lake Watershed DOC flux in tonnes of carbon per ha in 2012 and catchment delineation

4–5.0 Discussion

Modelling the C exported from the terrestrial to the inland aquatic system on a watershed scale elucidates the potential for allochthonous C storage in lake sediment. Within the SLW, physiographic differences, specifically percent area of wetlands and lakes, forest cover age structure (Table 4-2), and size of slow above and belowground DOM pools are the primary terrestrial forces driving long term DOC export to fluvial systems (Table 4-3). The inundation of littoral wetlands areas due to reservoir raising events can have a significant impact on the nutrient loading within a lake, generally (Glazebrook & Robertson, 1999; Langhans & Tockner, 2005) and in Sooke Reservoir in particular (Das, et al., 2009). However, the impact of the 2002 reservoir raising on terrestrial to aquatic DOC transfers was not included in this study, and therefore DOC flux values may be an underestimate of the long term C storage of terrestrial C in the reservoir. The slow DOM pools and selected DOC transfer parameters capture well the trend and magnitude of long term DOC flux observed over the study period. Long term trends in DOC load increases have been observed in areas of western and northern Europe, most likely due to acid deposition histories resulting from industrial development (Evans, et al., 2005; de Wit, et al., 2007). For the 1996 to 2012 period in the SLW, no significant trend was observed (Figure 4-3).

The current configuration of the CBM-CFS3 does not include a mechanism to model the short term (1-5 years) event-driven spikes in DOC load due to effects of disturbance on stream DOC concentrations. On some forested landscapes hydrologic events (i.e. storms and snowmelt) can be the source of approximately 86% of terrestrially-derived DOC to the aquatic environment (Raymond & Saiers, 2010). If more mobile sources of DOM (i.e. litter) are available due to disturbances such as forest harvesting or wildfire then this terrestrially-sourced DOC will be magnified initially and then deplete. The addition of a DOC fraction parameter from another, more mobile C pool (i.e. the aboveground very fast DOM) or a transfer function built into the CBM-CFS3 disturbance matrices could improve the model's ability to simulate the short term DOC export that would occur after disturbance.

DOC fraction parameters must be tuned based on the physiographic and hydrological characteristics of the study area in question. These differences can impact DOC transfer even within a small geographic area, as made evident by the need for three different fraction parameters values within an 8595 ha watershed. The annualized DOC flux parameters selected for the three catchment types only represent a small fraction of the slow above and belowground DOM pools; however, accumulation over many years could impact the C sequestration expectations, and therefore the watershed-scale C budget (Raymond & Saiers, 2010).

Dean and Gorham (1998) estimated that on average, world reservoirs sequester 400g of C per square meter per year. As stated for the 16 year study period, 4740.7 tC were sequestered in lake sediment assuming no C was respired to the atmosphere from the Sooke Reservoir. While the question of DOC fate was beyond the scope of this study the final destination of terrestrially-sourced C is an important component of coupled terrestrial-inland aquatic modelling efforts. Average DOC concentrations within and leaving Sooke Reservoir were lower than those recorded for the three catchments (Sooke Reservoir: 2.43mgC/L; Judge: 5.67mgC/L; Rithet: 3.47mgC/L; Council: 3.43mgC/L). Because terrestrially-sourced C in lakes can be equal to or greater than aquatic Gross Primary Production (GPP) (Polis & Power, 2004), lakes are often considered to be net sources of C while continuing to sequester C in lake sediments (Cole, et al., 2007). Due to enhanced particle trapping, the initial years after reservoir raising have elevated rates of C burial (Cole, et al., 2007). In contrast to one large reservoir raising event, the Sooke

Reservoir has been raised three times over the last 100 years, therefore the potentially elevated C burial rates have been distributed over time.

The absence of consistent DOC measurements for the three gauged catchments was a hindrance to the accuracy of annual DOC load estimates. While continuous stream flow data were available for all study years, DOC concentration measurements were recorded from 1997 to 2008, only at irregular intervals. Stream DOC concentration data are extremely valuable when attempting to understand the terrestrial C balance implications of C export via fluvial systems. However, DOC concentration is also a useful measure of toxicity and bioavailability of trace metals such as mercury (Ravichandran, 2004), lead (Klaminder, et al., 2006), and copper (Ashworth & Alloway, 2007). DOC also controls water acidity (Aherne, et al., 2008) and can enhance bacterial production (de Wit, et al., 2007). There is a requirement for more consistent DOC measurement in the catchments that flow into the Sooke Reservoir, not just for DOC flux estimation but also as a water quality surrogate for reservoir inflow streams.

The Sooke Lake water supply area should be considered in both a climate change adaptation and mitigation context. Potential increases in the frequency and magnitude of rainfall events with a warming climate may result in increased DOC export to the Sooke Reservoir and this reinforces the need for more consistent DOC monitoring in order to inform adaptation strategies. Dore, et al. (2013) reported that precipitation patterns have changed since monitoring began in the SLW in 1914. The IPCC predicts that in the Pacific Northwest and Western Canada, the variance in seasonal precipitation will increase and temperatures will rise steadily over the next century (IPCC, 2014). Drier summer soils, changes in decomposition rates and more rapid, intense flushes of DOC through higher intensity rainfall events could have water quality implications. Regarding mitigation efforts, there may be potential to include the Sooke Reservoir as a long term C sink; however more research is needed to understand the contribution of allochthonous C into the reservoir. In response to warming conditions, Creed et al. (2014) found that water yields tended to increase in conifer-dominated catchments and decrease in deciduous dominated catchments. However young conifer forests appeared less adaptable to warming conditions compared to older stands and young mixed stands (Creed, et al., 2014). Relative to deciduous stands, the inability of conifer stands to quickly adapt to warming conditions could result in drought stress and subsequent mortality. Preserving forest type and age characteristics that influence hydrological resilience will need to be prioritized in future water supply management plans as recreating these ecosystems could prove exceedingly difficult.

4–6.0 Conclusion

Connecting terrestrial and inland aquatic environments in C budget modelling efforts is a challenging endeavour due to the complexity of the individual systems and the multifaceted linkages that bind them. This study is a preliminary approximation of potential C export from terrestrial systems via DOC. The three gauged catchments have undergone varying levels of disturbance over the last century that have likely influenced the long term DOC loads being exported into the Sooke Reservoir however, DOC measurements do not exist prior to 1997 to verify this. Understanding the role forest ecosystems play in the global C cycle and, more specifically, integrating the aquatic components of those landscapes into modelling efforts will enable a more accurate determination of anthropogenic impacts on the C cycle.

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Chapter 5 –Examination of the effects deforestation, forest management and DOC transfers have on the historical C budget

5–1.0 Introduction

Climate change mitigation require a global effort to reduce the amount of greenhouse gases in the atmosphere. These gases consist primarily of CO_2, methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Efforts to decrease atmospheric concentrations of CO_2 require both reductions of anthropogenic emissions and improved means of C sequestration. The potential of forests in Canada to be net C sinks, while highly variable in space and time (Stinson, et al., 2011), can be considered to have a role in climate change mitigation. In temperate and boreal forests, while the natural disturbance regime is a primary driver of the ecosystem C balance, forest management activities also have an impact (Pan, et al., 2011). If forest management practices are amended to include C sequestration, management practices can be optimized to allow for the forested land base to sequester and store more C than it would have otherwise (Smyth, et al., 2014). This can be accomplished through various management practices, including forest conservation in parks and protected areas (Sharma, et al., 2013), enhanced silviculture and harvest optimization (Smyth, et al., 2014) and longer term utilization of harvested wood products that can displace more C intensive products (Dymond, 2012). However, projected future changes in natural disturbance patterns call into question the effectiveness of existing forest management mechanisms to achieve C sequestration objectives (Kurz, et al., 2008).

The aquatic component of a watershed must also be considered when optimizing forest management for C sequestration. Globally, human use of the terrestrial land base has increased the transfer of C to inland aquatic systems by as much as 1.0 pentagrams of C per year (Regnier, et al., 2013). Accounting for the export of terrestrial C via fluvial systems is necessary when evaluating the effect forest management has on the C budget of a watershed. While small relative to the land-atmosphere exchange of C, the land-inland aquatic exchange of C may account for a significant proportion of C that is generally assumed to be respired to the atmosphere (Kurz, et al., 2009) or remain within land ecosystems (Billet, et al., 2004). C burial in lake sediment is also an important component of whole-watershed C budgets and has unique implications for watersheds managed for water supply (Mulholland & Elwood, 1982; Marce, et al., 2008).

Since 1910, the SLW has undergone several different management regimes in response to economic, demographic, environmental and social value drivers. Forest management activities that incorporate changes in harvest rates, utilization levels (harvest efficiency), silvicultural activity such as planting and augmented growth (e.g. fertilization) and harvest residue utilization can have a positive cumulative mitigation effect on a land base over a protracted period of time (Smyth, et al., 2014). Though the SLW was privately owned and primarily managed for water supply as opposed to timber production, common forest practice and provincial forest management objectives influenced how the water supply area was managed over time.

The BC Greenhouse Gas Reduction Targets Act (Bill 44), introduced in 2007, mandates all public sector organizations to achieve C neutrality by 2010 (Capital Regional District, 2008). Although this legislation does not explicitly include municipal governments and regional districts (Capital Regional District, 2008), the CRD has implemented a roadmap to achieve this goal and plans to incorporate C capture and climate change adaptation into an integrated watershed management strategy for the water supply areas (Capital Regional District, 2008, p. 20)). Also, using the forest area of the water supply area as a C sequestration tool was identified as a strategic priority for the CRD to achieve its C neutrality goals (Capital Regional District, 2012). Depending on the forest ecosystem, managing forests for conservation purposes often increases the C stocks on the land base; however, natural disturbance patterns can have a substantial impact on the C density (Sharma, et al., 2013). To investigate how different forest management practices impact the C budget of the SLW water supply area (Figure 1-3) business as usual forest management from 1910 to 2012 (referred to as the Baseline management regime) will be compared to two alternative management scenarios for the same period. This comparison will incorporate DOC as a C export mechanism by drawing on the DOC fraction parameterization described in Chapter 4 and apply it to the entire length of the study period for the Baseline and two alternative management scenarios. Examining the impact of C export via fluvial systems in the context of forest management is vital to understand the interaction between management decisions and DOC export and its implications for landscape level C budgets.

5–2.0 Methods

Unlike the majority (93%) of forest land in BC which is a crown (public) possession, the SLW and adjacent areas became private land as part of the Esquimalt and Nanaimo Railway land grant in 1884. In 1911, the GVWD took possession of roughly 77 % of the Sooke Lake/reservoir catchment, managing the land in accordance with its priorities, primarily for Greater Victoria’s water supply. Other areas inside the catchment of the Sooke Reservoir but outside of GVWD/CRD ownership fell under the management priorities of the forest companies that owned them, namely for timber supply. Specifically, Lot 87 in the northeast of the study area and the Council Lake catchment (Figure 1-3), owned by Kapoor Lumber Ltd. represented a significant contrast in management priorities over the course of the study period compared to the portion of the SLW owned by the CRD (see Chapter 1 Section 1–5.0 Study Area History). Due to the potential negative implications private lands within the watershed being managed without consideration for water quality, the CRD, through a combination of land exchanges and purchases eventually acquired the vast majority of these lands. Including the Council Lake drainage that is piped into Sooke Reservoir, approximately 98% of the area that drains into Sooke Reservoir is now under CRD ownership[31]. Because of the different tenure history of Lot 87 and the Council catchment, the alternative management scenarios presented in this comparison retain the historical Baseline management within these areas. Alternative management is only applied to areas that were owned and operated by the GVWD/CRD for the entire study period.

Two alternative management regimes were chosen to simulate the effect different management choices would have had on the C budget of the SLW over the last 100 years. The alternative management scenarios identified to compare to Baseline model runs for the SLW include:

- **Scenario #1 (SC1) – Water Supply without Deforestation or Forest Management** – No forest harvesting or reservoir raising (flooding) between 1910 and 2012 within the original ownership boundary (disturbances in Lot 87 and Kapoor land maintained)
- **Scenario #2 (SC2) – Water Supply without Forest Management –** Reservoirs are created and raised as in Baseline model runs, however, no forest harvesting occurs between 1910 and 2012 within the original ownership boundary (disturbances in Lot 87 and Kapoor land maintained)

For the purposes of a comparison of management regimes, areas that were not under CRD tenure for the entire study period (and thus not subject to CRD management decisions) maintained the

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[31] Deception Reservoir (adjacent to Sooke Reservoir) is not part of the Sooke water system as it drains into Sooke River downstream of Sooke dam. Areas that drain into Deception Reservoir, while included in C model simulations (see Figure 1-3), are not considered in relation to ownership of Sooke catchment areas.

existing management regime and thus only the area administered by the CRD for the entire study period (80% of study area) was modified.

Data from the Sooke Forest cover-Disturbance geodataset dataset was modified to be consistent with the identified alternative management scenarios. SC1 exemplifies a scenario where the SLW was preserved for supplying drinking water to Greater Victoria and the demand for water resources could be completely supplied by the volume available in the original Sooke Lake. In this case, there is no need to expand the holding capacity of the reservoir above the original lake levels. Consequently, no logging occurs within the CRD tenure as the income from harvested wood products is not necessary to offset the cost of reservoir-expanding capital projects. Some disturbances that had occurred between 1910 and 2012 were preserved within the ownership of the CRD such as natural disturbances including wildfire and insect outbreaks, transportation corridor clearing for railway, access road and transmission line right-of-ways and escaped fires from adjacent lands.

For SC2, observed changes in reservoirs to meet water demand are maintained, resulting in reservoir creation and expansion. However, the capital projects necessary for the reservoir raising, including land clearing, engineering and dam construction, are assumed not financed by logging activity within the watershed, and therefore these disturbances do not take place. This management regime mimics that which has been in place since the mid-1990s whereby population increases in Greater Victoria have occurred (and are incorporated into future plans) but forestry activity within the water supply area is not permitted. As in SC1, natural disturbances, main transportation corridors and disturbances from escaped fires from adjacent lands were preserved within the tenure of the CRD.

The DOC fraction parameters established using data from the SLW for the period 1996-2012 and described in Chapter 4 serve as a basis for estimating the amount of C being exported from the land base via fluvial processes. Annual DOC load for the period was derived using [DOC] and stream flow data for the Rithet, Judge and Council creeks, the only consistently gauged catchments within the SLW. Using the mean per ha DOC load for the period, a sensitivity analysis was performed to develop the DOC transfer parameters required for the DOC export from the CBM-CFS3 slow aboveground and belowground DOM pools[32] to match the observed values from the three catchments. Allocating the parameters of gauged catchments to ungauged catchments was based on the work of Werner (2007) who used physiographic and hydrologic similarities of the Sooke catchments to scale up to the watershed level of analysis. The three unique transfer parameters derived for Rithet-, Council- and Judge-like catchments (0.945, 0.975, and 0.935, respectively[33]) were applied to the slow aboveground pool for the years 1910 to 2012. The transfer parameter from the slow belowground pool remained constant between the three catchments (0.99).

The modified Forest cover-Disturbance geodatasets that corresponded to the alternative management scenarios were subsequently run through Recliner and CBM-CFS3 (see Chapter 3 Section 3–4.1 Methods) to generate C stock and flux values for the study area. As SC1 and SC2 included the removal of disturbance and deforestation events, many areas that had transition to a different, managed growth curve post-disturbance in the Baseline scenario remained as unmanaged forest. Removal of disturbance and replanting events that had occurred in the

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[32] These are the only two CBM-CFS3 pools that allow for DOC export. The transfer parameter is a fraction of the release of carbon to the atmosphere and the release of carbon to DOC, where the default values dictate 100% of decay from the slow aboveground and belowground pools is released to the atmosphere.

[33] i.e. 94.5% of the decay from the slow aboveground pool is released to the atmosphere, 5.5% is exported as DOC.

Baseline run consequently resulted in stand species, age and growth characteristics being maintained until either another disturbance event impacted the stand or the end of the simulation.

5–3.0 Results

Without any large scale deforestation events on CRD-owned lands, the forested area in SC1 remained relatively stable over the study period (Figure 5-1). The proportion of non-forest areas occupied by Sooke Lake/Reservoir is almost equal to that of all other non-forest areas combined in 2012. In the Baseline and SC2 scenarios there is an almost 60/40 split between areas of reservoir/lake and all other non-forest areas (Table 5-1). While there is less than a 50 ha difference between the Baseline and SC2 management regimes, the deforestation that results from expanding the reservoir results in just over 540 ha more forest land in SC1 compared to the Baseline and SC2 scenarios.

Table 5-1 - Area of Analysis Units and non-forest in 1910 and Baseline, Scenario 1 and Scenario 2 in 2012

Analysis Unit	Description	Area in 1910 (ha)	Area in 2012 (ha)		
			Baseline	SC1	SC2
Productive Forested land					
1	Fir	5371	4326	5209	4830
2	Fir-Cedar	1048	760	938	964
3	Fir-Hemlock/Grand fir/Sitka Spruce	1097	1479	1182	1075
4	Fir-Alder/maple/poplar/arbutus	9	357	75	57
5	Cedar leading with conifer mix	35	48	61	55
6	Hemlock	5	6	11	6
7	Hemlock-Fir	217	247	276	258
8	Hemlock-Cedar	33	34	34	43
9	Broadleaf greater than 75% composition	8	20	33	34
10	Alder-Conifer Mix	18	13	14	14
	Total	**7841**	**7290**	**7833**	**7336**
Non-forest land					
	Sooke Lake/Reservoir	373 (49%)	813 (62%)	373 (49%)	813 (65%)
	Other Un-established/Non-forest land	382 (51%)	492 (38%)	389 (51%)	446 (35%)
	Total	**754**	**1305***	**762**	**1259**
* 80% of the change in non-forest land is due to reservoir creation, the remainder is from road/railway creation, etc.					

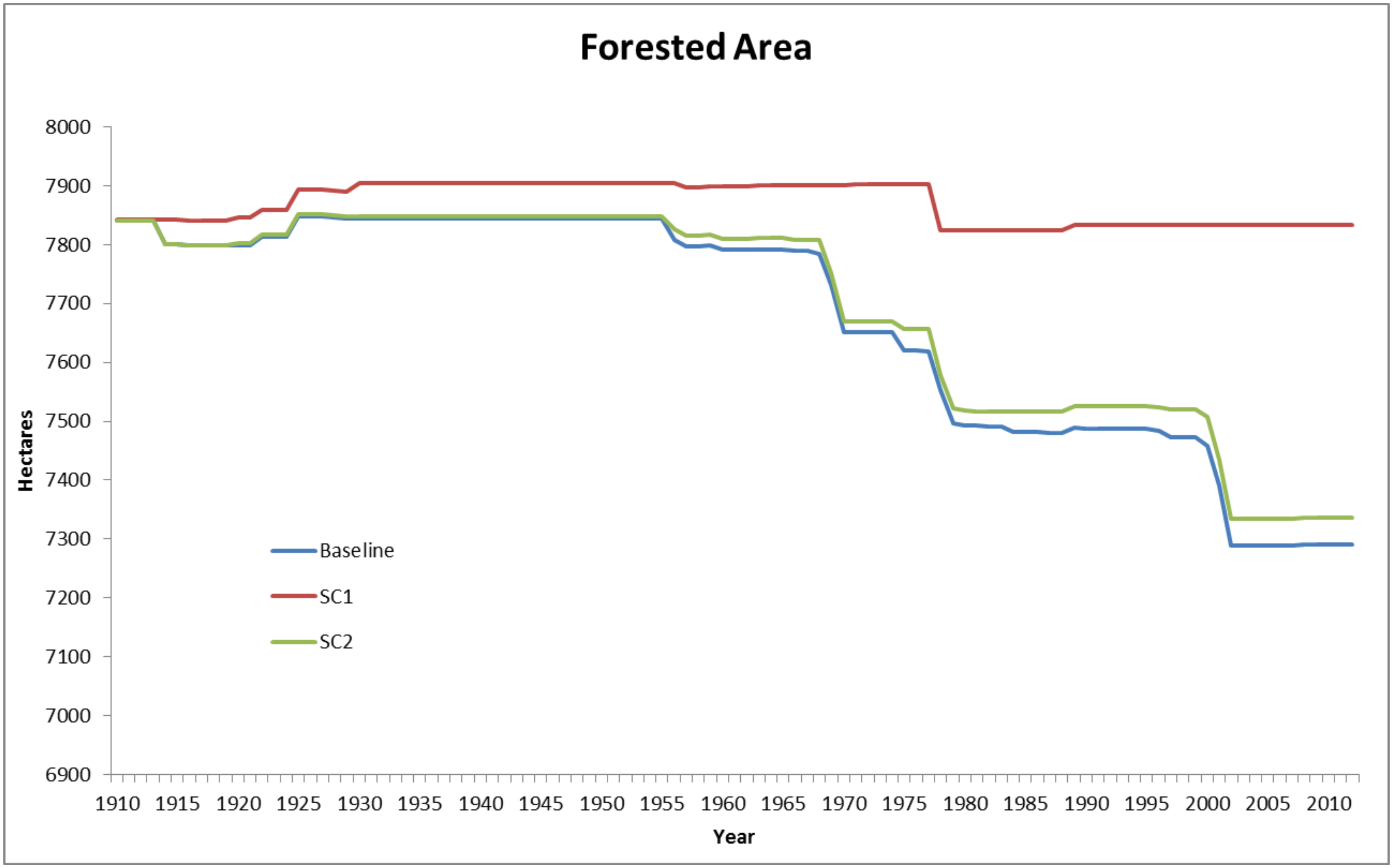

Figure 5-1 - Forested Area in Baseline, Scenario 1 and Scenario 2 management regimes

Area disturbed and disturbance type are the defining differences between the three management scenarios. Except for deforestation from the initial reservoir raising in the Baseline and SC2, the first 45 years of the study period exhibit almost identical disturbance patterns (Figure 5-2). This is not surprising considering the vast majority of the disturbances over this time frame occurred outside original CRD ownership. However, after 1955 the area clearcut, clearcut and residue burned and thinning events varies significantly among the three management regimes. These disturbance patterns had a resulting influence on the forest age class structure in 2012. Both SC1 (4360 ha) and SC2 (3947 ha) had considerably more forest older than 200 years that the Baseline management scenario (2057 ha) (Figure 5-3). In 2012 over 3500 ha were less than 80 years old in the Baseline scenario versus only 1306 ha and 1472 ha for SC1 and SC2, respectively.

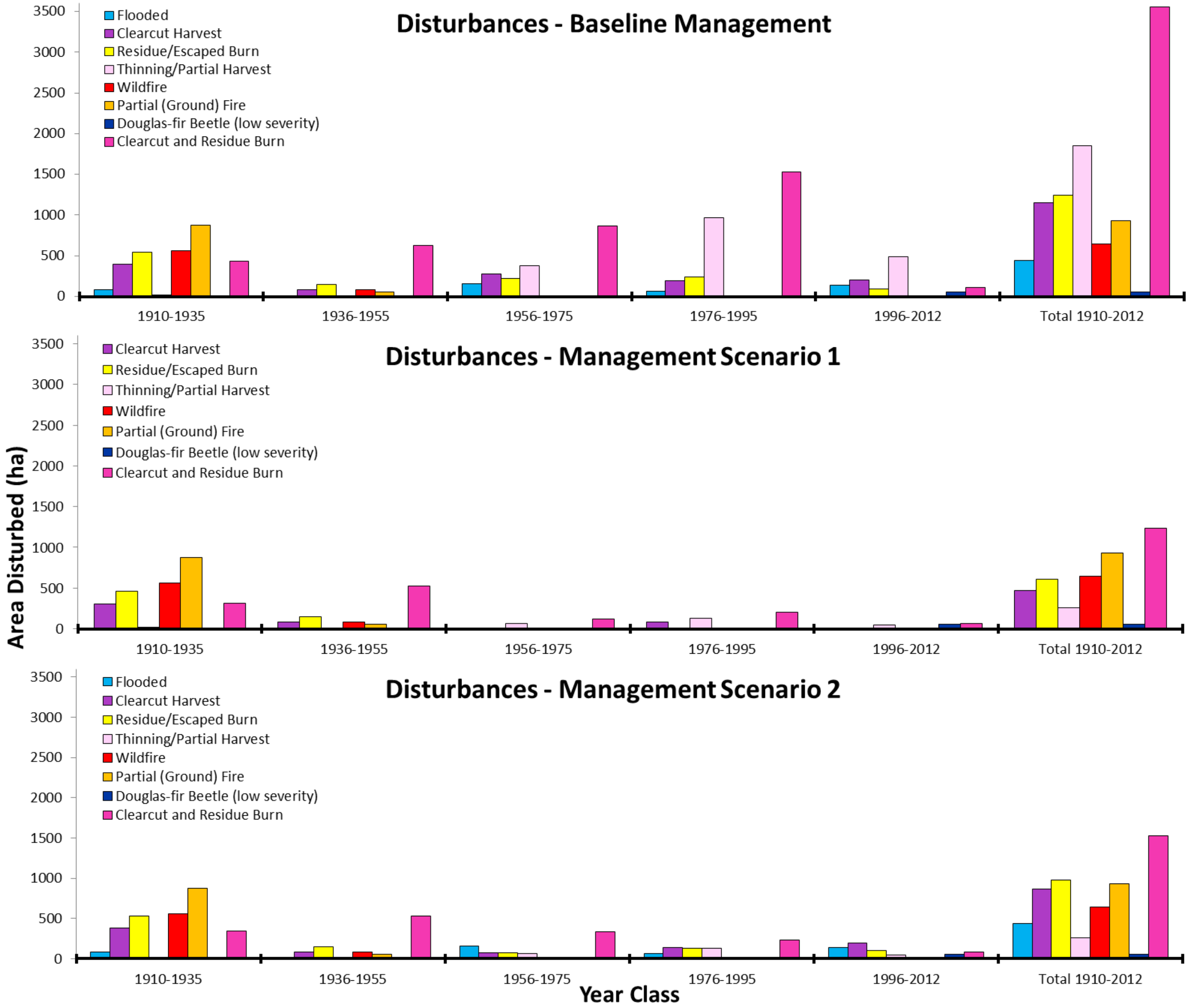

Figure 5-2 - Disturbances by period for Baseline, Scenario 1 and Scenario 2 management regimes

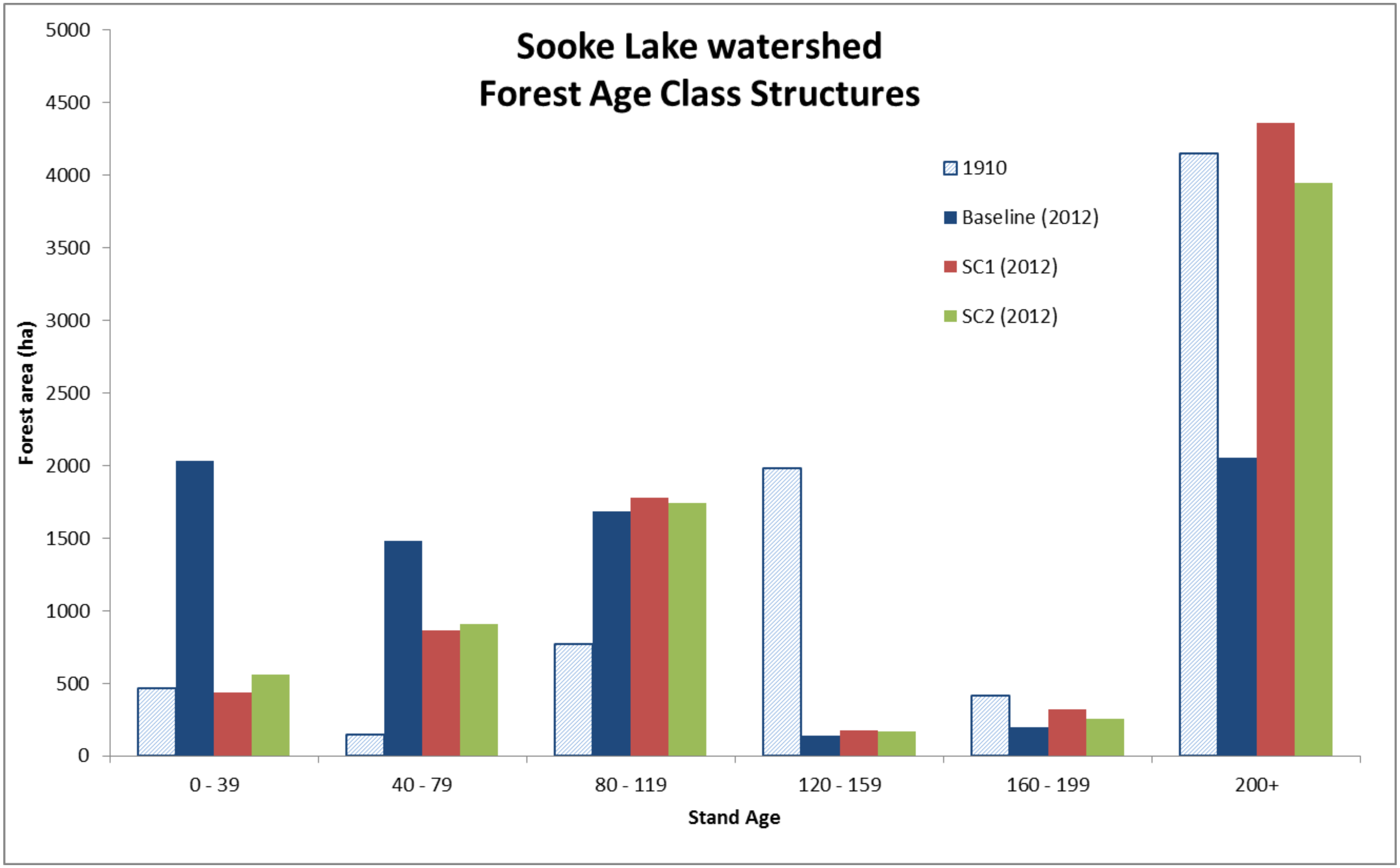

Figure 5-3 - Forest age class structures in 1910 and 2012 for Baseline, Scenario 1 and Scenario 2 management regimes

C stocks of live biomass (aboveground and belowground), detritus (litter and deadwood) and soil C were compared among the three management scenarios. Because of the inherent stability of the soil C pools, differences due to altered forest management regimes were minimal over the study period (Figure 5-4), ranging between 2.8 and 3.1 tC ha^{-1} by 2012 (Table 5-2).

Table 5-2 - Baseline, Scenario 1 and Scenario 2 carbon stocks and fluxes as of 2012

Flux/Pool		**Management Scenarios**		
		Baseline	**Scenario 1**	**Scenario 2**
Cumulative NBP (tC ha^{-1})	No DOC Export	-146.2	-39.4	-53.4
	DOC Export	-142.4	-35.2	-49.4
Carbon Stocks (tC ha^{-1})	Live Biomass	217.4	296.1	282.0
	Detritus	127.8	153.9	152.9
	Soil C	207.1	209.9	210.2
Cumulative DOC Export (tC ha^{-1})	Aboveground Slow	3.2	3.4	3.3
	Belowground Slow	0.7	0.7	0.7
	Total	3.9	4.1	4.0
Total DOC Export (tC ha^{-1}) (1910-2012)		30657.2	32819.5	32047.2
Total HWP Export (tC ha^{-1}) (1910-2012)		882746.2	354247.0	475183.9

Detritus stocks exhibited more pronounced differences, with SC2 and SC1 accumulating approximately 25.1 and 26.0 tC ha^{-1} more by 2012 than the Baseline scenario (Table 5-2). The differences became evident after the early 1960s; after which point, abrupt spikes in detritus accumulation during reservoir raising events were evident in the Baseline and SC2 management scenarios (Figure 5-4). Live biomass stocks in all three management scenarios began to recover after 1940 from a low between 231.0 tC ha^{-1} (Baseline) and 240.0 tC ha^{-1} (SC1) (Figure 5-4). However, by the mid-1950s, the recovery in stocks began to diverge, with SC1 and SC2 continuing to accumulate biomass whereas a continual decline was observed for the Baseline scenario until the early-1990s. In 1991 the C deficit exhibited by the Baseline relative to the SC1 and SC2 alternative management scenarios reached a high of 93.5 tC ha^{-1} and 83.5 tC ha^{-1}, respectively. Since then, this gap has been narrowed (Table 5-2). Net Biome Production (NBP) describes the overall ecosystem C exchange of a landscape over multi-decadal time spans (Chapin, et al., 2006), including the release/removal of C due to disturbances (Kurz, et al., 2009). Figure 5-5 shows the cumulative NBP (ΣNBP) of the three management regimes and the influence that including DOC as a C export mechanism has on the C budget over the 100-year study period.

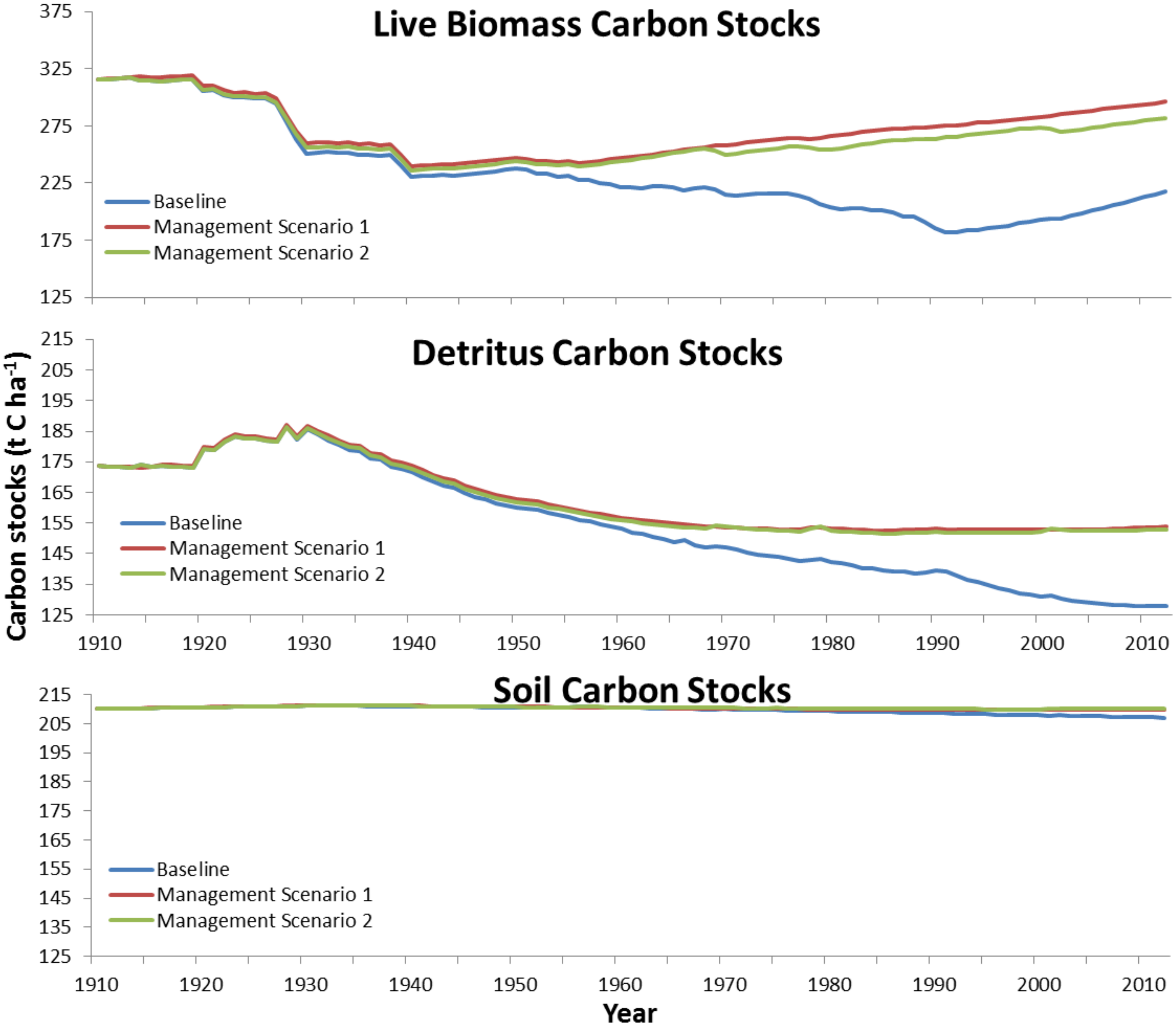

Figure 5-4 - Carbon stocks between 1910 and 2012 for Baseline, Scenario 1 and Scenario 2 management regimes

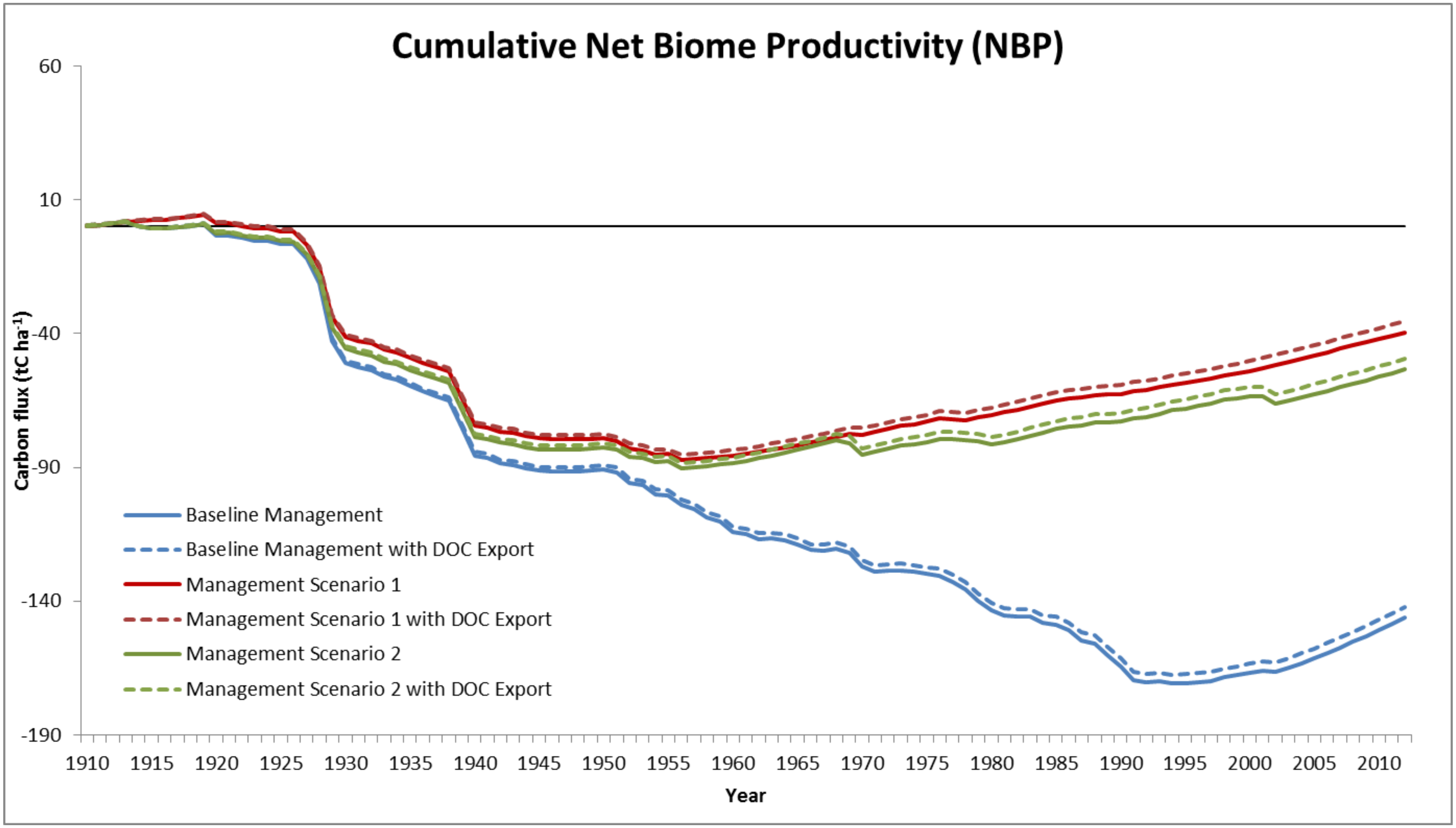

Figure 5-5 - Cumulative Net Biome Productivity with and without DOC as a carbon export mechanism

In the first 15 years of the simulation ΣNBP remained approximately C neutral in all three scenarios. In areas outside CRD tenure, the large scale removal of live biomass C through harvested wood products and release to the atmosphere from slash burning resulted in a watershed-wide decline to -98.7 (Baseline), -83.2 (SC1), and -85.8 (SC2) tC ha^{-1} in 1955 when including DOC export (ΣNBP^{DOC}). All scenarios were approximately 2.0 tC ha^{-1} lower without DOC as a C export mechanism. ΣNBP^{DOC} of the alternative management scenarios began to recover after 1955, whereas the Baseline management continued a negative trajectory. ΣNBP^{DOC} of SC1 and SC2 remained within approximately 10.0 tC ha^{-1} until the mid-1960s when SC2 experienced successive clearing and reservoir expansion deforestation events in 1970, 1980 and 2002 both increasing exports of C, and reducing the watershed's ability to recover biomass. ΣNBP^{DOC} for the Baseline scenario began to recover in 1994 from a low of -167.4 tC ha^{-1} (-170.7 tC ha^{-1} ΣNBP) to its current (2012) level of -142.4 tC ha^{-1} (-146.2 tC ha^{-1} ΣNBP). In contrast, SC1 did not decline below -85.0 tC ha^{-1} (1956) and recovered to -35.4 tC ha^{-1} by 2012. ΣNBP^{DOC} for SC2 was also at its lowest point in 1956 (-88.5 tC ha^{-1}). While deforestation events did temper the management regime's ability to recoup losses earlier in the century, ΣNBP^{DOC} had increased to -49.4 tC ha^{-1} by 2012. Not unexpectedly, total HWP export for the study period decreased between 46% and 60% in SC2 and SC1, respectively, from the Baseline watershed total of 882,746.2 tC (Table 5-2). The higher tonnage of exported HWP in SC2 was due to activities related to reservoir creation, expansion and access (such as road building).

Cumulative DOC (ΣDOC) export was greatest in SC1 (4.1 tC ha^{-1}) (Table 5-2) as the DOM stocks which feed DOC export in the model increased as forests aged. As well, the lack of deforestation for reservoir raising meant DOM stocks that were removed from the land base in the Baseline and SC2 management regimes were maintained and continued to decay and release

DOC in SC1. In the Baseline scenario, assuming none of the exported terrestrial DOC was respired to CO_2, over 102 years up to 30657.2 tC may have been sequestered in lake sediment. This Baseline value is 2162.4 tC less than that modelled for the SC1 and 1390.0 tC less than SC2 over the study period.

5–4.0 Discussion

The alternative management scenarios presented in this study allow for the quantification and direct comparison of different land management decisions and the resultant effect those decisions have on the C budget of a land base over an extended timeframe. SC1 represents a management regime where decisions leading to both reservoir creation and sustained yield forestry in the SLW were absent. By comparing SC1 with SC2 (which includes deforestation due to reservoir creation but not sustained yield forestry activity) the C budget consequences of these deforestation events can be investigated. Figure 5-5 demonstrates the stepped effect multiple reservoir raisings had on ΣNBP over the 100-year study period. On a watershed scale, the impact of deforestation resulted in a cumulative decrease of approximately 14.0 tC ha^{-1} by 2012[34], equivalent to 111,217.3 tC less being sequestered in the watershed. In contrast, sustained yield forestry activity within the CRD's tenure accounts for a 93.0 tC ha^{-1} difference in ΣNBP by 2012[35]. This shows that while deforestation due to reservoir creation removes biomass stocks and prohibits any forest sequestration from occurring on those lands again, the recurring removal of aboveground stocks in the form of harvested wood products had a substantially greater impact on

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[34] This is a comparison of SC1 with SC2 ΣNBP where neither scenario experiences forest management within the CRD ownership and the only difference is the presence of reservoir-related deforestation in SC2

[35] This is a comparison of SC2 with the baseline management ΣNBP where both scenarios experiences reservoir-related deforestation and the only difference is the absence of sustained yield forestry (forest management) in SC2 within the CRD ownership.

the C budget than did reservoir creation over the course of the study period. That said, the removal of C from the SLW during forestry operations is partially offset by renewed sequestration after stand reestablishment and the increased rate of growth in areas that have been converted from unmanaged old growth to managed forest after planting.

5–4.1 Harvested Wood Products

As per IPCC guidelines, the current assumption within CBM-CFS3 regarding HWP is that C exported as wood products is immediately released to the atmosphere as CO_2 at the time of harvest (IPCC, 1996). Caren Dymond, in collaboration with the C Accounting Team of the Canadian Forest Service developed a HWP model that runs within the framework of the CBM-CFS3 C pool and flow capabilities (CBMF-HWP). The HWP software models the C storage of wood products post-harvest by simulating primary milling, construction and secondary manufacturing, retirement from material in-use, and disposal and decay of forest products. Dymond (2012) applied this model for British Columbia (BC-HWPv1) with residency and disposal parameters unique to historic (1965-present) and future (present-2065) HWP utilization patterns. Input C is divided into lumber, chips, plywood, and panel mills; throughout manufacturing, different proportions of the C enter the combustion stage, as well as dump and landfill pools. Once considered “in-use”, the C is stored between 2 and 90 years, depending on the half-live of the pool (single family homes being the longest and shipping products being the shortest) (Dymond, 2012). Considering current harvest rotation ages of less than 50 years in managed forests (Trofymow, et al., 2008), the residency time of C in manufactured products could in fact be longer than that sequestered in managed forests. Once the wood product reaches the end of its half-life the C can either be transferred to a landfill pool or redirected to the combustion process. Dymond (2012) concluded that if residency of C in long-lived wood products were taken into account in the forest C budget for British Columbia, cumulative emissions over 100 years would be 11% lower than what are reported using current accounting rules. BC forest practices regarding HWP utilization have changed significantly over the last century (Dymond, 2012).

Unaccounted for in the SLW historical C budget is the C storage potential of the HWP exported from the study area. If HWP, specifically long-lived products such as structural wood used in single and multi-family homes were incorporated into the SLW C budget, the cumulative effect on emissions would be significant over the 100-year period. Including HWP in the C budget would have the largest impact on the Baseline scenario due to the extensive forestry activities inside the CRD ownership (Table 5-2). It would also modify the emissions observed in SC2 as logging and land clearing for reservoir creation in many ways mimics the disturbance matrix of forest harvest (Kurz, et al., 2009) producing HWP. Dymond (2012) investigated the impact of including HWP on the forest C budget in BC dating back to 1965; however, little work has been done to document HWP half-lives, product consumption patterns or life cycle dynamics in BC prior to 1965. As harvesting and forest clearing activities in the SLW date back to the mid-1910s, incorporating HWP into the Baseline and alternative management scenarios would require an investigation of HWP use during this period on Vancouver Island to minimize the uncertainty in HWP parameters.

5–4.2 Carbon Storage Mechanisms for Climate Change Mitigation

Following British Columbia Ministry of Environment (2011) guidelines for C stored in HWP, Man et al. (2013) explored two general forest management methods for increasing C sequestration and found that strategies that reduced harvest levels had greater C sequestration benefits than strategies that increased growth. For different ecosystems, and different scales of analysis a mix of forest management techniques is more likely to optimize forest C sequestration (Smyth, et al., 2014). In the SLW, the harvest reduction strategy exhibited in SC2 whereby the CRD-owned land becomes a reserve shows a stark increase in C stored in biomass pools in comparison with the Baseline. This occurs even without the added C storage benefit of HWP. However, using a forest reserve strategy whereby an area is removed from the harvesting land base can potentially have detrimental impacts on ecosystem C storage if unforeseen natural disturbances impact forest biomass, or climate change impacts on decay rates are not taken into account. In their case study Man, et al. (2013) found that if forest mortality increased by 25% in the reserve areas that C storage was actually reduced for part of the study period compared to the baseline and remained less than the baseline for the remainder of the 100-year study period if mortality increased to 50%. If climate change mitigation is to be integrated into the Sooke water supply area management plan then a fixed harvest level strategy should be considered for areas that succumb to natural disturbance as to avoid an overall reduction in C stored in watershed forests.

In 2012 the CRD commissioned a feasibility study of C offset projects on select land parcels where the existing management regime could allow for C credits to be granted (Living Carbon Investments Inc., 2012). Using available data, a simplified timber supply review and C accounting approach was performed to assess the potential for creditable C on these CRD properties. In their preliminary study several assumptions were made regarding the data used to estimate both Baseline and project scenario C budgets. The negligible effect of detrital C pools that include standing dead trees, coarse woody debris and litter, the application of Western Forest Products Analysis Units, stand volumes and broad site classes and the accuracy of VRI attributes given minimal field sampling were among these assumptions. On three of the four properties considered, improved forest management[36] was the preferred method for generating C credits (compared to avoided deforestation or afforestation/reforestation) based on a balance of project eligibility, risk and financial opportunity for the CRD. If sustained yield forestry would have continued after the mid-1990s the Sooke water supply area in its entirety could have been considered for accreditation based on improved forest management by reducing harvest levels and this management goal would have aligned with other CRD goals of water quality and habitat preservation. However, as the decision to cease harvest activity occurred prior to the introduction of C accounting legislation, this avenue was never pursued and is no longer a possibility. Other options exists for improved forest management for the SLW that include reduced emissions through minimizing natural disturbance, removal and thinning of diseased and supressed trees (Man, et al., 2013), managing competing brush and selecting long-lived HWP for the timber that is removed from the watershed (British Columbia Ministry of Environment, 2011).

5–4.3 Integration of Carbon Pools from Deforested lands

As CBM-CFS3 is a forest-centric C budget model, integrating other watershed components can be problematic. Investigating the impact deforestation due to reservoir creation has on the C budget of the SLW requires that the land area deforested and modelled in the Baseline and SC2 management regimes be included in order to preserve the same modelled land base in all scenarios. How CBM-CFS3 deals with areas deforested for reservoir flooding has an impact on the comparison between scenarios where deforestation does and does not take place. Deforestation due to reservoir creation disturbance matrices remove all biomass as would be done in other land-clearing disturbance types, but otherwise leaves DOM pools intact (Kurz, et

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[36] The study defines Improved Forest Management as efforts made to retain more carbon in the forest through changes in harvest, planting and management of a working forest.

al., 2009). In accordance with IPCC guidelines regarding accounting for C during deforestation events, the remaining C is transferred to the new land cover class (IPCC, 2003). The current version of CBM-CFS3 is not designed to estimate post-disturbance stocks and stock changes in deforested areas, specifically in flooded areas where the mechanisms for DOM decay differ in a submerged environment (Kurz, et al., 2009). Hence, when only the ‘forest remaining forest’ land cover class is modelled, the DOM stocks of a flooded area are transitioned out of the forested land base. This represents a substantial and abrupt C stock removal which does not allow for a valid study area-wide per ha comparison between different management scenarios. An alternative to this approach is to allow the stock and stock changes to persist within the simulations. While no live biomass is accumulating, DOM pools would continue to decay at the default CBM-CFS3 rates. Due to CBM-CFS3 limitations, the assumption that DOM pools continue to decay at the same rate as non-flooded land is unfounded. In a tropical setting, Galy-Lacaux et al. (1997) found that approximately 10% of flooded C (biomass and DOM) was released in gaseous form within the first two years of flooding. Conversely, reservoirs in boreal ecosystems can continue to emit C 70 years after construction. In the case of La Grande reservoir in northern Quebec, 31.3 x 10^{12} grams of C could be released from flooded soils over 100 years (Weissenberger, et al., 2010). Total area flooded and wetlands area flooded has a significant effect on the amount of GHGs (CO_2, CH_4) released to the atmosphere post-reservoir-raising (Kelly, et al., 1997). Without any knowledge of the decay rate of DOM stocks (and release to the atmosphere) on flooded land, the C flux for flooded areas post-disturbance were assumed to be null. To preserve the cross scenario comparison, the DOM stocks of deforested land were frozen at the time the land became deforested, thus preserving the C that resided in the DOM stocks in the simulated land base but eliminating the decay that would have resulted from these submerged pools being included in the simulation post-disturbance. This method of preserving deforested DOM C across different management scenarios enabled a valid cross-scenario comparison of post-deforestation C stocks as of 2012 (Figure 5-6). Different management pathways have a considerable impact on forest C biomass and DOM stocks, especially when these management decisions are compared over decadal time spans. Current C credit legislation dictates that C credits may not be granted unless the atmospheric effect of the C removals endures for a minimum of 100 years (British Columbia Ministry of Environment, 2011). This requires that the effects of management decision must be considered, at minimum, on a multi-decadal scale. The comparison of SC1 and SC2 with the 100-year Baseline C budget of the SLW enables the C budget effect of the specific management decisions that led to deforestation for reservoir creation as well as sustained forest harvest to be quantified. Also, the Baseline C budget allows for future extrapolation of C stocks and C fluxes. CBM-CFS3 does not integrate the potential effects of climate change into growth, decay or decomposition rates; however work is progressing to investigate the effects climate change may have (Metsaranta, et al., 2011). As this is a retrospective C budget, changing growth and decomposition dynamics observed in the Pacific Northwest over the 20th century (Boisvenue & Running, 2006) could be integrated to test CBM-CFS3's ability to model the effects of climate change on forest ecosystem C budgets and extrapolate future repercussions on similar watersheds.

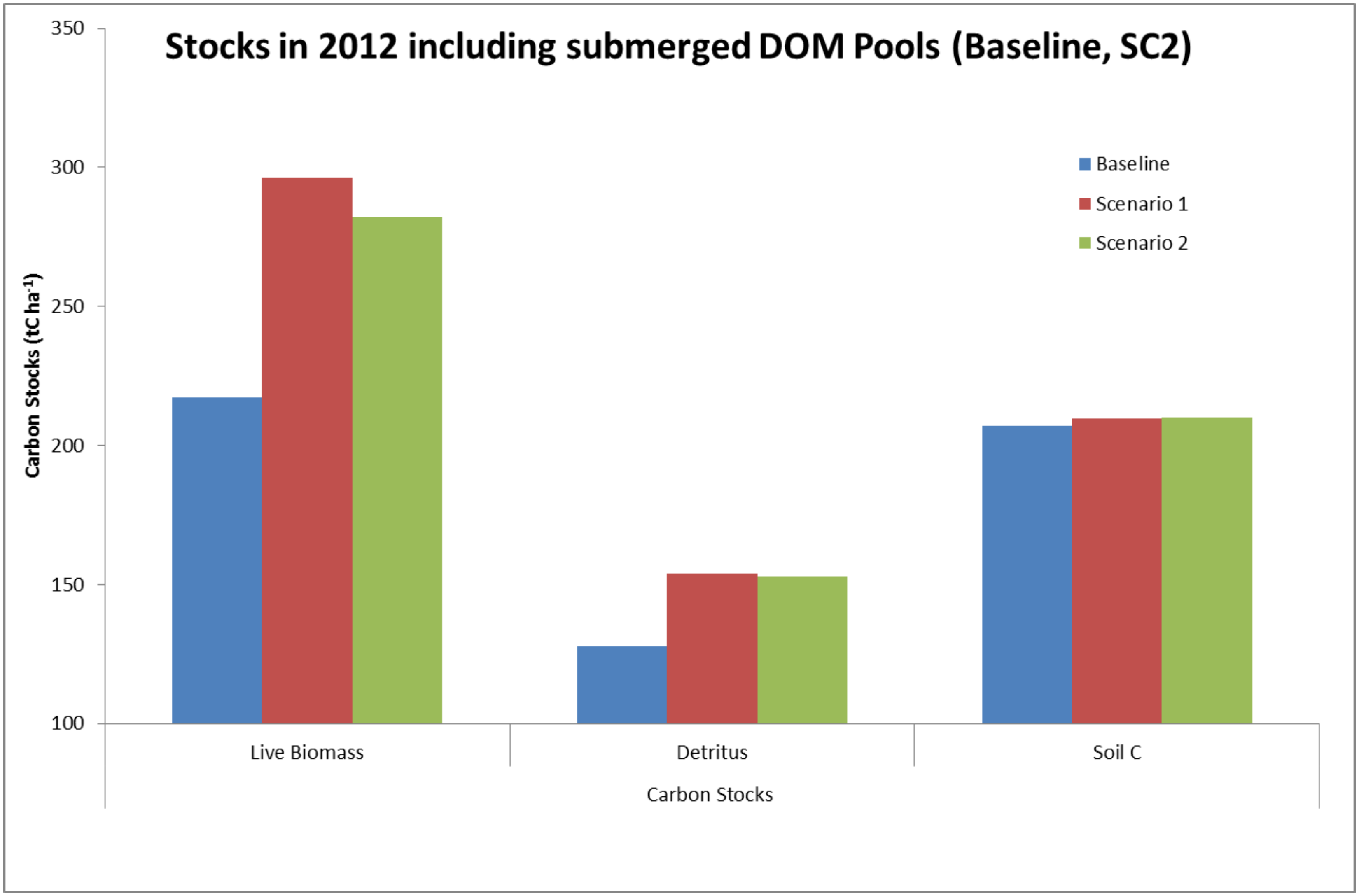

Figure 5-6 - Baseline and Alternative Management Scenario Carbon stocks in 2012

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Chapter 6 – Conclusion and Projections

Since 1910, the SLW has experienced considerable natural and anthropogenic disturbance that has altered the C stocks and C sink potential. The changes have been spatially distributed throughout the watershed; however, certain areas have experienced more concentrated disturbances, including lands adjacent to Sooke Lake and forest areas previously owned by forest companies. Management practices within the GVWSA have mainly focused on providing a consistent quality and quantity of water to residents of the CRD; a population that has expanded markedly over the 20th century (Capital Regional District, 2006). Transforming management priorities over time and purchasing lands from adjacent land holders within the Sooke Lake drainage have also affected the ability of the SLW as a whole to sequester and store C. The implications of past management decisions on forest C uptake in the Sooke water supply area is of considerable interest because it presents the current trajectory of C sequestration rates and allows decision makers to make site-specific, informed choices on future management practices to optimize C storage.

The SLW retrospective C budget has enabled a comparison of past management decisions on the Baseline scenario C stocks and fluxes. The distinctive Baseline management priorities and the recurring deforestation events due to reservoir creation and expansion presented a unique case study to examine the effect these decisions have on the C budget of an entire watershed over an extensive time period. SC1 estimates the management effects where the need for reservoir expansion and sustained yield forestry is absent, while SC2 retained the impact of recurring reservoir raising but without the sustained forestry seen in the Baseline scenario. The comparison of the three C budget scenarios over the 1910-2012 study period revealed that while deforestation through reservoir creation and recurring expansion did have a measureable impact on the watershed scale C budget as a whole, the overall impact was minimal, relative to the effect of half a century of sustained yield forestry activity.

6–1.0 Dissolved Organic Carbon in CBM-CFS3

An initial effort to integrate DOC export from the terrestrial system to the inland aquatic system demonstrated the magnitude of what this flux may be using a forestry-centric C model in a coupled system. As CBM-CFS3 has not been utilized in this manner previously, this research has clarified and utilized the mechanisms within the model's structure to estimate this seldom considered C transfer pathway. The DOC export parameters for Judge (6.5%) Rithet (5.5%) and Council (2.5%) catchment types developed in Chapter 4 enabled the cumulative effect of DOC export over the Baseline 100-year study period to be calculated (Figure 6-1). ΣNBP was 11%, 8% and 3% higher in SC1, SC2, and the Baseline scenario, respectively by 2012 compared to when DOC was not included as an export and potential sequestration mechanism. Both the sustained logging activity that slowed the accumulation of C in the DOM pools as well as reservoir related deforestation contributed to the differences, as the DOM stocks in flooded areas cease to exhibit a DOC flux once submerged.

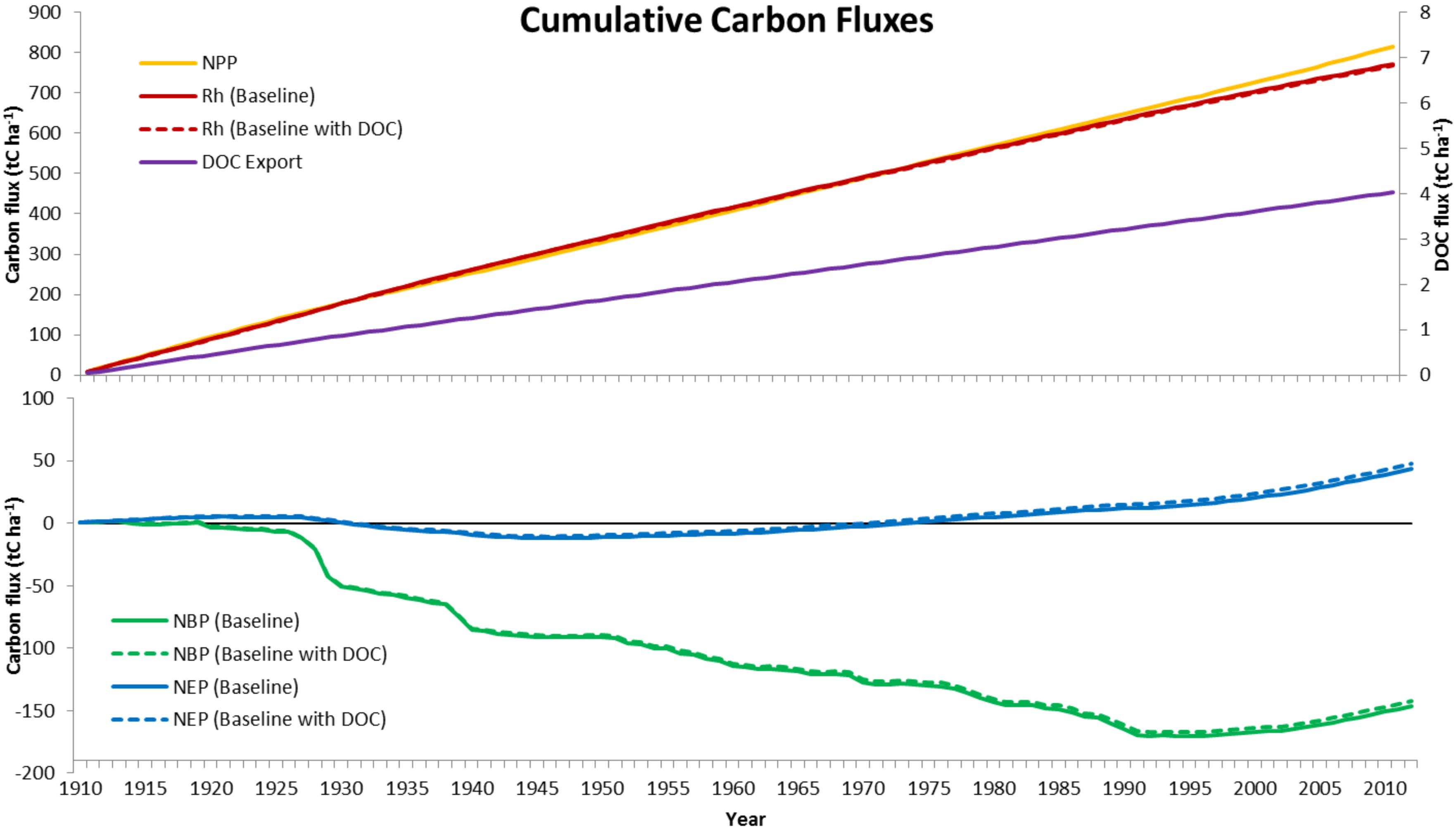

Figure 6-1 - Cumulative fluxes (1910-2012) with and without DOC export (NPP=Net Primary Productivity; Rh=Decomposition Releases; DOC=Dissolved Organic Carbon; NBP=Net Biome Productivity; NEP=Net Ecosystem Productivity)

Because of the relative stability of the slow DOM pools from which the DOC fraction parameter controls C export, and the absence of a more dynamic pool to export C from in the current model setup (e.g. aboveground very fast DOM pool), the expected post-disturbance response of DOC export was challenging to emulate. However, the current configuration does well to approximate post-disturbance effects on DOC export. For disturbances such as the large clear-cut and slash-burn events of the late 1920s in the Judge catchment, 62% of the aboveground slow DOM pool is exported to the atmosphere, the effects of which are observed through the significant drop in DOC export (Figure 6-2). Yet, over the next 12 years, DOC export increased by almost 7% due to higher transfers from aboveground slow DOM-donating pools (aboveground fast, very fast and medium) (Figure 4-1) that had increased in size post-disturbance.

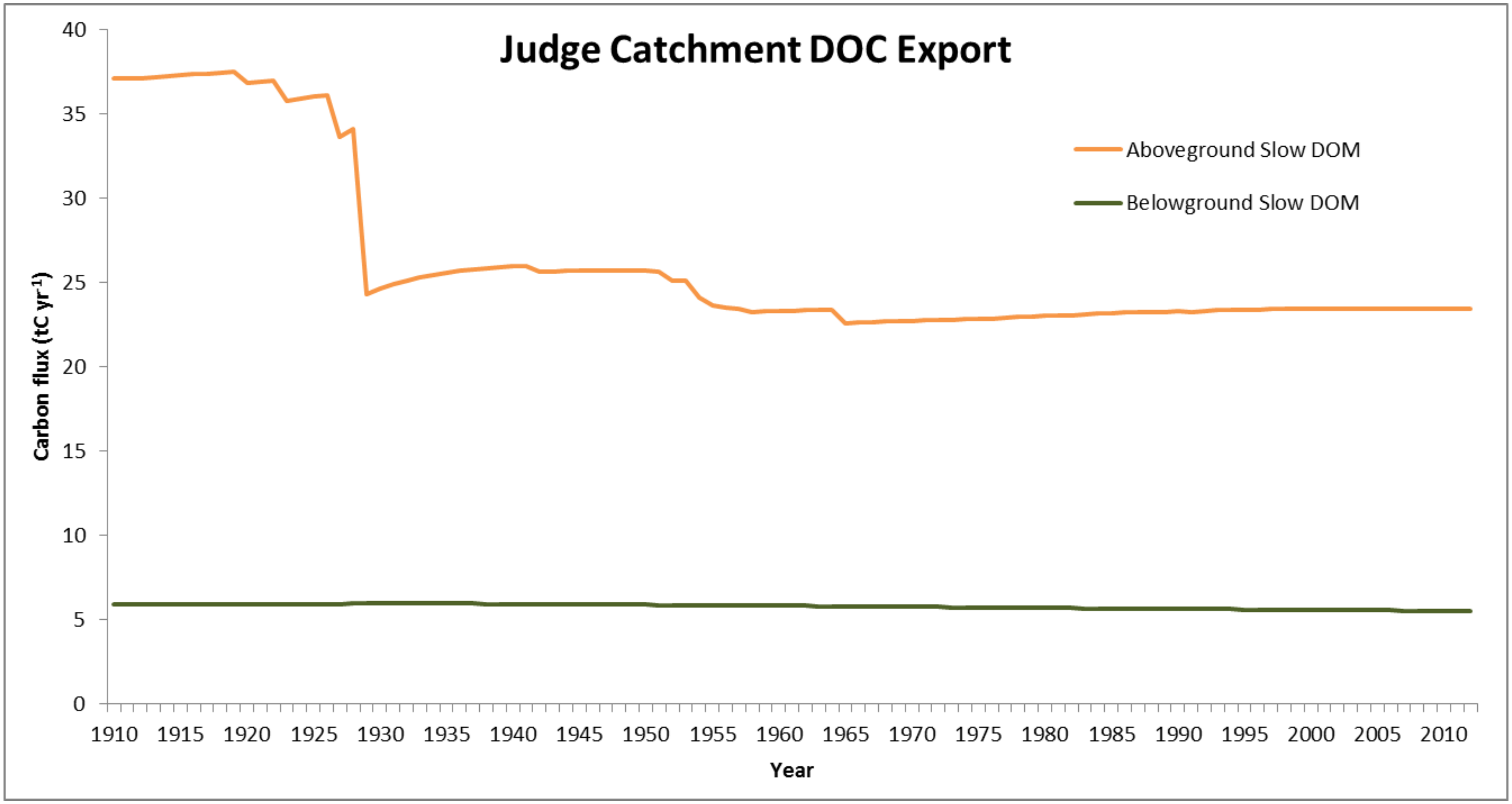

Figure 6-2 - Judge Catchment Dissolved Organic Carbon (DOC) export from aboveground and belowground slow Dead Organic Matter (DOM) pools

Future research that endeavours to more holistically couple the terrestrial and aquatic systems in a watershed scale C budget should attempt to integrate inland aquatic decay and autochthonous production parameters with those established for forest ecosystems. Such work was outside the scope of this study but would have improved the estimation of the net C effect that flooding events (such as those for hydro and water supply reservoirs) exert on the watershed scale C budget. Also, better estimates of the fraction of autochthonous (due to lake primary production) to allochthonous (due to terrestrial primary production) organic C sequestered in lake sediment could help to assess the long term C storage potential of inland aquatic systems. Future efforts to integrate DOC flux as a C export mechanism into CBM-CFS3 may consider including the transfer of C from other pools, specifically the aboveground very fast DOM pool to improve the model's ability to simulate the short term DOC fluxes that would occur after disturbance.

6–2.0 Dead Organic Matter Pool Initialization Sensitivity Analysis

CBM-CFS3 is a growth and yield data driven model relying heavily on information collected for the purposes of timber supply analysis (Kurz, et al., 2009); consequently, data pertaining to the initial state of DOM pools must be simulated prior to CBM-CFS3 model runs[37]. Default assumptions regarding the pre-settlement natural disturbance type and disturbance interval, which differ by terrestrial ecozone, are used in a process whereby initially empty C pools are initialized through stand-replacing disturbances. Typically between 10 and 30 rotations of growth-disturbance-growth are required until the above- and belowground slow DOM pools

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[37] The simulation of DOM pools is integrated into the CBM-CFS3 simulation software.

of two successive rotations reach a state of quasi-equilibrium with a difference tolerance of 1.00% (Kurz, et al., 2009).

A sensitivity analysis was performed on the Baseline C budget to understand the variability around the default DOM initialization parameters for the SLW. Due to a higher degree of certainty about the pre-settlement disturbance type, the default disturbance return interval was the only parameter investigated. The 300 year default disturbance return interval for the Pacific Maritime ecozone (Kurz, et al., 2009) was tested against return intervals of 150 and 450 years[38]. While the default disturbance return interval for the Pacific Maritime ecozone was used in the SLW historical C budget, future use of CBM-CFS3 in this ecozone employing a reduced value such as that expressed by Murray (1994) will have a proportionally greater effect on DOM pool initialization than would a longer disturbance interval (Figure 6-3). What little variation that was observed in the detritus C pools was most evident through comparison of the 150 year and 300 year return intervals; however the variations did not exceed 4.5 tC ha^{-1} in any given year (Figure 6-4). Conversely, differences in soil C exhibited among the three disturbance return intervals were more pronounced (Figure 6-5) with the 150 year return interval containing between 23.0 and 31.5 tC ha^{-1} less than the default. The 450-year return interval deviated less, between 7.7 and 10.7 tC ha^{-1} more than the default over the study period. Establishing a more extensive ground plot network in the SLW to investigate stand ages in different areas and stand types would improve the estimation of the more recent disturbance return interval. Also, collection and analysis of lake cores for charcoal residue would temporally expand the understanding of the pre-settlement disturbance return interval for the watershed.

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[38] 300 years +/- 150 years was regarded as a logical testing range with Murray (1994) using select ground plots inside the Sooke Lake watershed to estimate a 127 year mean fire interval and Parminter (1995), indicating return intervals ranging from between 100 to 500 years for the Coastal Western Hemlock zone.

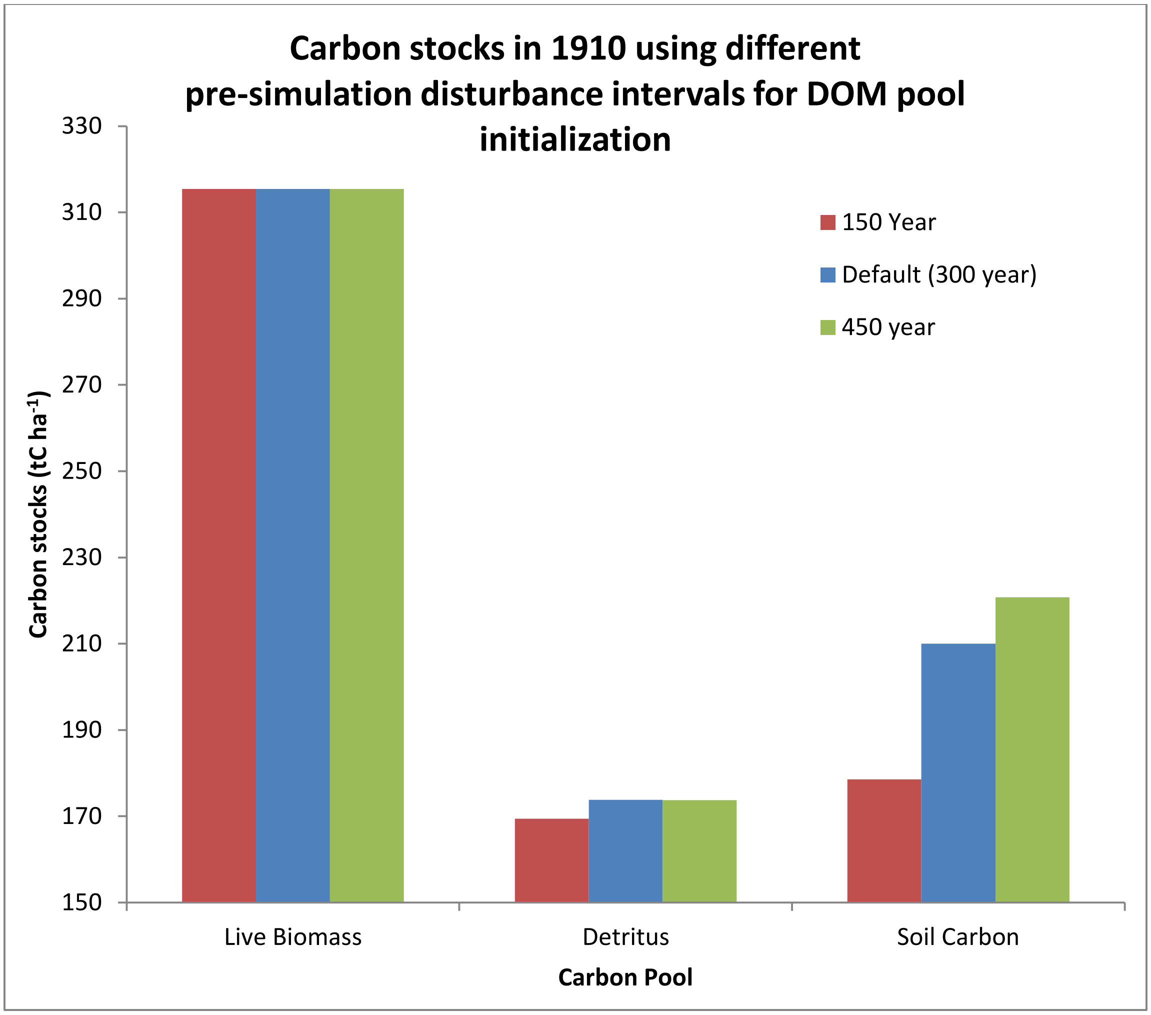

Figure 6-3 - Carbon stocks in 1910 using default and alternate pre-simulation Dead Organic Matter (DOM) pool initialization disturbance intervals

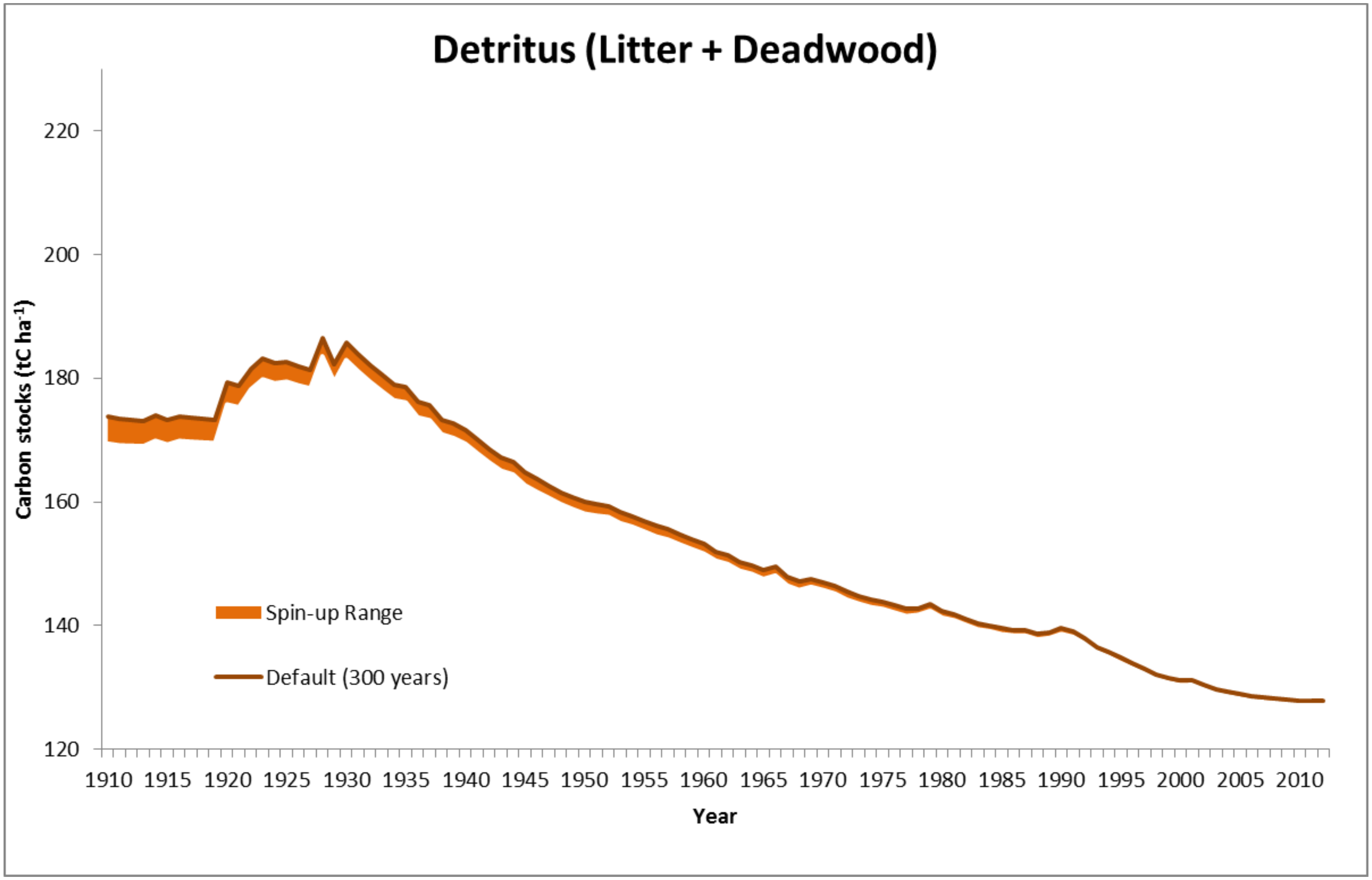

Figure 6-4 – Change in detrital Dead Organic Matter (DOM) pool using a range of disturbance intervals for model initialization

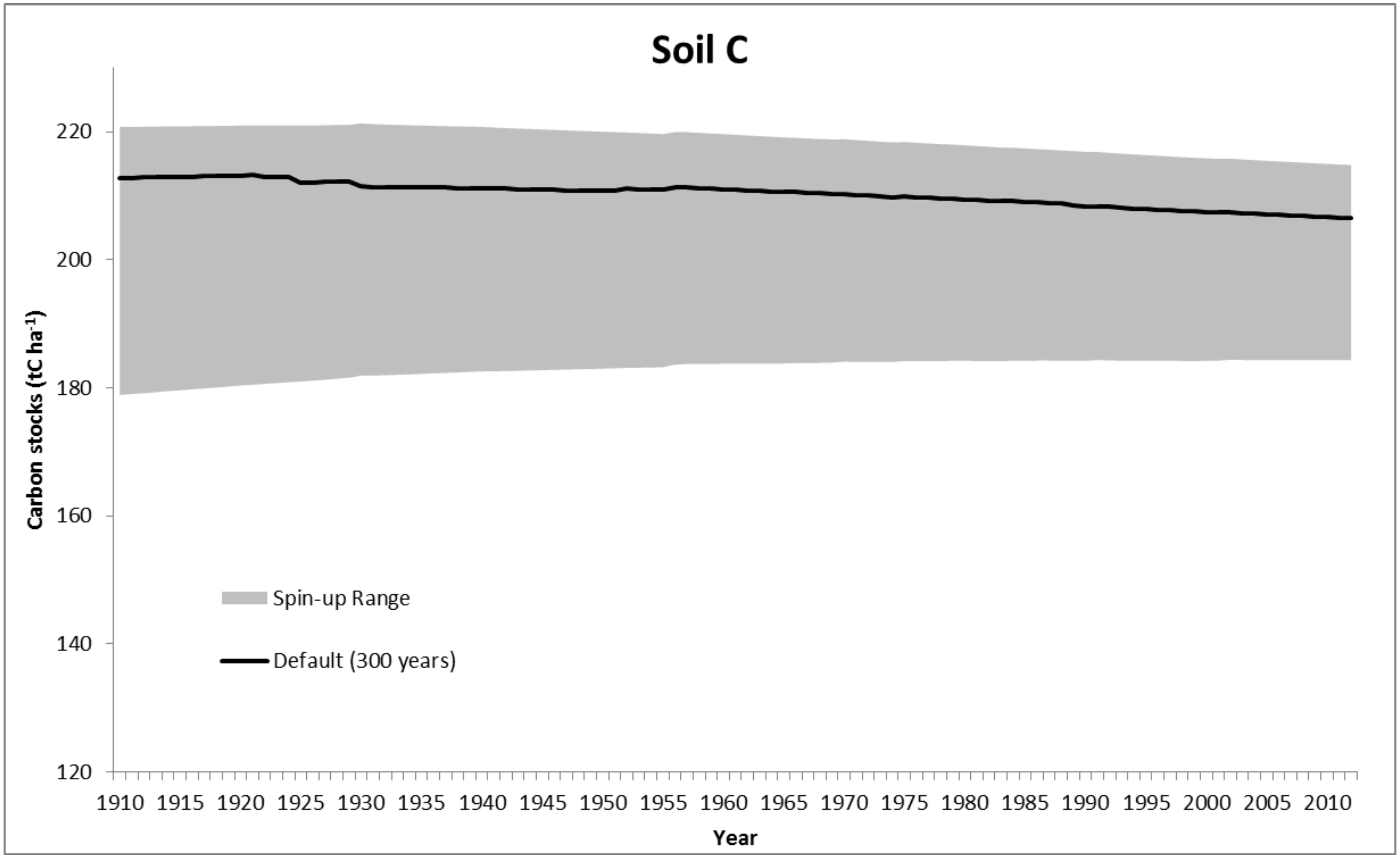

Figure 6-5 – Change in soil carbon Dead Organic Matter (DOM) pool using a range of disturbance intervals for model initialization

6–3.0 Projections of Carbon Stocks and Fluxes

Understanding past changes in forest C also helps decision makers understand the legacy of past management decisions on future C stocks and fluxes. Specifically, the long Baseline C budget presented here enables past trends in ecosystem C fluxes to be identified and future scenarios to be extrapolated. Projections were made 100 years into the future to the year 2112. The projections do not incorporate any effect that climate change may have on growth, decay or disturbance rates (Burton & Cumming, 1995; Kurz, et al., 2008) within the SLW. Also, this estimation assumes the successful execution of current management practices that prohibit any large area anthropogenic disturbance and endeavour to curtail unforeseen natural disturbances. The SLW would be the strongest C sink in 2024 with 2.64 tC ha^{-1} being sequestered, after which the increase in Rh is greater than the increase in NPP (Figure 6-6). Given current (2012) management priorities, total ecosystem C stocks will not achieve pre-disturbance (1910) levels until 2075 (Figure 6-7). The Cumulative effect of DOC export reaches 7.6 tC ha^{-1} by 2112 meaning that ΣNBP would reach C neutrality 3 years sooner (2074) than if DOC was not included as an export mechanism (2077) (Figure 6-8). The prevalence of old-growth forests (>300 years old) in the SLW prior to 1910 means that recovery from any stand-destroying disturbance may take hundreds of years. This reality is now reflected in current GVWSA management plans but was not a high priority in management plans for the majority of the study period.

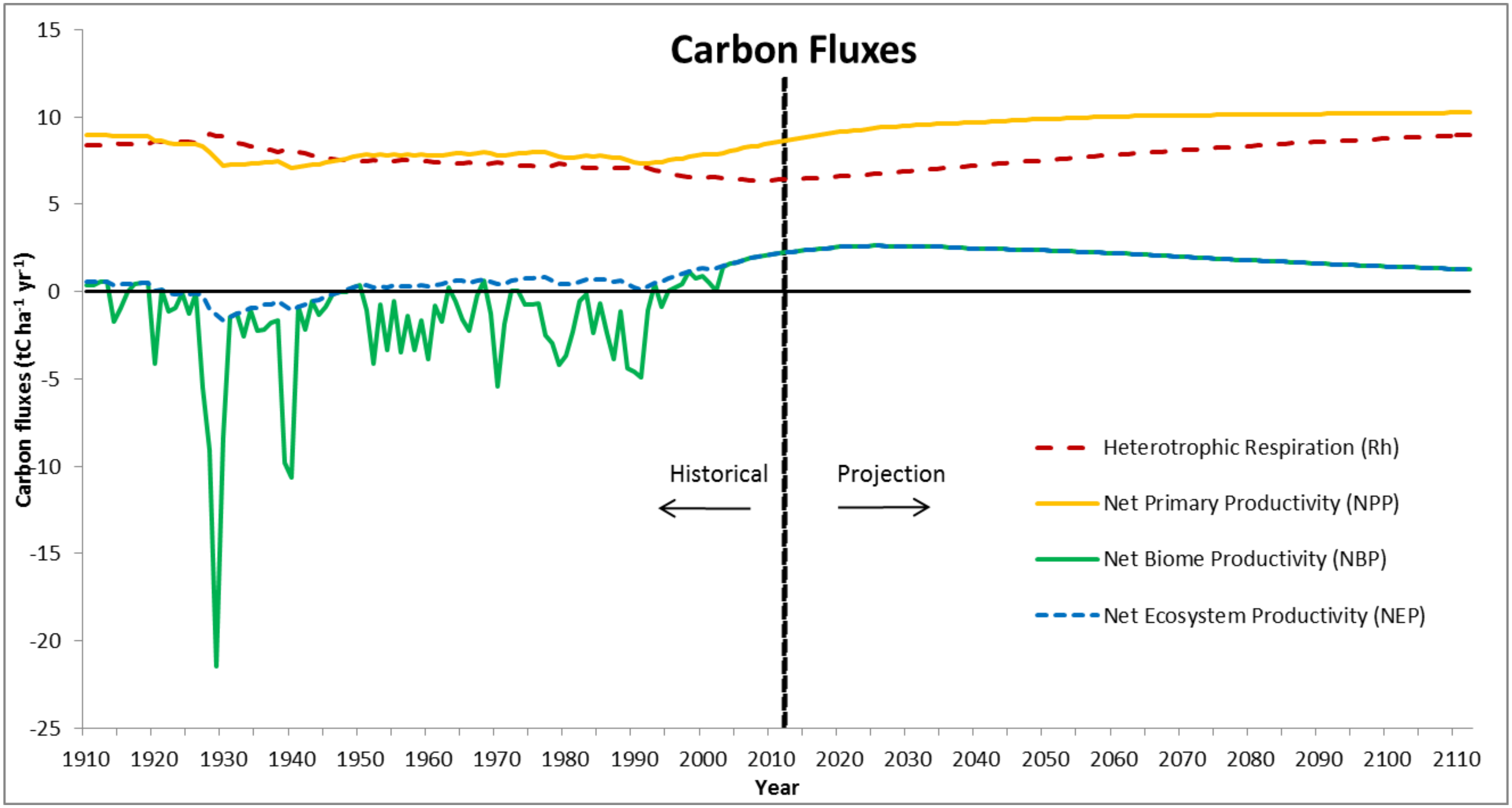

Figure 6-6 - Historical (1910-2012) and projected (2013-2112) carbon fluxes for the Sooke Lake watershed

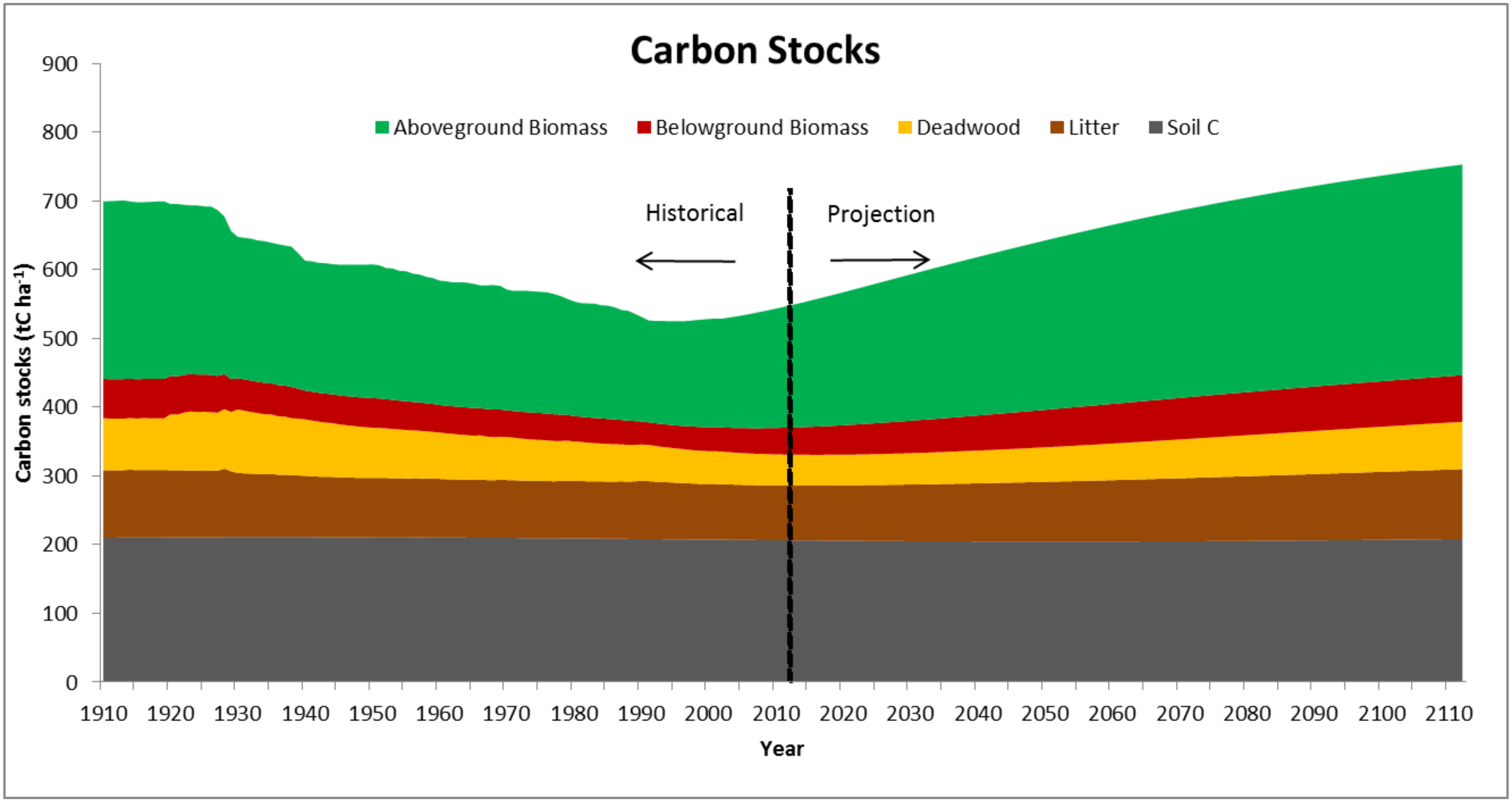

Figure 6-7 - Historical (1910-2012) and projected (2013-2112) carbon stocks for the Sooke Lake watershed

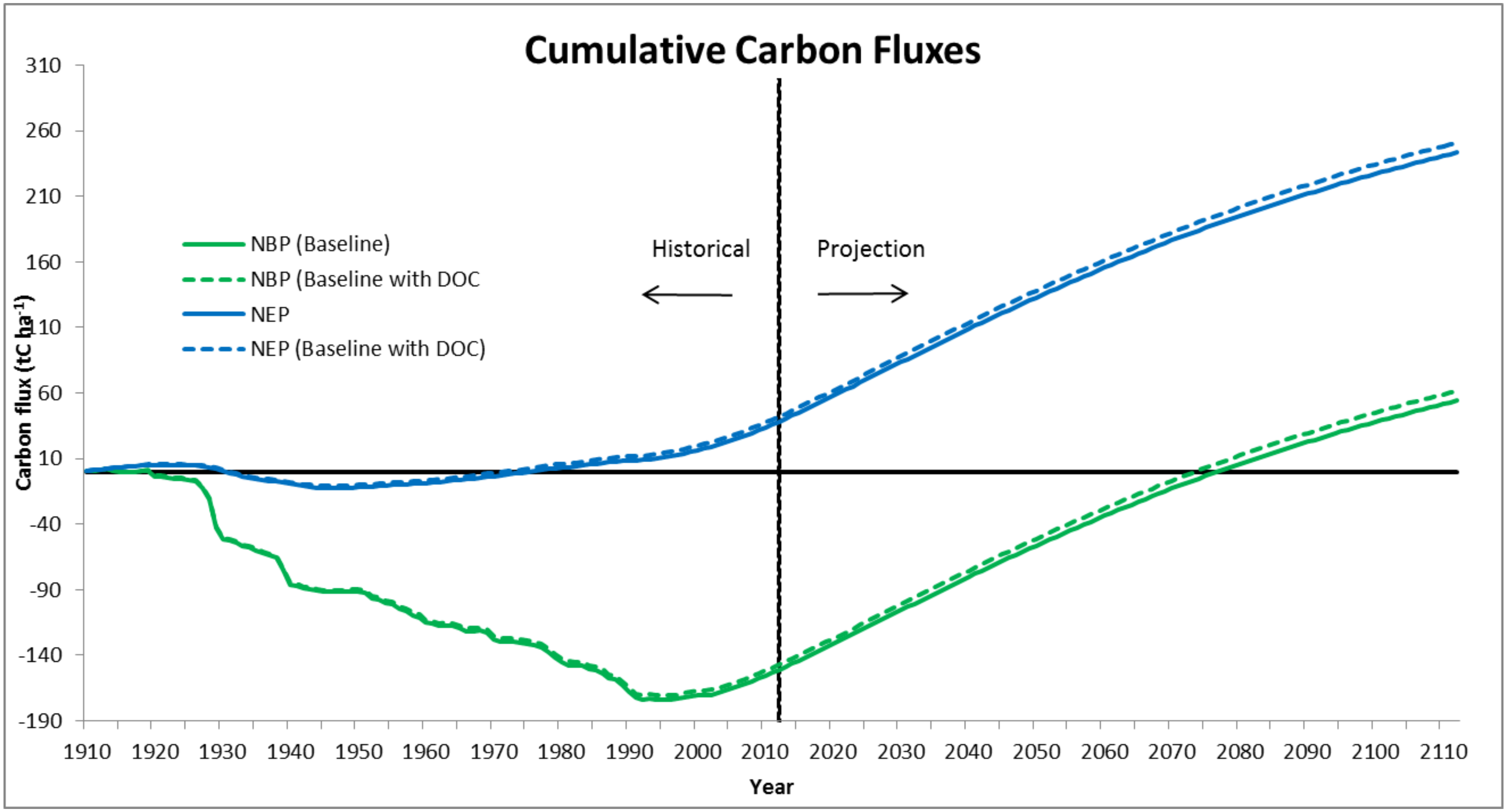

Figure 6-8 - Historical (1910-2012) and projected (2013-2112) cumulative Net Ecosystem Productivity and Net Biome Productivity for the Sooke Lake watershed

6–4.0 Future Work

Future work on the SLW C budget should investigate how alternative management regimes could affect future C stocks and fluxes, accounting for C storage in HWP and improving the understanding of DOC permanence in lake sediment. As CBM-CFS3 improvements arise, integrating the effects of climate change on tree growth, and DOM turnover in the SLW could allow for plausible C stock distributions and fluxes to be generated under a range of climate change scenarios. As well, potential changes in disturbances, such as fire, or insect and disease outbreaks could be included in modelling efforts.

6–5.0 References

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Appendix

Appendix A – GVWSA Data Catalog (also available from “GVWSA_Selected_Data_Catalog.xlsx”)

Sooke-Lake Study Area:

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Map of Sooke Lake/Clearing areas	1911	FC_DIST_LAKE LEVEL	-	CRD	TBD	By Westholme Lumber Co. Ltd.	Survey of 1911 Sooke lake shoreline with areas to be cleared for initial dam raising, some description of wetlands adjacent to lake, volume values
Timber Type Plan	1925	FC	-	CRD	CB4	By Ryan McIntosh Hibberson Blair Timber Co. Ltd.	Cruise blocks - in hanger. MAP NOTES: Cedar poles and pilings not estimated
Orthophoto	1957	IMG	-	CRD	Digital	N/A	Ortho mosaic of image year for Sooke watershed
Historical fire map	1964	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical fire polygons for the Sooke, Leech and Goldstream watersheds
Forest Cover map	1964	FC_DIST	1" = 20 chains	CRD	Rolled Map Cabinet #2, Box 10	By D.W. Smith	accompanying report (prior to 2nd raising) - see notes. MAP NOTE: Control for base map from provincial topographic surveys. Forest cover interpretation from mature timber cruise examinations (1951-52), immature inventory field examination strips (1960-64) and vertical airphotographs (1956). Forest types include only those species which contain 20% or more of the net volume per acre.
Orthophoto	1968	IMG		CRD	Digital	N/A	Ortho mosaic of image year for Sooke watershed
Forest Cover map	1976	FC_DIST	1" = 20 chains	CRD	Rolled Map Cabinet #2, Box 3	By Horth Forestry	Logged, burned and planting information - has typed volumes in "typed report" (paper maps with legend, plastic maps for digitizing) also plastic for goldstream. MAP NOTE: Plainmetric base map developed from provincial surveys and mapping branch control information. Forest cover interpretation from 1974-75 field surveys and prior survey records, plotted on BC government 1972 vertical air photographs as per this sheet, updated for history boundaries from 1975 airphotos. Effective map data Dec 31 1975
Council Lands map	1980	FC_DIST	-	CRD	Digital		Forest cover typing, disturbance dates, planting dates, stand tending and dates
Orthophoto	1984	IMG	-	CRD	Digital	N/A	Ortho mosaic of image year for Sooke watershed
Kapoor forest cover map	1992	FC_DIST	-	CRD	Digital		Forest cover typing, disturbance dates, planting dates, stand tending and dates
Pest event polygons	1996	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical pest event polygons from 1910 to 1996 recorded for the GVWSA

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Forest Cover map (a, b and Council)	1996	FC_DIST	1:10000 , 1:15000	CRD	CB 4: SR - FC - S1 - 96.1 THROUGH S6	CRD	Forest cover typing, disturbance dates, planting dates, stand tending and dates
Sooke Lake Bathymetry	1999	DIST	-	CRD	Digital	Kevin Telmer (UVic)/ Terra Remote Sensing	Sooke Lake bathymetry and lake level polygons derived from bathymetric survey - used to delineate extent of raising events
Orthophoto	2002	IMG	-	CRD	Digital	N/A	Ortho mosaic of image year for Sooke watershed
Modified forest cover/ forest fuel inventory	2006	FC_DIST	-	CRD	Digital	CRD	Combination of past and updated inventories. Includes forest cover and disturbance attributes such as species compoistion, stand ages, site index, logging dates, etc.
LiDAR DEM	2008	REF	-	CRD	Digital	Uvic	DEM used, in conjunction with ownership boundary, to delineate the three major watersheds that make up the GVWSA
LiDAR Canopy Height Model	2008	REF	-	CRD	Digital	Uvic	Was not used to construct the combined disturbance-forestcover geodatabase but could be used to inform attributes at a later date
Orthophoto	2011	IMG	-	CRD	Digital	N/A	Ortho mosaic of image year for Sooke watershed
Pest event polygons	2012	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical pest event polygons from 1997 to 2012 recorded for the GVWSA
Sooke Original Wetlands	2012	FC	-	CRD	Digital	Mike Burrell	Historical wetlands that had been flooded during previous reservoir raising, partially based off of lake bathymetry
VRI inventory	2012	FC_DIST	-	CRD	Digital	FDI Forest Dimensions Inc.	VRI Phase 1 polygon delimination/attributing
Orthophoto	1930-37	IMG	-	NAPL - mosaiced/ortho rectified by McElhanney Consulting Services Ltd	Digital	N/A	Ortho mosaic of image year for Sooke watershed
Forest cover maps (Sooke, Council, SE Shawnigan)	1955-56	FC/DIST	-	MOF	TBD	?	Stand species, age or height and recent disturbance year/type

Goldstream Study Area:

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Orthophoto	1926	IMG	-	NAPL	Not yet ordered	N/A	Ortho mosaic of image year for Sooke watershed (98% coverage)
Orthophoto	1930	IMG	-	NAPL	Not yet ordered	N/A	Ortho mosaic of image year for Sooke watershed (100% coverage)
Orthophoto	1937	IMG	-	NAPL	Not yet ordered	N/A	Ortho mosaic of image year for Sooke watershed (40% coverage)
Cruise Map of Lot 27 - Goldstream	1950	FC	1" = 200 ft	CRD	CB1 - 9A		
Cruise Map of Lot 14 & 16 - Goldstream	1950	FC	1" = 200 ft	CRD	CB1 - 9A		
Goldstream logging, burn, planting history	1951	FC_DIST	1 " = 20 chains	CRD	CB1 - 9F		
Orthophoto	1957	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution
Forest Cover Sketch Map - Section 42 & 43, Goldstream Distrcit	1959	FC	1" = 400 ft	CRD	CB1 - 5D		
Historical fire map	1964	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical fire polygons for the Sooke, Leech and Goldstream watersheds
Forest Cover - Sooke and Goldstream	1964	FC	1" = 20 chains	CRD	CB2 - Rolled Map Cabinet #2, Box 10	By D.W. Smith	
Forest Cover - Goldstream (original)	1964	FC	1" = 20 chains	CRD	Rolled on Hanger: Pre-1970 Forest Cover - Logging Plans Located in Rolled Map Holder #1, Box E1 -	Goldstream; D.W. Smith	
Forest Cover - Goldstream (Colour Coded Forest Cover & burned areas)	1964	FC_DIST	1" = 20 chains	CRD	Rolled on Hanger: Pre-1970 Forest Cover - Logging Plans Located in Rolled Map Holder #1, Box E1	Goldstream; D.W. Smith	
1976 Forest Cover of Goldstream	1976	FC	1 " = 20 chains	CRD	CB1 - 9E		
1976 Forest Cover of Goldstream - site class colour coded)	1976	FC	1 " = 20 chains	CRD	CB1 - 9E		

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Goldstream Forest Cover (1976) - 1989 Aerial Fertilized Areas (hand drawn)	1976	FC	1 " = 20 chains	CRD	CB1 - 10B		
Forest Cover - Goldstream	1976	FC	1" = 20 chains	CRD	CB2 - Rolled Map Cabinet #2, Box 4	By Horth Forestry	
1976 Forest Cover of Goldstream with hand drawn logging history 1978 - 1985	1976	FC_DIST	1 " = 20 chains	CRD	CB1 - 9E		
Goldstream Forest Cover (1976) - Stand Tending Areas (hand drawn)	1976	FC_DIST	1 " = 20 chains	CRD	CB1 - 10B		
Kapoor Property - Forest Cover	1984	FC	1: 10000	CRD	CB1		
Orthophoto	1984	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution
Goldstream Forest Cover	1986	FC	1:10000	CRD	CB4		
Goldstream Forest Cover	1989	FC	1:10000	CRD	CB4		
1989 Forest Cover Goldstream Watershed	1989	FC	1:10, 000	CRD	Rolled Map Holder #1, Box A4 - paper		
Goldstream Forest Cover	1990	FC	1:10000	CRD	CB4		
Forest Cover (mylar)	1990	FC	1:10, 000	CRD	Rolled Map Holder #1, Box D1 - Mylar	Goldstream; by HHL	
Goldstream Forest Cover	1991	FC	1:10000	CRD	CB4		
Goldstream Forest Cover	1992	FC	1:10000	CRD	CB4 - 2 sheets		
Species Distribution	1992	FC	1: 15000	CRD	CB1		
Age Distribution	1992	FC	1: 15000	CRD	CB1		
Goldstream Forest Cover	1993	FC	1: 5000	CRD	CB4 - GS - FI - S1 - 93.1 THROUGH TO S6		
Goldstream Forest Cover	1993	FC	1: 10000	CRD	CB4 - GS - FI - SS - 93.1 GS - FI - SN - 93.1		

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Goldstream Forest Cover	1993	FC	1:15000	CRD	CB4 - GS - FI - 93.1		
Goldstream Forest Cover	1994	FC	1: 5000	CRD	CB4 - GS - FC - S1 - 94.1 THROUGH TO S7		
Goldstream Forest Cover	1994	FC	1:10000	CRD	CB4 - GS - FC - SS - 93.1 GS - FC - SN - 93.1		
Goldstream Forest Cover	1994	FC	1:10000	CRD	CB4 - GS - FC - UNSP - 94.1		
Goldstream Forest Cover	1994	FC	1:15000	CRD	CB4 - GS - FC - 94.1		
Goldstream Forest Cover	1995	FC	1: 5000	CRD	CB4 - GS - FC - S1 - 95.1 THROUGH TO S7		
Goldstream Forest Cover	1995	FC	1:10000	CRD	CB4 - GS - FC - SS - 95.1 GS - FC - SN - 95.1		
Goldstream Forest Cover	1995	FC	1:15000	CRD	CB4 - GS - FC - 95.1		
Goldstream Forest Cover (Kapoor / Waugh)	1995	FC	1:10000	CRD	CB1 - GS - FC - SS - 95.1		
Goldstream Forest Cover (Kapoor / Waugh)	1995	FC	1:10000	CRD	CB1 - GS - FC - SN - 95.1		
Kapoor Property - Age Class	1995	FC	1: 40000	CRD	CB1		
1995 Forest Cover Map	1995	FC	1:10, 000	CRD	Rolled Map Holder #1, Box B1 - Mylar	Goldstream; by HHL	
Pest event polygons	1996	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical pest event polygons from 1910 to 1996 recorded for the GVWSA
Goldstream Forest Cover	1996	FC	1: 5000	CRD	CB4 - GS - FC - S1 - 96.1 THROUGH S7		
Forest Cover - Sooke / Goldstream	1996	FC	1: 10000	CRD	CB4 - SR - FC - SN - 96.1 & SR - FC - SS-96.1 GS - FC-GN-96.1 & GS-FC-GS-96.1		

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Kapoor Proposal - Forest Inventory	1996	FC	1: 10000	CRD	CB1 - WM - KAPOOR - INV		
Forest Cover - Goldstream	1997	FC	1: 5000	CRD	CB4 - GS - FC - S1 - 97.1 THROUGH S7		
1997 Annual Report Map - Goldstream (Original)	1997	FC	1:10, 000	CRD	Rolled Map Holder #1, Box C3 - paper		
Orthophoto	1998	IMG	-	CRD	CRD servers	N/A	B&W, 50cm resolution
Orthophoto	1999	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution
Orthophoto	2002	IMG	-	CRD	CRD servers	N/A	B&W, 50cm resolution
Orthophoto	2005	IMG	-	CRD	CRD servers	N/A	Colour, 30cm resolution
Modified forest cover/ forest fuel inventory	2006	FC_DIST	-	CRD	Digital	CRD	Combination of past and updated inventories. Includes forest cover and disturbance attributes such as species composistion, stand ages, site index, logging dates, etc.
Orthophoto	2007	IMG	-	CRD	CRD servers	N/A	Colour, 20cm resolution
LiDAR DEM	2008	REF	-	CRD	Digital	Uvic	DEM used, in conjunction with ownership boundary, to delineate the three major watersheds that make up the GVWSA
Orthophoto	2009	IMG	-	CRD	CRD servers	N/A	Colour, 20cm resolution
Orthophoto	2011	IMG	-	CRD	CRD servers	N/A	Colour, 20cm resolution
Pest event polygons	2012	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical pest event polygons from 1997 to 2012 recorded for the GVWSA
VRI inventory	2012	FC_DIST	-	CRD	Digital	FDI Forest Dimensions Inc.	VRI Phase 1 polygon delimination/attributing
Forest cover map	1955-56	FC/DIST	-	MOF	TBD	?	Stand species, age or height and recent disturbance year/type
1974 Forest Cover inventory (3 maps)	1974/75	FC	1'+ 10 chains	CRD	Rolled Map Holder #1, Box A4 - mylar		
Logging History - Golstream Watershed	1978-1985	DIST	1" = 20 chains	CRD	CB4		
Original Forest Cover - Goldstream Watershed	NA	FC	?	CRD	CB2 - Rolled Map Cabinet #2, Box 17		

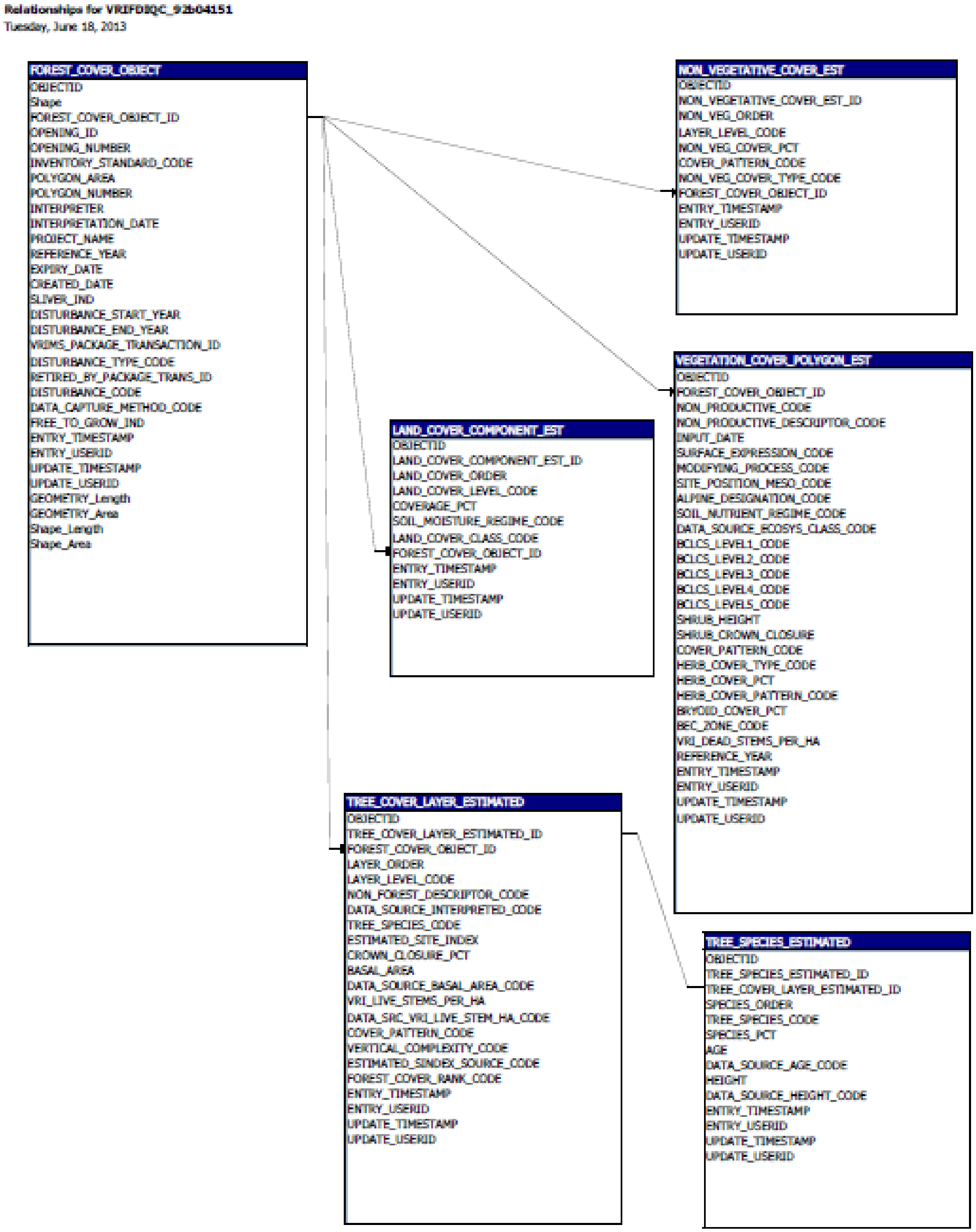
Leech Study Area:

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Orthophoto	1930	IMG	-	NAPL	Not yet ordered	N/A	Ortho mosaic of image year for Sooke watershed (50% coverage)
Orthophoto	1937	IMG	-	NAPL	Not yet ordered	N/A	Ortho mosaic of image year for Sooke watershed (98% coverage)
Topological map of Leech River Timber Tract (Forest Cover with burned areas)	1938	FC_DIST	1" = 20 chains	CRD	Rolled Map Holder #1, Box E1	Leech; Leech Timber Company	Pre-1970 Forest Cover - Logging Plans
Orthophoto	1938	IMG	-	NAPL	Not yet ordered	N/A	Ortho mosaic of image year for Sooke watershed (60% coverage)
Orthophoto	1957	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution, partial coverage
Historical fire map	1964	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical fire polygons for the Sooke, Leech and Goldstream watersheds
Orthophoto	1968	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution, minor coverage
Preliminary Topography / Roads / Forest Cover (Sheet 4 & 8)	1975	FC	1:5,000	CRD	Rolled Map Holder #1, Box A1 - paper	MacDonald Lake / Leech River	logged, brush, rock, scrub, cleared
Preliminary Topography / Roads / Forest Cover (Sheet 5)	1975	FC	1:5,000	CRD	Rolled Map Holder #1, Box A1 - paper	Wolf Lake to Sooke / Leech River	logged, brush, rock, scrub, cleared
Preliminary Topography / Roads / Forest Cover (Sheet 7)	1975	FC	1:5,000	CRD	Rolled Map Holder #1, Box A1 - paper	Survey Mtn. Leech	logged, brush, rock, scrub, cleared
Orthophoto	1984	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution, partial coverage
Pest event polygons	1996	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical pest event polygons from 1910 to 1996 recorded for the GVWSA
Orthophoto	1996	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution, partial coverage
Orthophoto	1999	IMG	-	CRD	CRD servers	N/A	B&W, 1m resolution
Orthophoto	2002	IMG	-	CRD	CRD servers	N/A	B&W, 50cm resolution
WFP_Forest_Cover_Polys	2005	FC_DIST	-	CRD	Digital	Western Forest Products	forest cover inventory attributes
Orthophoto	2005	IMG	-	CRD	CRD servers	N/A	Colour, 30cm resolution
Modified forest cover/ forest fuel inventory	2006	FC_DIST	-	CRD	Digital	CRD	Combination of past and updated inventories. Includes forest cover and disturbance attributes such as species compoisition, stand ages, site index, logging dates, etc.

Map Title	Year	Type	Scale	Source	Data Location	Author	Description
Orthophoto	2007	IMG	-	CRD	CRD servers	N/A	Colour, 20cm resolution
LiDAR DEM	2008	REF	-	CRD	Digital	Uvic	DEM used, in conjunction with ownership boundary, to delineate the three major watersheds that make up the GVWSA
Orthophoto	2009	IMG	-	CRD	CRD servers	N/A	Colour, 20cm resolution
TimberWestForestCover	2010	FC_DIST	-	CRD	Digital	TimberWest	forest cover inventory attributes
Orthophoto	2011	IMG	-	CRD	CRD servers	N/A	Colour, 20cm resolution
Pest event polygons	2012	DIST	-	PFC	Digital	Courtesy of Gurp Thandi	Historical pest event polygons from 1997 to 2012 recorded for the GVWSA
VRI inventory	2012	FC_DIST	-	CRD	Digital	FDI Forest Dimensions Inc.	VRI Phase 1 polygon delimination/attributing
Forest cover map	1955-56	FC/DIST	-	MOF	TBD	?	Stand species, age or height and recent disturbance year/type
Historical Forest Cover / Planimetric - Leech River		FC	-	CRD	5C		

Appendix B – VRI Flattening Procedure/Attributes (also available from “Flattening_attributes.xlsx”)

Initial Table Structure:



Relationships for VRIFDIQC_92b04151
Tuesday, June 18, 2013

FOREST_COVER_OBJECT
OBJECTID
Shape
FOREST_COVER_OBJECT_ID
OPENING_ID
OPENING_NUMBER
INVENTORY_STANDARD_CODE
POLYGON_AREA
POLYGON_NUMBER
INTERPRETER
INTERPRETATION_DATE
PROJECT_NAME
REFERENCE_YEAR
EXPIRY_DATE
CREATED_DATE
SLIVER_IND
DISTURBANCE_START_YEAR
DISTURBANCE_END_YEAR
VRIMS_PACKAGE_TRANSACTION_ID
DISTURBANCE_TYPE_CODE
RETIRED_BY_PACKAGE_TRANS_ID
DISTURBANCE_CODE
DATA_CAPTURE_METHOD_CODE
FREE_TO_GROW_IND
ENTRY_TIMESTAMP
ENTRY_USERID
UPDATE_TIMESTAMP
UPDATE_USERID
GEOMETRY_Length
GEOMETRY_Area
Shape_Length
Shape_Area

NON_VEGETATIVE_COVER_EST
OBJECTID
NON_VEGETATIVE_COVER_EST_ID
NON_VEG_ORDER
LAYER_LEVEL_CODE
NON_VEG_COVER_PCT
COVER_PATTERN_CODE
NON_VEG_COVER_TYPE_CODE
FOREST_COVER_OBJECT_ID
ENTRY_TIMESTAMP
ENTRY_USERID
UPDATE_TIMESTAMP
UPDATE_USERID

VEGETATION_COVER_POLYGON_EST
OBJECTID
FOREST_COVER_OBJECT_ID
NON_PRODUCTIVE_CODE
NON_PRODUCTIVE_DESCRIPTOR_CODE
INPUT_DATE
SURFACE_EXPRESSION_CODE
MODIFYING_PROCESS_CODE
SITE_POSITION_MESO_CODE
ALPINE_DESIGNATION_CODE
SOIL_NUTRIENT_REGIME_CODE
DATA_SOURCE_ECOSYS_CLASS_CODE
BCLCS_LEVEL1_CODE
BCLCS_LEVEL2_CODE
BCLCS_LEVEL3_CODE
BCLCS_LEVEL4_CODE
BCLCS_LEVEL5_CODE
SHRUB_HEIGHT
SHRUB_CROWN_CLOSURE
COVER_PATTERN_CODE
HERB_COVER_TYPE_CODE
HERB_COVER_PCT
HERB_COVER_PATTERN_CODE
BRYOID_COVER_PCT
BEC_ZONE_CODE
VRI_DEAD_STEMS_PER_HA
REFERENCE_YEAR
ENTRY_TIMESTAMP
ENTRY_USERID
UPDATE_TIMESTAMP
UPDATE_USERID

LAND_COVER_COMPONENT_EST
OBJECTID
LAND_COVER_COMPONENT_EST_ID
LAND_COVER_ORDER
LAND_COVER_LEVEL_CODE
COVERAGE_PCT
SOIL_MOISTURE_REGIME_CODE
LAND_COVER_CLASS_CODE
FOREST_COVER_OBJECT_ID
ENTRY_TIMESTAMP
ENTRY_USERID
UPDATE_TIMESTAMP
UPDATE_USERID

TREE_COVER_LAYER_ESTIMATED
OBJECTID
TREE_COVER_LAYER_ESTIMATED_ID
FOREST_COVER_OBJECT_ID
LAYER_ORDER
LAYER_LEVEL_CODE
NON_FOREST_DESCRIPTOR_CODE
DATA_SOURCE_INTERPRETED_CODE
TREE_SPECIES_CODE
ESTIMATED_SITE_INDEX
CROWN_CLOSURE_PCT
BASAL_AREA
DATA_SOURCE_BASAL_AREA_CODE
VRI_LIVE_STEMS_PER_HA
DATA_SRC_VRI_LIVE_STEM_HA_CODE
COVER_PATTERN_CODE
VERTICAL_COMPLEXITY_CODE
ESTIMATED_SINDEX_SOURCE_CODE
FOREST_COVER_RANK_CODE
ENTRY_TIMESTAMP
ENTRY_USERID
UPDATE_TIMESTAMP
UPDATE_USERID

TREE_SPECIES_ESTIMATED
OBJECTID
TREE_SPECIES_ESTIMATED_ID
TREE_COVER_LAYER_ESTIMATED_ID
SPECIES_ORDER
TREE_SPECIES_CODE
SPECIES_PCT
AGE
DATA_SOURCE_AGE_CODE
HEIGHT
DATA_SOURCE_HEIGHT_CODE
ENTRY_TIMESTAMP
ENTRY_USERID
UPDATE_TIMESTAMP
UPDATE_USERID

Table Relationships:

Table Relationships (Sooke Study area)			
Table 1	**Table 2**	**Relationship**	**Key Used**
FOREST COVER_OBJECT	NON_VEGETATIVE_COVER_EST	1:1	FOREST_COVER_OBJECT_ID
FOREST COVER_OBJECT	LAND_COVER_COMPONENT_EST	1:3	FOREST_COVER_OBJECT_ID
FOREST COVER_OBJECT	TREE_COVER_LAYER_ESTIMATED	1:2	FOREST_COVER_OBJECT_ID
TREE_COVER_LAYER_ESTIMATED	TREE_SPECIES_ESTIMATED	1:5	TREE_COVER_LAYER_ESTIMATED_ID

Model Builder Inputs/Outputs

(A) Flatten_Species_LC_NP

Pre-processing	Inputs	Description	Primary Intermediates	Output	Description	Further Processing
Select study area by location where FOREST_COVER_OBJECT polygons intersect Sooke Study Area (WSA_study_area): Export as SOOKE_FC_polys	SOOKE_FC_polys	All FOREST_COVER_OBJECT polygons that intersect the Sooke Water Supply area study area (WSA_study_area) (1448 polygons)	SP_1_2_join; SP_3_$_join; Layer_1_Species_5; SP_1_2_3_4_JOIN; FINAL_SP_1_2_3_4_5_JOIN	FC_NP	Flattened TREE_COVER_LAYER where LAYER_ORDER =1 joined with flattened TREE_SPECIES_LAYER where SPECIES_ORDER = 1-5 joined with NON_VEGETATIVE_COVER_EST where NON_VEG_ORDER =1	Join ouput files, remove redundant fields and export as SOOKE_FC__2012_FLAT_v2
	TREE_COVER_LAYER_ESTIMATED	VRI table				
	TREE_SPECIES_ESTIMATED	VRI table				
	NON_VEGETATIVE_COVER_EST	VRI table				
	LAND_COVER_COMPONENT_EST	VRI table	LC_1_2; LANDCOVER_3	LC_1_2_3	Flattened LAND_COVER_COMPONENT_EST where LAND_COVER_ORDER = 1-3	

(B) Species_concatenate_field_create

Pre-processing	Inputs	Description	Primary Intermediates	Output	Description	Further Processing
	SOOKE_FC__2012_FLAT_v2	Flattened output from "Flatten_Species_LC_NP"	SOOKE_FC__2012_FLAT_v2_5 SOOKE_FC__2012_FLAT_v2_6	SOOKE_FC__2012_FLAT_v3_0	Final flattened file with added/concatenated field attributes	NOTES_2012 field added; non-productive rock outcrop polygons that

(C) Extract_2006_attributes						
Pre-processing	**Inputs**	**Description**	**Primary Intermediates**	**Output**	**Description**	**Further Processing**
From SOOKE_FC__FLAT_v_3_1 select all polygons where SI_2012 = NULL (removes young stands (2-30 yrs old) stands as well as non-forest stands where SI_2012=0). Export as "Old_Forest_polys_2012".	SOOKE_FC__2012_FLAT_v3_1	Concatenated/updated field output from "Species_concatenate_field_create"	Clip_output_%n%; select_output_%n%	copy_output_%n%	Individual 2006 forestcover polygons that are clipped to and take up the majority of the Old_forest_polys_2012 polygon of which they are contained	Merge all "copy_output" polygons then spatially join this feature (using the CONTAINS rule) to the SOOKE_FC_2012_FLAT_V3_1 feature. Remove unwanted attributes. Exported as

Selected VRI 2012 Attributes:

VRI Table Name	VRI Field Name	Description	Name Changed to	Note
FOREST_COVER_OBJECT	Shape	Polygon geometry	Shape	
FOREST_COVER_OBJECT	FOREST_COVER_OBJECT_ID	Unique polygon ID	ID_2012	Added non-productive rock outcrops within the Sooke watershed were given a unique ID greater than the highest FOREST_COVER_OBJECT_ID that exists for the entire GVWSA VRI dataset
FOREST_COVER_OBJECT	REFERENCE_YEAR	Year of the photo source or survey that was used to generate the VRI attributes	REF_YR_2012	Used in conjunction with AGE_1_2012 to calcuate DE_2012
FOREST_COVER_OBJECT	DISTURBANCE_END_YEAR	Ending year of the disturbance event	DIST_END_YEAR_2012	
LAND_COVER_COMPONENT_EST	LAND_COVER_CLASS_CODE	The codes for the land cover Classification Land cover types within the polygon that contribute to the overall polygon description, but are too small to be delineated using current guidelines, may be described by land cover components. The sub-division of a polygon by a quantified Land Cover Component, allowing nonspatial resolution for modeling of wildlife habitat capability	LC_CLASS_1_2012; LC_CLASS_2_2012; LC_CLASS_3_2012	These three fields were concatenated with a dash between coverage percent and soil moisture regime for the 3 land cover orders (i.e. where LAND_COVER_ORDER = 1, 2, or 3 in LAND_COVER_COMONENT_EST table)
LAND_COVER_COMPONENT_EST	COVERAGE_PCT	The percentage coverage of a polygon occupied by each Land Cover Component. Generally, sizes under 10% will not be used	LC_CLASS_1_2012; LC_CLASS_2_2012; LC_CLASS_3_2012	
LAND_COVER_COMPONENT_EST	SOIL_MOISTURE_REGIME_CODE	A class-based code approximating the average amount of soil water available annually for evapotranspiration by vascular plants, averaged over many years. Soil moisture Regime is an interpretive attribute for estimation of site potential and site series classification. The value is between 0 and 8 or blank	LC_CLASS_1_2012; LC_CLASS_2_2012; LC_CLASS_3_2012	
NON_VEGETATIVE_COVER_EST	NON_VEG_COVER_TYPE_CODE	Designated type for all of the observable non-vegetated land cover within a polygon	NV_CLASS_2012	These three fields were concatenated with a dash between non-veg cover percent and cover pattern code. Only 1 NON_VEG_ORDER exists
NON_VEGETATIVE_COVER_EST	NON_VEG_COVER_PCT	Area of a polygon that the non-vegetated portion covers, expressed as a percentage	NV_CLASS_2012	
NON_VEGETATIVE_COVER_EST	COVER_PATTERN_CODE	Herb cover pattern is a code that describes the spatial distribution of the herbaceous species within the polygon. Herb cover pattern is used to describe the herb layer spatial distribution. Examples include clumps of herbaceous species on rocky outcrops, scattered patches or individual herbs or solid, continuous herbaceous cover	NV_CLASS_2012	

VRI Table Name	VRI Field Name	Description	Name Changed to	Note
TREE_COVER_LAYER_ESTIMATED	ESTIMATED_SITE_INDEX	Contains a numeric value that equates to a site's value, as compared to the species. Derived site index is an model predicted site index for tree layers with a leading species age greater than 30 years. Site index is the mean height of the dominant and codominant trees will attain at a base index age (50 years) used for the purposes of estimating forest site growth capability. The site index is based on a normalized set of coefficients calibrated to reflect the range of heights for a given tree species	SI_2012	This field was further populated later with forestcover_2006 site index values and site index values generated using SiteTools v3.3
TREE_COVER_LAYER_ESTIMATED	TREE_SPECIES_CODE	A code indicating the type of tree species in the layer. A "leading" species is identified as being the highest percent composition based on basal area or, if a very young stand, the relative number of stems per hectare. Species must be above a specified diameter to be recognized in the species composition of the layer. Species are described in terms of Genus, Species and variety. See code list	SPECIES_2012	For SPECIES_1, the two TREE_SPECIES_CODE fields (one from the COVER_LAYER_ESTIMATED and one from SPECIES_ESTIMATED) were concatenated in order to ensure all leading species designations were being used. For all non-leading species codes only the SPECIES_ESTIMATED code was available. The leading and 4 subsequent species codes were concatenated with their respective SPECIES_PCT values into one field in the format SSPPPSSPPP..... etc. where SS is the two barrelled species code and PPP is the three barrelled percent value. NOTE: species codes FDC and PLC were truncated to FD and PL, respectively. SPECIES_2012 was also used to calcuate COVER_STATUS
TREE_SPECIES_ESTIMATED	TREE_SPECIES_CODE	A code indicating the type of tree species in the layer. A "leading" species is identified as being the highest percent composition based on basal area or, if a very young stand, the relative number of stems per hectare. Species must be above a specified diameter to be recognized in the species composition of the layer. Species are described in terms of Genus, Species and variety	SPECIES_2012	
TREE_SPECIES_ESTIMATED	SPECIES_PCT	Percentages of the layer that each tree species occupies. For older stands, tree species percentage is based on relative basal area; for younger stands, tree species percentage is based on the number of stems per hectare. Tree species percentage is estimated to the nearest percent for all living trees above a specified diameter	SPECIES_2012	

VRI Table Name	VRI Field Name	Description	Name Changed to	Note
TREE_SPECIES_ESTIMATED	AGE	Age is an average age, weighted by basal area, of the dominant, co-dominant and high intermediate trees for the leading and second species of each tree layer identified. Stand age can be based on an estimate from aerial photographs. Note: Dominant trees have well developed crowns that extend above the general level of the trees around them. Co-dominant trees have crowns forming the general level of trees around them. High intermediate trees have smaller crowns slightly below but extending into the general level of trees around them. This value is not generally present for co-dominant species in the stand	AGE_1_2012; AGE_2_2012	No height or age data exists for species 3-5 and therefore were not included
TREE_SPECIES_ESTIMATED	HEIGHT	The average height, weighted by basal area, of the dominant, co-dominant, and high intermediate trees for the leading and second species of each tree layer identified. Note: Dominant trees have well developed crowns that extend above the general level of the trees around them. Co-dominant trees have crowns forming the general level of trees around them. High intermediate trees have smaller crowns slightly below but extending into the general level of trees around them. This value is not generally present for co-dominant species in the stand	HT_1_2012; HT_2_2012	

Appendix C – Metadata File (also available from "area_Sooke_disturbance_v2-3-meta_v1.txt")

sooke_disturbance_v2.3.txt

1. Data Set Overview

1.1 Data Set Identification

A forest cover and disturbance GIS coverage for the Sooke-Council Watershed Study Area (SWSA) (Version 2-3).

1.2 Study Overview

Data was prepared by combining all available forest inventory and disturbance data for use in developing a retrospective and current C budget for the Greater Victoria Water Supply Area (GVWSA) managed by the Capital Regional District Integrated Water Services (CRD-IWS).

1.3 Data Set Introduction

Forest cover and disturbance variables were derived from historical forest cover maps for the years 1955/56, 1964, 1975, 1980, 1996 and 2006, as well as 1911 Sooke lake-land clearing map, 1925 Timber cruise map, fire history, a 20 meter resolution stand height datset derived from a 2006 LiDAR survey, and a Vegetation Resource Inventory (VRI) completed for 2012. These data sources were assembled into a combined disturbance-forest cover/land cover geodatabase. The dataset is stored as an ArcGIS feature class located on the Pacific Forestry Centre NAS at: \\Pfc-unix\rferris\ecology\GVWSA\GIS\Geodatabases\Sooke_Watershed_10.gdb\Sooke_LC_DIST_1910to2012_v2_3. A copy of this file also resides with the CRD-IWS.

1.4 Related Data Sets

Several datasets were used to create this combined coverage. All files are located on the Pacific Forestry Centre Unix server at: \\Pfc-unix\rferris\ecology\GVWSA\GIS\Geodatabases\Sooke_Watershed_10.gdb

---->Roads

This dataset contained all major roads up to 2012 and was created using data from the CRD in conjunction with additional roads digitized from aerial imagery. An approximate date of the road being established is located in the dataset and is populated with values interpreted using the aerial imagery.
Located at: \\Pfc-unix-rferris\ecolgoy\GVWSA\GIS\Sooke_Watershed_10.gdb\ROADS\Sooke_roads_AREA

---->Disturbance

This dataset contains major disturbance and treatment types and dates. Disturbance data is sorted into 6 related type and date fields while treatment information is sorted into 5 related type and date fields.
Located at: \\Pfc-unix-rferris\ecolgoy\GVWSA\GIS\Sooke_Watershed_9.gdb\LC_DIST\Sooke_CombinedDist

---->Pre-disturbance forestcover

This dataset contains pre-disturbance forest cover for all polygons in the Disturbance dataset for snapshot years 1910, 1955, 1964, 1975, and 1996.
Located at: `\\Pfc-unix-rferris\ecolgoy\GVWSA\GIS\Sooke_Watershed_9.gdb\LC_DIST\Sooke_PreDistrubanceLC`

---->VRI landcover

This dataset contains all landcover, species, date of establishment, and site index information for the Sooke-Council watershed circa 2012.
Located at: `\\Pfc-unix-rferris\ecolgoy\GVWSA\GIS\Sooke_Watershed_10.gdb\Sooke_landcover_2012`

---->Disturbance-landcover/forestcover dataset

This dataset contains all disturbance and treatment data from the Disturbance layer, pre-disturbance forest cover data, post-disturbance forestcover and old forest stand type data derived from the VRI landcover.
Located at: `\\Pfc-unix-rferris\ecolgoy\GVWSA\GIS\Sooke_Watershed_9.gdb\LC_DIST\Sooke_CombinedDist`

Note: additional information on the above mentioned datasets can be found in the metadata directory.

Documentation of fields selected, merged and combined for the sooke_disturbance_v2.0 disturbance history dataset is located at:

- --->VRI flattening excel spreadsheet
- --->Data catalogue spreadsheet
- --->Data dictionary spreadsheet

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2. Investigator(s)

2.1 Principal Investigator(s) Name and Title

Dr. J.A. (Tony) Trofymow: Research Scientist - Soil Ecology (PFC, CFS, NRCAN)
Byron Smiley: MSc Candidate- Geography (UVic / PFC)

2.2 Title of Investigation

Retrospective and current C budgets for Greater Victoria Water Supply Area Lands - Phase 1: Assembly of a combined disturbance-forestcover/landcover geodatabase

2.3 Contact Information

Contact 1

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2.4 Field and/or laboratory staff:
Co-op students: Taylor Denouden

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5. Site description
The study was conducted in the Sooke-Council Watershed Study Area (SWSA) located within the Greater Victoria Water Supply Area (GVWSA) on the south end of Vancouver Island, British Columbia, roughly 30 kilometers NW of the city of Victoria.

The study covers the joint Sooke and Council Watersheds with UTM co-ordinates (Zone 10, NAD83):
NW Extent: 443541mE, 5383796mN
NE Extent: 450844mE, 5385248mN
SW Extent: 446227mE, 5373622mN
SE Extent: 452557mE, 5372954mN
Centroid of Study Area: 448464mE, 5378982mN

The Sooke Lake Watershed is part of the Victoria Highland physiographic region of Vancouver Island (Yorath and Nasmith, 1995) and is within the Very dry maritime Coastal Western Hemlock biogeoclimatic subzone (CWHxm) spanning the east (CWHxm1) and west (CWHXM2) variants of the subzone with annual precipitation averaging 1500 mm of which 75% falls as rain during the months of October to March. The annual mean temperature is 9.4 degrees Celsius (Pojar et al. 1991). This subzone has a maritime climate with typically cool summers and mild winter, though can experience significant dry conditions during the summer. The study area is characterized by well rounded, gently to moderately sloping terrain with elevation ranging between 190m and 850m, and is within approximately 15 km of the coast. Douglas-fir (Pseudotsuga menziesii) is the dominant tree species on dry to mesic site series, though wetter site series will contain western red-cedar (Thuja plicata) and western hemlock (Tsuga heterophylla) (Green and Klinka 1994). Soils within the area are typically loamy to coarse-skeletal Dystric Brunisols or Humo-Ferric Podzols that developed over a well drained, gravelly sandy till depostied during the last glacial maximum (10,000-29000 BP years). Localized bedrock exposures in the form of minor bluffs, cliffs and knolls are evident through the watershed.

---

8. Data Description

8.1 Data Organization

Data is arranged by Polygon.

8.2 Image and Data Format

ArcGIS Feature Class.
Projection: UTM, Zone 10, NAD83

8.3 Data Characteristics

Column number: columns header: variable description

1: ID	unique ID
2: AREA	Polygon area (m2)
3: HECTARES	Polygon area (hectares)
4: PERIMETER	Polygon perimeter (m)
5: LC_CLASS_1910	Land cover classification of polygon in 1910
6: LC_DESC	Description of LC_CODE
7: SPECIES_1910	Forestcover species composition in 1910
8: DE_1910	Date of stand establishment as of 1910
9: NOTE_1910	Explanation of how DE_1910 was determined
10: SI_1910	Site index as of 1910
11: VOLUME	Volume of stand in 1910
12: AGE_1910	Age of stand based on DE_1910 field
13: HT_1910	Height of stand in 1910 - not populated
14: DIST_1_YEAR	Year of first stand disturbance
15: DIST_1_TYPE	Type of first stand disturbance
16: DIST_2_YEAR	Year of second stand disturbance
17: DIST_2_TYPE	Type of second stand disturbance
18: DIST_3_YEAR	Year of third stand disturbance
19: DIST_3_TYPE	Type of third stand disturbance
20: DIST_4_YEAR	Year of fourth stand disturbance
21: DIST_4_TYPE	Type of fourth stand disturbance
22: DIST_5_YEAR	Year of fifth stand disturbance
23: DIST_5_TYPE	Type of fifth stand disturbance
24: DIST_6_YEAR	Year of sixth stand disturbance

```
25: DIST_6_TYPE         Type of sixth stand disturbance
26: TREAT_YR_1          year of first treatment event
27: TREAT_TYPE_1        type of first treatment event
28: TREAT_YR_2          year of second treatment event
29: TREAT_TYPE_2        type of second treatment event
30: TREAT_YR_3          year of third treatment event
31: TREAT_TYPE_3        type of third treatment event
32: TREAT_YR_4          year of fourth treatment event
33: TREAT_TYPE_4        type of fourth treatment event
34: TREAT_YR_5          year of fifth treatment event
35: TREAT_TYPE_5        type of fifth treatment event
36: CRUISE_ID           Cruise block ID
37: SPECIES_1_1925      leading species in 1925 cruise
38: SPECIES_2_1925      second species in 1925 cruise
39: SPECIES_3_1925      third species in 1925 cruise
40: DENSITY_SP1         density of leading species in m3/HA
41: DENSITY_SP2         density of second species in m3/HA
42: DENSITY_SP3         density of third species in m3/HA
43: NOTES               Notes pertaining to 1925 cruise map use
44: LC_CLASS_1955       Land cover classification of polygon in 1955
45: SPECIES_1955        Forestcover species composition in 1955
46: DE_1955       Date of stand establishment as of 1955
47: NOTE_1955           Explanation of how DE_1955 was determined
48: SI_1955       Site index as of 1955
49: HT_1955       Height of stand in 1955
50: AGE_1955      Age of stand based on DE_1955 field
51: LC_CLASS_1964       Land cover classification of polygon in 1964
52: SPECIES_1964        Forestcover species composition in 1964
53: DE_1964       Date of stand establishment as of 1964
54: NOTE_1964           Explanation of how DE_1964 was determined
55: SI_1964       Site index as of 1964
56: LC_CLASS_1975       Land cover classification of polygon in 1975
57: SPECIES_1975        Forestcover species composition in 1975
58: DE_1975       Date of stand establishment as of 1975
59: NOTE_1975           Explanation of how DE_1975 was determined
60: SI_1975       Site index as of 1975
61: LC_CLASS_1996       Land cover classification of polygon in 1996
62: SPECIES_1996        Forestcover species composition in 1996
63: DE_1996       Date of stand establishment as of 1996
64: NOTE_1996           Explanation of how DE_1996 was determined
65: SI_1996       Site index as of 1996
66: LC_CLASS_2012       Land cover classification of polygon in 2012
67: SPECIES_2012        Forestcover species composition in 2012
68: DE_2012       Date of stand establishment as of 2012
69: NOTE_2012           Explanation of how DE_2012 was determined
```

```
70: SI_2012       Site index as of 2012
71: VRI_ID              Unique ID refering to the VRI polygon from which 2012 attributes
were used
72: COVER_STATUS        Current (2012) forest cover status denoting deforested,
disturbed, old forest, non-forest and afforested polygons
73: LiDAR_HT_NOTES      A comment field for populating polygons with LiDAR height values
74: LiDAR_SI_NOTES      A comment field for populating polygons with LiDAR Site index
values
75: LiDAR_HT      Stand height based off of 2006 LiDAR top height values
76: SI_2006       LiDAR derived Site index
77: Shape_Length        polygon perimeter
78: Shape_Area          polygon area


FOOTNOTES:

FOOTNOTE 1
(A) LANDCOVER CLASS (LC_CLASS)            (B) SPECIES CODE              (C) TREATMENT
CODE                          (D) DISTURBANCE CODE
Code  Landcover Type          CBM   Code  Species Type            CBM   CODE  Code
      Treatment Type              CBM/OR      CODE  Code  Disturbance Type
TC    Treed Coniferous  1200  AC    Poplar                  199   50    P     Planted
                  1     10    Fw    Wildfire
TM    Treed Mixed       303   BG    Grand fir         201   51    Tp    Partial Thinning
      132   11    Fh    Human caused fire
TB    Treed Broadleaf         304   BL    Subalpine fir                 NA    G     Grass
Seeded                  132   11    Fsb   Slash burn
WE    Wetland                 702   CW    Western Red Cedar       NA    M     Mechanical
            166   12    Fpb   Partial burn
IN    Infrastructure          1802  DR    Red Alder         199         50    MP
      Mechanical/Planting         162   13    Frp   Residual pile burn
SH    Shrub             500   FD    Douglas Fir             NA    MG    Mechanical/Grass
seeding     149   14    Frt   Residual pile burn for transmission line
AG    Agricultural Land 402   HW    Western Hemlock   199         50    PG
      Planting/Grass seeding      162   15    Fto   Pile burn and ash trucked out
GP    Gravel Pit        1403  MB    Broadleaf Maple   199         53    PTp
      Planting/Partial Thinning   204   20    Lc    Clearcut logging
RZ    Road Surface            201   PW    Western White Pine      199   50    MPG
      Mechanical/planting/grassing  149   21    Lct   Clearcut logging for transmission
line
BR    Bedrock                 204   PL    Lodgepole Pine          8     52    Pa
      Afforestation               10    22    La    Partial logging
LA    Lake              106   SS    Sitka Spruce
            235   23    Ll    Land-clearing logging for reservoir
```

```
RN    Railway                 142   RA    Arbutus
                  234   24    Lr    Land-clearing logging for road
TL    Transmission Line
      169   25    Lsb   Historical Logging and Slash burn
RE    Reservoir
      162   30    Lrp   Logging and Residual pile burn

      235   31    Lls   Land-clearing logging with slashburn for reservoir

      235   32    Llp   Land-clearing logging and pile burn for reservoir

      234   33    Llr   Land-clearing logging and pile burn for road

      2     40    IBD   Douglas-fir Beetle (Trace or low severity)
```

NOTE: harvest related fires that occur in the same year as harvest were given a unique disturbance code (i.e. Lsb)

Stem volumes had been converted from Board Feet in the original cruise to cubic meters using a constant of 2.35 to allow for imperial to metric units. This underestimates actual standing volume, as scaled values for board feet include implicit assumptions (eg. loss from saw kerf, round logs to dimension lumber) and are thus milled lumber volume not standing volume. Without specific diameter and merchantibilty standards a more appropriate conversion factor cannot be applied.

FOOTNOTE 2
Information for DE_1910, DE_1955, DE_1964, DE_1975 and DE_2012 (dates of establishment): These dates were determined using disturbance and planting information from individual forest cover maps, and VRI dates of establishment. For the examples below, DISTURBANCE represents either, DIST_1_YEAR, DIST_2_YEAR, DIST_3_YEAR, DIST_4_YEAR, DIST_5_YEAR, or DIST_6_YEAR, PLANTING_DATE represents TREAT_YR_1, TREAT_YR_2, TREAT_YR_3, TREAT_YR_4, or TREAT_YR_5 where the corresponding TREAT_TYPE_1, TREAT_TYPE_2,... code is "P", "MP", "PG", "PTp", or "MPG".
The validity of DE_1910, DE_1955, DE_1964, DE_1975, DE_1996, and DE_2012 was checked using historic orthophotos where possible. Values were changed to -9 for any polygons which contained non-productive landcover types after a disturbance event. for .
NOTE: -9 indicates that there is no stand established.

```
      For DE_1910:
            IF there is no DISTURBANCE < 1910
                  And IF no DISTURBANCE > 1910
```

```
                  THEN DE_1910 = DE_2012

            IF there is no DISTURBANCE < 1910
                  And IF there is DISTURBANCe > 1975
                  THEN DE_1910 = 1975 age class mid point

            IF last DISTURBANCE < PLANTING_DATE <= 1910),
                  THEN DE_1910 = PLANTING_DATE

            IF last DISTURBANCE < PLANTING_DATE <=1910),
                  AND If there is no PLANTING_DATE < 1910 AND PLANTING_DATE > last DISTURBANCE,
                  THEN DE_1910 = last DISTURBANCE + 1

      For DE_1955:
            IF there is no DISTURBANCE < 1955
                  And IF no DISTURBANCE > 1955
                  THEN DE_1955 = DE_2012

            IF there is no DISTURBANCE < 1955
                  And IF there is DISTURBANCe > 1975
                  THEN DE_1955 = 1975 age class mid point

            IF last DISTURBANCE < PLANTING_DATE <= 1955),
                  THEN DE_1955 = PLANTING_DATE

            IF last DISTURBANCE < PLANTING_DATE <=1955),
                  AND If there is no PLANTING_DATE < 1955 AND PLANTING_DATE > last DISTURBANCE,
                  THEN DE_1955 = last DISTURBANCE + 1

      For DE_1964:
            IF there is no DISTURBANCE < 1964
                  And IF no DISTURBANCE > 1964
                  THEN DE_1964 = DE_2012

            IF there is no DISTURBANCE < 1964
                  And IF there is DISTURBANCe > 1975
                  THEN DE_1964 = 1975 age class mid point

            IF last DISTURBANCE < PLANTING_DATE <= 1964),
                  THEN DE_1964 = PLANTING_DATE

            IF last DISTURBANCE < PLANTING_DATE <=1964),
```

```
            AND If there is no PLANTING_DATE < 1964 AND PLANTING_DATE > last DISTURBANCE,
            THEN DE_1964 = last DISTURBANCE + 1

    For DE_1975:
        IF there is no DISTURBANCE < 1975
            And IF no DISTURBANCE > 1975
            THEN DE_1975 = DE_2012

        IF there is no DISTURBANCE < 1975
            And IF there is DISTURBANCe > 1975
            THEN DE_1975 = 1975 age class mid point

        IF last DISTURBANCE < PLANTING_DATE <= 1975),
            THEN DE_1975 = PLANTING_DATE

        IF last DISTURBANCE < PLANTING_DATE <=1975),
            AND If there is no PLANTING_DATE < 1975 AND PLANTING_DATE > last DISTURBANCE,
            THEN DE_1975 = last DISTURBANCE + 1

    For DE_1996:
        IF there is no DISTURBANCE < 1996
            And IF no DISTURBANCE > 1996
            THEN DE_1996 = DE_2012

        IF there is no DISTURBANCE < 1996
            And IF there is DISTURBANCe > 1996
            THEN DE_1996 = 1975 age class mid point

        IF last DISTURBANCE < PLANTING_DATE <= 1996),
            THEN DE_1996 = PLANTING_DATE

        IF last DISTURBANCE < PLANTING_DATE <=1996),
            AND If there is no PLANTING_DATE < 1996 AND PLANTING_DATE > last DISTURBANCE,
            THEN DE_1996 = last DISTURBANCE + 1

    For DE_2012:
        IF there is no DISTURBANCE < 2012
            And IF no DISTURBANCE > 2012
            THEN DE_2012 = VRI date of establishment already contained in dataset

            IF last DISTURBANCE < PLANTING_DATE <= 2012),
            THEN DE_2012 = PLANTING_DATE
```

```
IF last DISTURBANCE < PLANTING_DATE <=2012),
      AND If there is no PLANTING_DATE < 2012 AND PLANTING_DATE > last DISTURBANCE,
      THEN DE_2012 = last DISTURBANCE + 1
```

8.3.1 Sample Data Record

```
1:    ID= 2297
2:    AREA= 292.925811
3:    HECTARES= 0.029292
4:    PERIMETER= 71.44137
5:    LC_CLASS_1910= SH
6:    LC_DESC=
7:    SPECIES_1910=
8:    DE_1910= -100
9:    NOTE_1910=
10:   SI_1910= 0
11:   VOLUME= 0
12:   AGE_1910= 0
13:   HT_1910= 0
14:   DIST_1_YEAR= 1930
15:   DIST_1_TYPE= Fpb
16:   DIST_2_YEAR= 1986
17:   DIST_2_TYPE= Lc
18:   DIST_3_YEAR= 0
19:   DIST_3_TYPE=
20:   DIST_4_YEAR= 0
21:   DIST_4_TYPE=
22:   DIST_5_YEAR= 0
23:   DIST_5_TYPE=
24:   DIST_6_YEAR= 0
25:   DIST_6_TYPE=
26:   TREAT_YR_1= 1987
27:   TREAT_TYPE_1= P
28:   TREAT_YR_2= 0
29:   TREAT_TYPE_2=
30:   TREAT_YR_3= 0
31:   TREAT_TYPE_3=
32:   TREAT_YR_4= 0
33:   TREAT_TYPE_4=
34:   TREAT_YR_5= 0
35:   TREAT_TYPE_5=
36:   CRUISE_ID= 29
```

```
37:   SPECIES_1_1925= Fd
38:   SPECIES_2_1925=
39:   SPECIES_3_1925=
40:   DENSITY_SP1= 75.391454
41:   DENSITY_SP2= 0
42:   DENSITY_SP3= 0
43:   NOTES=
44:   LC_CLASS_1955= SH
45:   SPECIES_1955=
46:   DE_1955= -100
47:   NOTE_1955=
48:   SI_1955=
49:   HT_1955=
50:   AGE_1955=
51:   LC_CLASS_1964= SH
52:   SPECIES_1964=
53:   DE_1964= -100
54:   NOTE_1964=
55:   SI_1964= 0
56:   LC_CLASS_1975= SH
57:   SPECIES_1975=
58:   DE_1975= -100
59:   NOTE_1975=
60:   SI_1975= 0
61:   LC_CLASS_1996= TC
62:   SPECIES_1996= FD080PL015HW005
63:   DE_1996= 1987
64:   NOTE_1996= Planting date
65:   SI_1996= 21
66:   LC_CLASS_2012= TC
67:   SPECIES_2012= FD080PL015HW005
68:   DE_2012= 1987
69:   NOTE_2012= Planting date
70:   SI_2012= 21
71:   VRI_ID= 0
72:   COVER_STATUS= DF
73:   LiDAR_HT_NOTES= LiDAR Height copied from adjacent stand
74:   LiDAR_SI_NOTES=
75:   LiDAR_HT= 31.2
76:   SI_2006= 27.1
77:   Shape_Length= 57.521338
78:   Shape_Area= 232.288342

----------------------------------------------------------------------
9.  Data Manipulations
```

LAKE LEVEL

Pre- and post-reservoir raising lake levels (and inundated areas) were inferred from bathymetric survey data, verified by orthophotography, the 2012 VRI lake level (digitized by CRD-IWS), and historic surveyed map data for earlier maps (i.e. 1911 Sooke Lake map). Lake levels linework derived from these map layers was altered slightly to ensure a logical progression of lake levels from one raising to the next.

DISTURBANCE COVERAGE

The 1911, 1955/56, 1964, 1975, 1996, and 2006 maps, as well as the wildfire and slash burn map provided by Gurp Thandi at PFC were the major sources of data for disturbance events. 2006 modified forestcover geometry was used to delineate most of the disturbed stands, with some cut into smaller polygons for cases where delineation of the event was mistmatched with other data sources. These polygons were then populated with disturbance date and type and date of establishment (interpretted from age) information from each disturbance map. Where date discrepancies occurred between multiple map sources for the same disturbance event, the data source which was published closer to the disturbance event was used. When logging events were presented as a date ranges in a data sources, the range was simplified to the latest date; the point at which the stand was fully cleared. Finally, disturbance events given a type but no date in the forestcover maps were inferred using the ortho-imagery in combination with the older forestcover maps to determine an approximate date based on adjacent disturbed areas.

The extent of area cleared for individual reservoir raising events was derived from the 1911 map, 1975 map, 2011 imagery and the bathymetric survey lake level information provided by the CRD-IWS. Areas cleared for the 1915 and 1970 raising were assumed to have been slash burned, while the area cleared for the 2002 raising was pile burned with the ash trucked out. The 1970 and 2002 cleared areas that were not flooded were assumed to be planted the year following the reservoir raising event. These burning and planting assumptions align with known common practices for these time periods.

A dataset showing all roads and railways in the study area was also unioned into the dataset. These roads were sourced from data supplied by the CRD, with some additional roads digitized (and buffered to create separate polygons) using the ortho-imagery. Road construction dates (dates of deforestation) were inferred via aerial photo interpretation. Roads were only included and therefore considered deforestation events if they fulfilled two criteria: 1) The roads were of a permanent nature (ie. existed for >50 years), and; 2) The constructed right-of-way was not less than 10 meters wide (as observed using airphotos) allowing for a separate polygon to be delineated. Roads were buffered at either 5 or 7.5 meters depending on the observed right of way width creating road corridor polygons of either 10 or 15 meters wide.

PRE-DISTURBANCE FOREST COVER

The disturbance dataset was used to determine which areas of the forest cover maps needed to be digitized (i.e. which areas need post-disturbance forest cover information). Forest cover information was sought from the forestry maps just prior to the disturbance date. Pre-disturbance forest cover polygons were then clipped to the required disturbance boundary. Land cover, species, and site index attributes were populated for each of the 1910, 1955, 1964, 1975, and 1996 map years from their respective data sources.Areas inundated during the 1915 reservoir raising were inferred based on adjacent mature forest stands from the 1964 map, and missing Council and Lot 87 regions on the 1964 and 1975 map were filled using the 1955 map polygon attributes. Disturbed polygon slivers were eliminated from the pre-distrubance forest cover data set.

VRI DATASET

The VRI data was reformatted from its link table version in order to convert the data into a useable form for merging with the historical data sources. The preliminary nature of the VRI Phase 1 attributing required that the 2012 VRI polygons be augmented with some of the 2006 Modified forestcover attributes through an extraction process to derive missing site index values (Appendix C). These two procedures resulted in the bulk of the processing that was required for the VRI inventory to be compiled with the historical forestcover and disturbance data. Breast height age was also calculated in this process. Due to the more coarse nature of polygon delineation in the VRI dataset relative to the 2006 forest cover inventory, some non-forest polygons had to be added from the 2006 forest cover inventory. In cases where well-delineated, non-forest polygons were present in the 2006 forest cover data and absent in the VRI coverage, the polygons were copied and added [Update] into the VRI dataset. The records added were limited to wetland and bedrock landcover types. These new polygons were given VRI_ID values greater than those assigned to any other GVWSA VRI polygons.

COMPILED DISTURBANCE AND LANDCOVER DATASET

The disturbance dataset and pre-disturbance landcover/forestcover dataset were unioned [Unioned] together to establish all pre-disturbance forest cover types. Attributes were back-casted through previous years in which the stand was undisturbed or only partially disturbed, and the entire 1925 timber cruise map was overlaid with the data set. In some cases, forest stand information was also cast forward to fill in data gaps for undisturbed or partially time polygons. 1925 species and volume fields were populated after the overlay by first calculating the metric equivalent (cubic meters) of the volumes given and then calculating a volume per hectare value for only the forested polygons original cruise block area.

Date of establishment for each disturbed stand was derived from either planting or disturbance information captured in the disturbance attributes. Stands that were planted were given the planting year as their date of establishment, while stands that were not planted and left to regenerate naturally were given a date of establishment of the disturbance date previous to the stand regenerating plus one year. Most pre-1910 establishment dates are based on the 1975 age class mid point as data for this forest cover map was collected when the vast majority of the Sooke watershed had not been disturbed. Also, the scale that the 1975 forest cover map attributes were collected was superior relative to other data sources for Sooke for that era.

Sliver polygons were eliminated using an area less than 100m2 and area to perimeter ratio less than four selection rule. Bedrock and wetland areas were also eliminated based on this rule as because registration errors between these features on each map resulted in an increase in the number of these small features. These features were then re-added using bedrock and wetland features sourced from a combination of the existing VRI wetlands and rock outcrop polygons and 2006 forest cover inventory wetland and rock outcrop polygons that were not evident in the VRI dataset.

The VRI dataset was used to complete the disturbance and landcover dataset for both old growth stands and post-disturbance forest cover. Land cover, species, date of establishment, and site index fields were added for 2012 information. The VRI polygons which intersected with disturbed areas were erased to prevent producing unnecessary sliver polygons. This old forest coverage was then unioned with the historic land cover dataset and the appropriate 2012 fields were populated with the VRI data.

Finally, post-disturbance landcover was captured from the 2012 dataset by clipping the VRI to the extent of the disturbed polygons and then dissolving all attributes except for landcover, species, and date of establishment in the 2012 dataset. The clipped and dissolved 2012 feature was overlaid with the historic disturbance and landcover feature and the appropriate 2012 fields in this coverage were populated. The DE_2012 field for these old stands were already populated in the VRI dataset and these values were preserved.

LIDAR DERIVED SITE INDEX

As the VRI dataset did not include site index values for all stands within the SWSA, a LiDAR derived site index was generated. Using the 20 meter resolution LiDAR height metrics collected in 2006 for the Sooke and Goldstream watersheds and provided by Dr. Olaf Niemann, the 100th height quartile was selected as a measure of stand height. In accordance with common forestry practice of selecting the top height of a site tree within a 10m plot, this LiDAR method, though at a different resolution, conforms to that of Wulder et al. (2010). LiDAR plot (20m cell) heights were scaled up to the stand level. The stand height values, 2012 leading species and age (2006 minus date of establishment in 2012) were input into the Batch SiteTools version 3.3 and site index values were generated using the embedded site index equations. Height (and therefore site index) values were not generated for stands 20 years old or less (date of establishment 1986 and younger) as LiDAR’s ability to capture a representative stand top height values is severely limited). For these stands a site index value from previous inventories was used to populate SI_2012

These LiDAR derived site index values were backcast within the dataset (ie. SI_1996, SI_1975, etc.) for all stands until a point at which the leading species had changed. For stands where this occurred, a site index value that from the historical inventories that coincided with the historical leading species was used.

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10. Errors and Limitations

As a combination of several coverages, each collected at different scales and for different purposes, error is introduced by the omissions and inaccuracies of each data source. The accuracy of these data sources in dependent on the scale to which they were collected. The degree of which the data of different sources spatially agree is dependent on the georeferenceing accuracy. As well, artificial features may exist where the boundaries of datasets collected relative to different basemaps meet.

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11. Software

11.1 Software Description

ArcGIS v9.3.1, ArcGIS v10.0 from ESRI were used for compilation and manipulation of mapping files.

Geomatica v8.0.0 and OrthoEngine v10.3.2 image processing software from PCI, Inc. were used to orthorectify and mosaic the 1911 Sooke Lake mapphotos. Image works, GCP works are the sub-programs of Geomatica that were used in this project.

A HP Designjet T2300 scanner was used for all historical map scanning work (1911 Sooke Lake map except). TIFFs were scanned in at 300 DPI with a "background removal" option enabled. Images were then croppped in Photoshop.

Batch Tools Version 3.3. Developed by Research Branch, BC Ministry of Forests and RamSofy Systems Ltd., Victoria, BC

11.2 Software Access

Geomatica and OrthoEngine are proprietary software developed by PCI, Inc. Contact PCI for details.

PCI, Inc.
50 West Wilmot St.
Richmond Hill
Ontario, Canada   L4B 1M5
(905) 764-0614
(905) 764-9604 (fax)

ArcGIS is proprietary software developed by ESRI. Contact ESRI for details.
ESRI CANADA LIMITED (Pacific Region)
404-1200 West Pender Street
Vancouver, B.C. V6E 2S9
Mr. Myron Doherty
Phone: 604-682-4652
Fax: 604-682-5692
E-mail: pacificsales@esricanada.com
URL: http://www.esricanada.com

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14.1 Document Revision Date

March 24 2014

14.2 Document Author

Byron Smiley, Taylor Denouden, J. Trofymow

14.3 Keywords

Disturbance history, TEM, forest cover, feature class, GIS, Sooke Watershed, Vancouver Island, BC

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15. Data Access

15.1 Contact for Data Centre/ Data Access Information

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Canadian Forest Service/ Service canadien des forets
Natural Resources/ Ressources naturelles Canada
Pacific Forestry Centre/ Centre forestier du Pacifique
506 west Burnside Road, Victoria, B.C. V8Z 1M5
Government of Canada/ Gouvernement du Canada
250-363-0677
250-363-0775 (facs./téléc)
ttrofymow@pfc.forestry.ca

Appendix D –Procedure for LiDAR-derived site index Generation

Byron Smiley

Nov 2013 – January 2014

Procedure: Derivation of LiDAR forest stand height from 2006 Biometrics for the Sooke-Lake Watershed

Note: 2006 LiDAR derived biometrics (20m resolution) courtesy of Dr. Niemann's lab

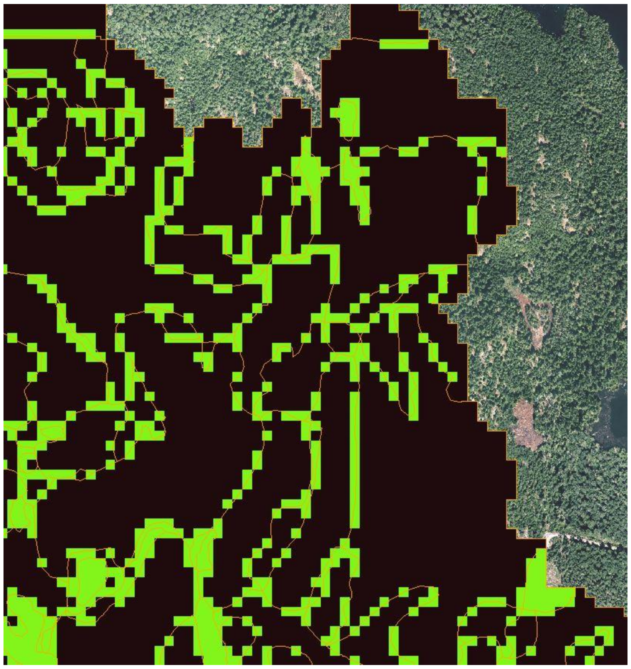
1) Create fishnet (polygons squares and centroid points) from LiDAR biometrics raster

2) Extract Band 21 (100th height quartile) from LiDAR Height Quartile (LDQ) data

3) Determine cells that have >= 85% of their area within a forest cover stand

    a. Dissolve disturbance coverage to include only 2012 age, species and land cover information
    b. Union 2012_AGE_Species data with fishnet to get cells with >=85% within individual polygons
    c. Select and export cells with >=85% area within a polygon
    d. Join to fishnet and populate new "RASTERIZE" field with '1' if "PERCENT" field is NOT NULL (ie. >=85%, interior cell) and '0' if "PERCENT" field IS NULL (ie. <85%, boundary cell)

4) Create a boundary cell filter by Rasterizing data from step (**4d)** to 20m cells with "RASTERIZE" field (Creates bcf_85)



5) Filter out boundary cells from height data **(2)** using raster calculator by multiplying boundary cell filter by height (Creates nbc_85)

6) Convert height = 0 and-0 values into -888 values using raster calculator (Identifies boundary cells)

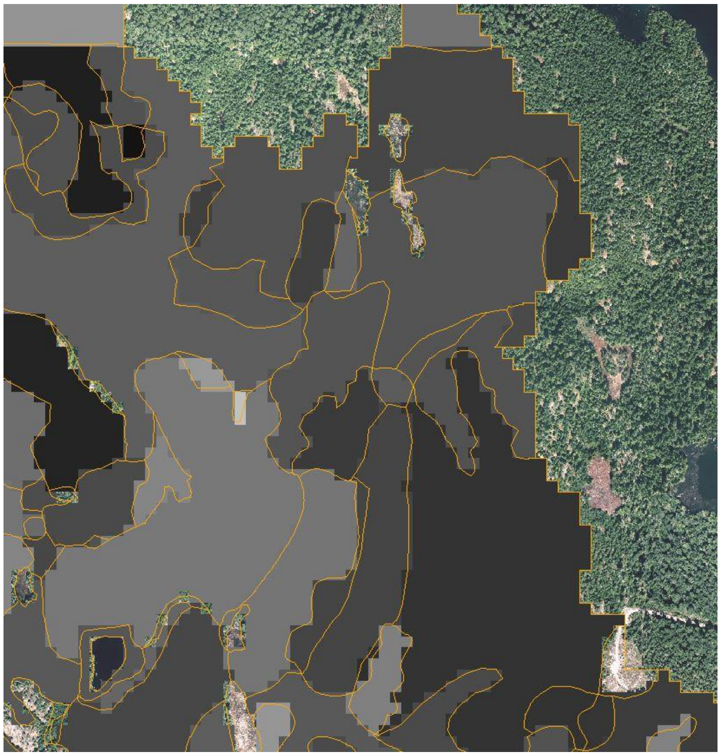
   a. Select 0 and -0 values by creating a new raster (ie. zcs_85) (***(("LiDAR_top_ht_20m") == 0) & (("LiDAR_top_ht_20m") == - 0)***)
   b. Reclass this raster to 1 values =-888 and all others = 0 (ie. zcr_85)
   c. Use raster calculator to ADD this raster to height raster (ie. hrc_85)
   d. Remove odd outliers (heights in stands above 86m (ie. 124))
   e. Select -999 and -888 values using SET NULL and set as NoData (ie. hns_85)

Result → 3.26-81.39 (top height), -999, -888 values = NoData

7) Manually rasterize SP_DE_2012 data using centroids to preserve cell to cell registration with LiDAR height data (intersect) (Rasterize using SP_DE_2012_FID)

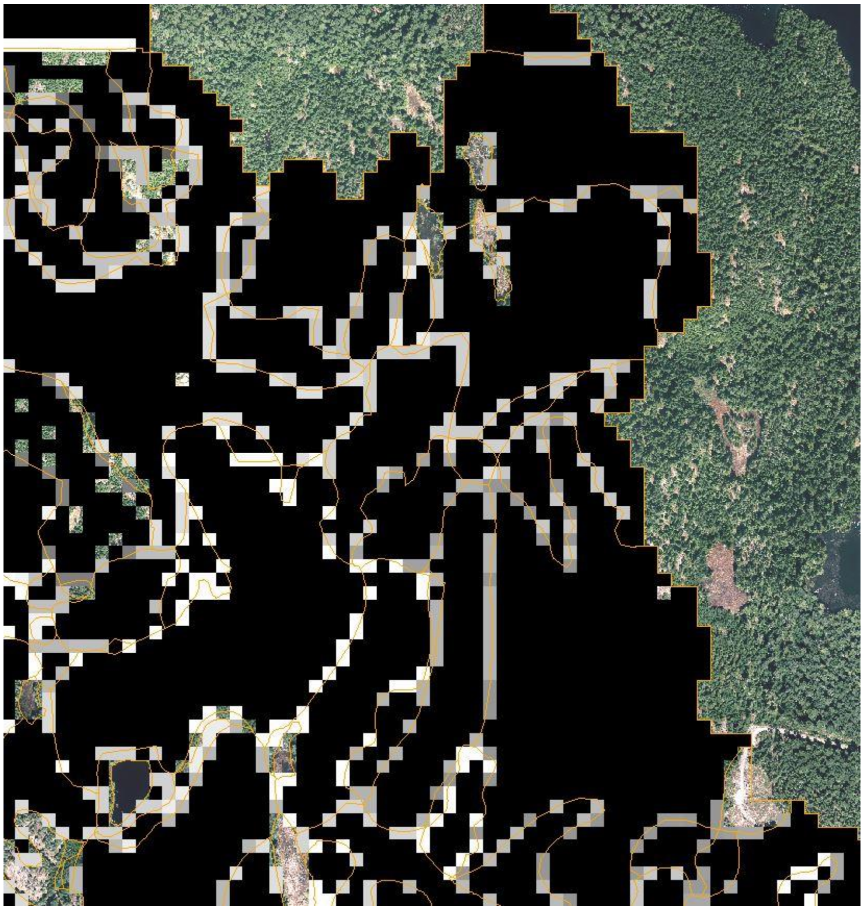
8) Calculate height using interior cells → Zonal Statistics → mean → Step 7 as zone input and Step 6 result as data input

   NOTE: non forest areas were deleted from zones (in step 7)



Result→ Stand mean height using lidar cell top height

9) Populate boundary cells with stand averages to have height on a cell basis



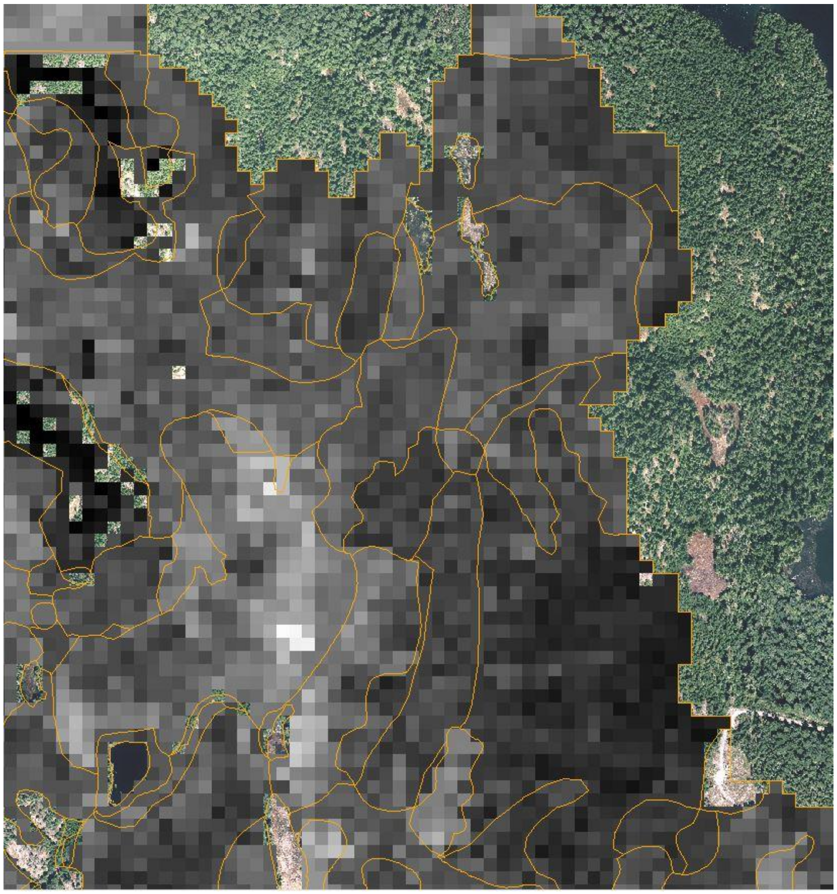
   a. Reclass previously created boundary filter so boundary cells =1 and all others =0
   b. Set -999 values to no data using dataset from step 9a
   c. Raster calculator boundary filter by multiplying with previously created stand height raster (step 8)

10) Using raster calculator, ADD boundary cell height raster (where non-boundary =0) to non-boundary cell height raster (where boundary =0)

Result: Full within polygon height variations with boundary cells populated with polygon averages for which their cell centroid is within

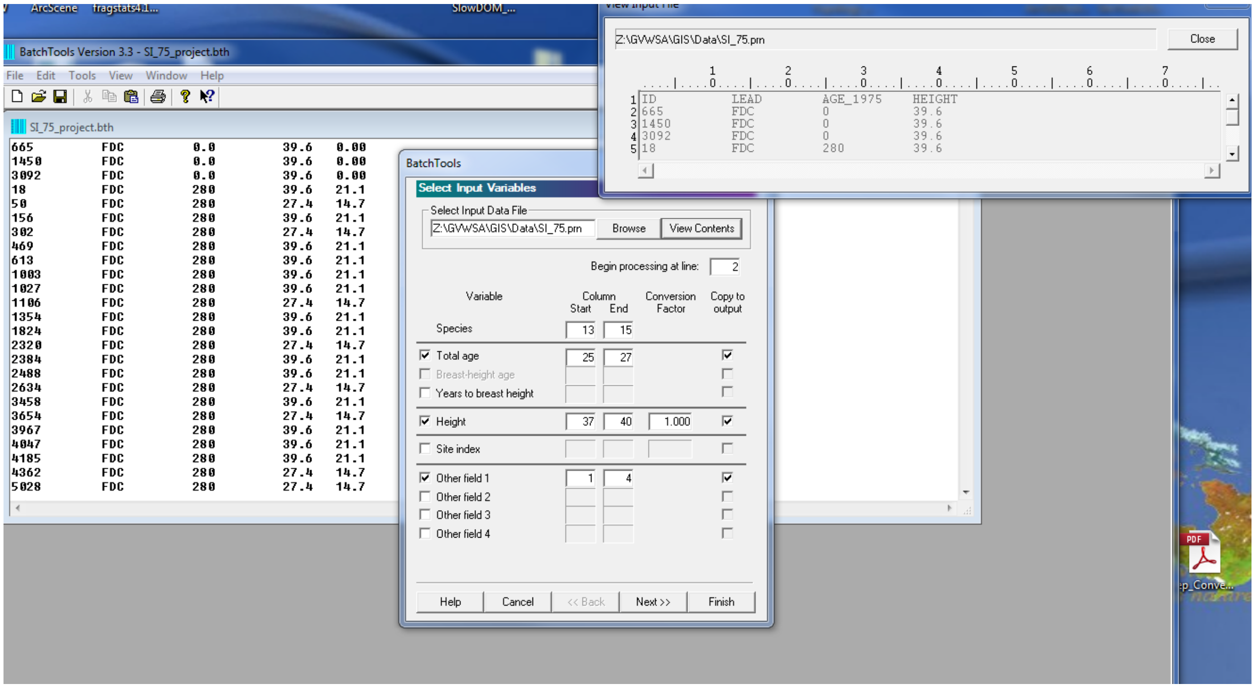
11) Convert LiDAR stand and cell heights into a vector format
   a. Use 'Convert Raster to Point' tool for both the stand height and lidar cell height datasets
   b. 'Spatially Join' (Intersect match option) both files produced in step 11a to the original polygon cell fishnet for the watershed
   c. 'Spatial Join' file created in step 11b to the SP_DE_2012 polygon file using the CONTAINS match option

Result: Species and establishment date as of 2012 polygon layer with lidar derived stand height attribute (step 11b gives you a vector representation that includes the within stand height variation data)



12) Remaining polygons without a height are small polygons that either:
    a. Had zone average heights generated for them but the CONTAINS rule used during the final spatial join did not attribute a height to them as no cell was completely "CONTAINED" within the polygon -- in these cases the stand height attribute must be manually extracted from the stand height raster into the height field of the vector file
    b. Were long narrow polygons that did not have a cell that was >85% within a polygon and therefore no generation of a stand mean height was possible--- in these cases polygon stand height was populated using a stand height from an adjacent polygon with the same (or similar) stand age and composition

13) Run data through SiteTools Batch version 3.3 to calculate site index values
    a. Export attribute table attributes stand species, date of establishment in 2012 and LiDAR derived stand height and OBJECTID (to rejoin to polygons later) to a text or comma separated value table
    b. Reformat species to just leading species value code (NOTE: for douglas-fir and lodgepole pine the coastal codes are FDC and PLC, respectively)
    c. Reformat date of establishment to age (2006 minus 2012 date of establishment (DE_2012))
    d. Save file as a .prn file for input into SiteTools
    e. Open Batch SiteTools version 3.3 (http://www.for.gov.bc.ca/hre/sitetool/getsware.htm) and add input .prn file (Figure 1)



```
665         FDC     0.0     39.6  0.00
1450        FDC     0.0     39.6  0.00
3092        FDC     0.0     39.6  0.00
18          FDC     280     39.6  21.1
50          FDC     280     27.4  14.7
156         FDC     280     39.6  21.1
302         FDC     280     27.4  14.7
469         FDC     280     39.6  21.1
613         FDC     280     39.6  21.1
1003        FDC     280     39.6  21.1
1027        FDC     280     39.6  21.1
1106        FDC     280     27.4  14.7
1354        FDC     280     39.6  21.1
1824        FDC     280     39.6  21.1
2320        FDC     280     27.4  14.7
2384        FDC     280     39.6  21.1
2488        FDC     280     39.6  21.1
2634        FDC     280     27.4  14.7
3458        FDC     280     39.6  21.1
3654        FDC     280     27.4  14.7
3967        FDC     280     39.6  21.1
4047        FDC     280     39.6  21.1
4185        FDC     280     39.6  21.1
4362        FDC     280     27.4  14.7
5028        FDC     280     27.4  14.7
```

Select Input Data File: Z:\GVWSA\GIS\Data\SI_75.prn

Begin processing at line: 2

Variable	Column Start	Column End	Conversion Factor	Copy to output
Species	13	15		
☑ Total age	25	27		☑
☐ Breast-height age				☐
☐ Years to breast height				☐
☑ Height	37	40	1.000	☑
☐ Site index				☐
☑ Other field 1	1	4		☑
☐ Other field 2				☐
☐ Other field 3				☐
☐ Other field 4				☐

Z:\GVWSA\GIS\Data\SI_75.prn

```
         1         2         3         4         5         6         7
....|....0....|....0....|....0....|....0....|....0....|....0....|....0....|..
1 ID          LEAD        AGE_1975    HEIGHT
2 665         FDC         0           39.6
3 1450        FDC         0           39.6
4 3092        FDC         0           39.6
5 18          FDC         280         39.6
```

f. Select input and output column widths, output data file name (.out file), site index source (Site index equations or growth intercept models) and click finish to generate Site index output

g. Rejoin data using OBJECTID to polygonal dataset

Result → polygonal dataset with Batch SiteTools-generated site index values

NOTE: that height (and therefore site index) was not generated for stands 20 years old or less (date of establishment 1986 and younger) as LiDAR's ability to capture a representative stand top height values is severely limited). For these stands a site index value from previous inventories was used to populate SI_2012

Appendix E – Land cover/Forest cover-Disturbance geodataset Data Dictionary (also available from “Sooke_disturbance_schema.xlsx”)

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
1	ObjectID	Identifier	unique ID		Arc generated field.	2297	
2	Shape		Geometry		Field holds the geometry of the feature		
3	AREA	m2	Polygon area (m2)		Geometric calculation in final stages of dataset creation.	292.925811	
4	HECTARES	hectares	Polygon area (hectares)		Geometric calculation in final stages of dataset creation.	0.029292	
5	PERIMETER	m2	Polygon perimeter (m)		Geometric calculation in final stages of dataset creation.	71.44137	
6	LC_CLASS_1910		Land cover classification of polygon in 1910	TC, TM, TB, WE, IN, SH, AG, GP, RZ, BR, LA, RN, TL, RE, RI	Landcover class was mainly derived from landcover type displayed in individual forest cover maps. 1910 values were populated with data from future years when no disturbance occured between these years, and inferred from adjacent stands when disturbance event did take place prior to the next map year in 1955.	TC	
7	LC_DESC	text	Description of LC_CODE	Treed Coniferous, Treed Mixed, Treed Broadleaf, Wetland, Infrastructure, Shrub, Agricultural Land, Gravel Pit, Road Surface, Bedrock, Lake, Railway, Transmission Line, Reservoir, River	Landcover desription is a written name of the 1910 landcover codes	Treed Coniferous	Refer to VRI for coding
8	SPECIES_1910	text	Forestcover species composition in 1910	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species was mainly derived from species infromation contained in individual forest cover maps. 1910 values were populated with data from future years	FD100	

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
9	DE_1910	year	Date of stand establishment as of 1910		Date of establishment was established using one of four methods. When available, the planting date following the previous disturbane date was used as a the date of establishment, and for unplanted stands, the date of establishment was assumed to be the date of previous disturbance plus one year. For old stands which were undisturbed, the VRI date of establishment which was based on tree ring analysis was back-casted through previous years. For forest stands prior to the first known disturbance in an area, the following disturbance year minus the mean fire interval of 127 years was used to estimate an establishment date.	1695	
10	NOTE_1910		Explanation of how DE_1910 was determined		Note fields are a record of which method was used to determine date of establishment		
11	SI_1910	num	Site index as of 1910		Site index was mainly derived from site index information displayed on individual forest cover maps. 1910 values are populated solely from future map data which was back-casted through years where no disturbances occurred.	0	
12	VOLUME	num	Volume of stand in 1910		This field remains unpopulated.	0	*not populated*
13	AGE_1910		Age of stand based on DE_1910 field		This field remains unpopulated.	0	
14	HT_1910		Height of stand in 1910 - not populated		This field remains unpopulated.	0	*not populated*
15	DIST_1_YEAR	year	Year of first stand disturbance		Disturbance year information is populated with values from individual forest cover maps, and inferred values for unknow fire dates derived using aerial imagery.	1930	

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
16	DIST_1_TYPE	text	Type of first stand disturbance	Fw, Fh, Fsb, Fgb, Fpb, Frp, Lc, La, Ll, Lsb, Lrp, Fto	Disturbance type information is populated with data from individual forest cover maps, and was verified using aerial imagery.	Fpb	
17	DIST_2_YEAR	year	Year of second stand disturbance		Disturbance year information is populated with values from individual forest cover maps, and inferred values for unknow fire dates derived using aerial imagery.	1986	
18	DIST_2_TYPE	text	Type of second stand disturbance	Fw, Fh, Fsb, Fgb, Fpb, Frp, Lc, La, Ll, Lsb, Lrp, Fto	Disturbance type information is populated with data from individual forest cover maps, and was verified using aerial imagery.	Lc	
19	DIST_3_YEAR	year	Year of third stand disturbance		Disturbance year information is populated with values from individual forest cover maps, and inferred values for unknow fire dates derived using aerial imagery.	-1	
20	DIST_3_TYPE	text	Type of third stand disturbance	Fw, Fh, Fsb, Fgb, Fpb, Frp, Lc, La, Ll, Lsb, Lrp, Fto	Disturbance type information is populated with data from individual forest cover maps, and was verified using aerial imagery.		
21	DIST_4_YEAR	year	Year of fourth stand disturbance		Disturbance year information is populated with values from individual forest cover maps, and inferred values for unknow fire dates derived using aerial imagery.	-1	
22	DIST_4_TYPE	text	Type of fourth stand disturbance	Fw, Fh, Fsb, Fgb, Fpb, Frp, Lc, La, Ll, Lsb, Lrp, Fto	Disturbance type information is populated with data from individual forest cover maps, and was verified using aerial imagery.		
23	DIST_5_YEAR	year	Year of fifth stand disturbance		Disturbance year information is populated with values from individual forest cover maps, and inferred values for unknow fire dates derived using aerial imagery.	-1	
24	DIST_5_TYPE	text	Type of fifth stand disturbance	Fw, Fh, Fsb, Fgb, Fpb, Frp, Lc, La, Ll, Lsb, Lrp, Fto	Disturbance type information is populated with data from individual forest cover maps, and was verified using aerial imagery.		
25	DIST_6_YEAR	year	Year of sixth stand disturbance		Disturbance year information is populated with values from individual forest cover maps, and inferred values for unknow fire dates derived using aerial imagery.	-1	

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
26	DIST_6_TYPE	text	Type of sixth stand disturbance	Fw, Fh, Fsb, Fgb, Fpb, Frp, Lc, La, Ll, Lsb, Lrp, Fto	Disturbance type information is populated with data from individual forest cover maps, and was verified using aerial imagery.		
27	TREAT_YR_1	year	year of first treatment event		Treatment year information is populated with values from individual forest cover maps.	1987	
28	TREAT_TYPE_1	text	type of first treatment event	P, Fa, Fg, Tp, W, J, G, Pr, M, MP, MG, PG, PTp, MPG	Treatment type information is populated with data from individual forest cover maps.	P	
29	TREAT_YR_2	year	year of second treatment event		Treatment year information is populated with values from individual forest cover maps.	-1	
30	TREAT_TYPE_2	text	type of second treatment event	P, Fa, Fg, Tp, W, J, G, Pr, M, MP, MG, PG, PTp, MPG	Treatment type information is populated with data from individual forest cover maps.		
31	TREAT_YR_3	year	year of third treatment event		Treatment year information is populated with values from individual forest cover maps.	-1	
32	TREAT_TYPE_3	text	type of third treatment event	P, Fa, Fg, Tp, W, J, G, Pr, M, MP, MG, PG, PTp, MPG	Treatment type information is populated with data from individual forest cover maps.		
33	TREAT_YR_4	year	year of fourth treatment event		Treatment year information is populated with values from individual forest cover maps.	-1	
34	TREAT_TYPE_4	text	type of fourth treatment event	P, Fa, Fg, Tp, W, J, G, Pr, M, MP, MG, PG, PTp, MPG	Treatment type information is populated with data from individual forest cover maps.		
35	TREAT_YR_5	year	year of fifth treatment event		Treatment year information is populated with values from individual forest cover maps.	-1	
36	TREAT_TYPE_5	text	type of fifth treatment event	P, Fa, Fg, Tp, W, J, G, Pr, M, MP, MG, PG, PTp, MPG	Treatment type information is populated with data from individual forest cover maps.		
37	CRUISE_ID	Identifier	Cruise block ID		Cruise ID is derived from the block ID given in the 1925 timber cruise map.	29	
38	SPECIES_1_1925	text	leading species in 1925 cruise	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species fields were populated in the order of highest to lowest volume of each timber cruise block species that was given.	Fd	
39	SPECIES_2_1925	text	second species in 1925 cruise	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species fields were populated in the order of highest to lowest volume of each timber cruise block species that was given.		

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
40	SPECIES_3_1925	text	third species in 1925 cruise	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species fields were populated in the order of highest to lowest volume of each timber cruise block species that was given.		
41	DENSITY_SP1	num	Volume of leading species in m3/HA		1925 merchantible volume per hectare values were generated for each species within a given cruise block based on the board feet value given on the map. These values were converted from board feet to cubic meters. Then, using the area of only forested polygons within the cruise block, the cubic meter volume was calcuated on a per hectare basis. This was done for each cruise block with volume information available. Where none existed, a value of zero was entered.	75.391454	
42	DENSITY_SP2	num	Volume of second species in m3/HA		1925 merchantible volume per hectare values were generated for each species within a given cruise block based on the board feet value given on the map. These values were converted from board feet to cubic meters. Then, using the area of only forested polygons within the cruise block, the cubic meter volume was calcuated on a per hectare basis. This was done for each cruise block with volume information available. Where none existed, a value of zero was entered.	0	
43	DENSITY_SP3	num	Volume of third species in m3/HA		1925 merchantible volume per hectare values were generated for each species within a given cruise block based on the board feet value given on the map. These values were converted from board feet to cubic meters. Then, using the area of only forested polygons within the cruise block, the cubic meter volume was calcuated on a per hectare basis. This was done for each cruise block with volume information available. Where none existed, a value of zero was entered.	0	

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
44	NOTES		Notes pertaining to 1925 cruise map use		Notes for the 1925 cruise map were any species information or disturbance notes contained within the individual cruise blocks.		
45	LC_CLASS_1955		Land cover classification of polygon in 1955	TC, TM, TB, WE, IN, SH, AG, GP, RZ, BR, LA, RN, TL, RE, RI	Landcover class was mainly derived from landcover type displayed in individual forest cover maps. 1955 values were populated with data from future years when no disturbance occured between these years, and inferred from adjacent stands where appropriate map coverage was unavailable.	TC	
46	SPECIES_1955	text	Forestcover species composition in 1955	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species was mainly derived from species infromation contained in individual forest cover maps. 1910 values were populated with data from future years when no disturbances occurred between these years.		
47	DE_1955	year	Date of stand establishment as of 1955		Date of establishment was established using one of four methods. When available, the planting date following the previous disturbane date was used as a the date of establishment, and for unplanted stands, the date of establishment was assumed to be the date of previous disturbance plus one year. For old stands which were undisturbed, the VRI date of establishment which was based on tree ring analysis was back-casted through previous years. For forest stands prior to the first known disturbance in an area, the following disturbance year minus the mean fire interval of 127 years was used to estimate an establishment date.	-100	
48	NOTE_1955		Explanation of how DE_1955 was determined		Note fields are a record of which method was used to determine date of establishment		

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
49	SI_1955	num	Site index as of 1955		Site index was mainly derived from site index information displayed on individual forest cover maps. 1955 values are populated solely from future map data which was back-casted through years where no disturbances occurred since this data was unavailable on the 1955 forest cover maps.		
50	HT_1955	num	Height of stand in 1955		Height values are recorded for data sourced from the 1955 forest cover maps, which display the value as a class. This information was recorded as the midpoint of the class range in meters		
51	AGE_1955		Age of stand based on DE_1955 field		Age values are recorded for data sourced from the 1955 forest cover maps, which display the value as a class. This information was recorded as the midpoint of the class range in years.		
52	LC_CLASS_1964		Land cover classification of polygon in 1964	TC, TM, TB, WE, IN, SH, AG, GP, RZ, BR, LA, RN, TL, RE, RI	Landcover class was mainly derived from landcover type displayed in individual forest cover maps. 1964 values were populated with data from future years when no disturbance occured between these years, and inferred from adjacent stands where appropriate map coverage was unavailable.	TC	
53	SPECIES_1964	text	Forestcover species composition in 1964	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species was mainly derived from species infromation contained in individual forest cover maps. 1910 values were populated with data from future years when no disturbances occurred between these years.	FD100	

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
54	DE_1964	year	Date of stand establishment as of 1964		Date of establishment was established using one of four methods. When available, the planting date following the previous disturbane date was used as a the date of establishment, and for unplanted stands, the date of establishment was assumed to be the date of previous disturbance plus one year. For old stands which were undisturbed, the VRI date of establishment which was based on tree ring analysis was back-casted through previous years. For forest stands prior to the first known disturbance in an area, the following disturbance year minus the mean fire interval of 127 years was used to estimate an establishment date.	-100	
55	NOTE_1964		Explanation of how DE_1964 was determined		Note fields are a record of which method was used to determine date of establishment		
56	SI_1964	num	Site index as of 1964		Site index was mainly derived from site index information displayed on individual forest cover maps. 1964 values are populated with future map data which was back-casted through years where no disturbances occurred.	0	
57	LC_CLASS_1975		Land cover classification of polygon in 1975	TC, TM, TB, WE, IN, SH, AG, GP, RZ, BR, LA, RN, TL, RE, RI	Landcover class was mainly derived from landcover type displayed in individual forest cover maps. 1975 values were populated with data from future years when no disturbance occured between these years, and inferred from adjacent stands where appropriate map coverage was unavailable.	TC	
58	SPECIES_1975	text	Forestcover species composition in 1975	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species was mainly derived from species infromation contained in individual forest cover maps. 1910 values were populated with data from future years when no disturbances occurred between these years.		

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
59	DE_1975	year	Date of stand establishment as of 1975		Date of establishment was established using one of four methods. When available, the planting date following the previous disturbane date was used as a the date of establishment, and for unplanted stands, the date of establishment was assumed to be the date of previous disturbance plus one year. For old stands which were undisturbed, the VRI date of establishment which was based on tree ring analysis was back-casted through previous years. For forest stands prior to the first known disturbance in an area, the following disturbance year minus the mean fire interval of 127 years was used to estimate an establishment date.	-100	
60	NOTE_1975		Explanation of how DE_1975 was determined		Note fields are a record of which method was used to determine date of establishment		
61	SI_1975	num	Site index as of 1975		Site index was mainly derived from site index information displayed on individual forest cover maps. 1975 values are populated with future map data which was back-casted through years where no disturbances occurred.	0	
62	LC_CLASS_1996		Land cover classification of polygon in 1996	TC, TM, TB, WE, IN, SH, AG, GP, RZ, BR, LA, RN, TL, RE, RI	Landcover class was mainly derived from landcover type displayed in individual forest cover maps. 1996 values were populated with data from future years when no disturbance occured between these years, and inferred from adjacent stands where appropriate map coverage was unavailable.	TC	
63	SPECIES_1996	text	Forestcover species composition in 1996	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	Species was mainly derived from species infromatic	FD080PL015 HW005	

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
64	DE_1996	year	Date of stand establishment as of 1996		Date of establishment was established using one of four methods. When available, the planting date following the previous disturbane date was used as a the date of establishment, and for unplanted stands, the date of establishment was assumed to be the date of previous disturbance plus one year. For old stands which were undisturbed, the VRI date of establishment which was based on tree ring analysis was back-casted through previous years. For forest stands prior to the first known disturbance in an area, the following disturbance year minus the mean fire interval of 127 years was used to estimate an establishment date.	1987	
65	NOTE_1996		Explanation of how DE_1996 was determined		Note fields are a record of which method was used to determine date of establishment	Planting date	
66	SI_1996	num	Site index as of 1996		Site index was mainly derived from site index information displayed on individual forest cover maps. 1996 values are populated with future map data which was back-casted through years where no disturbances occurred.	21	
67	LC_CLASS_2012		Land cover classification of polygon in 2012	TC, TM, TB, WE, IN, SH, AG, GP, RZ, BR, LA, RN, TL, RE, RI	Landcover class was mainly derived from the leading landcover class depicted in the VRI dataset, some alterations were made to reflect a consistent land cover code scheme	TC	
68	SPECIES_2012	text	Forestcover species composition in 2012	Ba, Cw, Dr, Fd, Hw, Mb, Yc, Pw, Pl, Ss, Se, Ra, Pj	This field was generated from the concatenation of 5 possible species and percent composition fields within the Sooke-Council study area. These fields are found the the VRI TREE_SPECIES_ESTIMATED table	FD080PL015 HW005	

#	Field Name	Unit	Description	Permissible Values	Source	Example	Notes
69	DE_2012	year	Date of stand establishment as of 2012		This field was initially generated from VRI reference year minus the age of the leading species. Changes were subsequently made to reflect known disturbance and planting dates of the stand that were not reflected in the VRI stand age value	1987	
70	NOTE_2012		Explanation of how DE_2012 was determined		This field was populated during the corroboration of age/stand establishment dates and describes how and what values were altered	Planting date	
71	SI_2012	num	Site index as of 2012		This field is a compilation of estimated site index values from 2 VRI tables (TREE_COVER_LAYER_ESTIMATED, TREE_SPECIES_ESTIMATED) and site index values generated from leading species age and height attributes using BCMOF SiteTools Batch software	21	
72	VRI_ID	num	Unique ID refering to the VRI polygon from which 2012 attributes were used		This is a VRI generated ID field	0	
73	COVER_STATUS	text	Describes the current status (2012) of the polygon	DF (Disturbed forest) OF (Original Forest), NF (Non-forest), DE (Deforested), AF (Afforested))	Generated from current land cover and past disturbance event information	DF	
74	Shape_Length	meters	ArcGIS generated polygon perimeter field		Generated by ArcGIS on the fly	3453.850151	
75	Shape_Area		ArcGIS generated polygon area field		Generated by ArcGIS on the fly	154956.5688	

Appendix F – Land Clearing logging and biofuel removal Disturbance Matrix

Dist_ Code	SoDist_ ID	Source	Sink	Proportion of Source Pool to Sink Pool
Llb	1024	Softwood Submerchantable	Products	1
Llb	1024	Softwood Stem Snag	Products	1
Llb	1024	Softwood Other	Products	0.86
Llb	1024	Softwood Other	Aboveground Fast DOM	0.14
Llb	1024	Softwood Merchantable Stemwood	Products	1
Llb	1024	Softwood Foliage	Aboveground Very Fast DOM	1
Llb	1024	Softwood Fine Roots	Belowground Very Fast DOM	0.5
Llb	1024	Softwood Fine Roots	Aboveground Very Fast DOM	0.5
Llb	1024	Softwood Coarse Roots	Aboveground Fast DOM	0.5
Llb	1024	Softwood Coarse Roots	Belowground Fast DOM	0.5
Llb	1024	Softwood Branch Snag	Products	1
Llb	1024	Peat	Peat	1
Llb	1024	Medium DOM	Medium DOM	1
Llb	1024	Hardwood Submerchantable	Products	1
Llb	1024	Hardwood Stem Snag	Products	1
Llb	1024	Hardwood Other	Products	0.86
Llb	1024	Hardwood Other	Aboveground Fast DOM	0.14
Llb	1024	Hardwood merchantable stemwood	Products	1
Llb	1024	Hardwood Foliage	Aboveground Very Fast DOM	1
Llb	1024	Hardwood Fine Roots	Belowground Very Fast DOM	0.5
Llb	1024	Hardwood Fine Roots	Aboveground Very Fast DOM	0.5
Llb	1024	Hardwood Coarse roots	Aboveground Fast DOM	0.5
Llb	1024	Hardwood Coarse roots	Belowground Fast DOM	0.5
Llb	1024	Hardwood Branch Snag	Products	1
Llb	1024	Black Carbon	Black Carbon	1
Llb	1024	Belowground Very Fast DOM	Belowground Very Fast DOM	1
Llb	1024	Belowground Slow DOM	Belowground Slow DOM	1
Llb	1024	Belowground Fast DOM	Belowground Fast DOM	1
Llb	1024	Aboveground Very Fast DOM	Aboveground Very Fast DOM	1
Llb	1024	Aboveground Slow DOM	Aboveground Slow DOM	1
Llb	1024	Aboveground Fast DOM	Belowground Fast DOM	1

Appendix G –Procedure: Input, generation and display of spatial data from CBM-CFS3

Byron Smiley
May 2014 – June 2014

Procedure: Input, generation and display of spatial data from CBM-CFS3

Programs used:

- **Recliner (Hammock)**
    - **Contact:** Max Fellows, Scott Morken
    - **Description:** program to covert or combine vector files (i.e polygonal…..shp, feature class, etc.) to raster files and partition into unique, rasterized parameter groups for input into CBM-CFS3. Recliner can base the unique parameter groups on the attributes of the vector file
- **Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3):**
    - **Contact:** Stephen Kull et al.
    - **Description:** landscape level model of forest ecosystem carbon dynamics
- **CBMPlotter:**
    - **Contact:** Gary Zhang
    - **Description:** uses the parameter group raster generated from Recliner and spatially explicit output from CBM-CFS3 to generate .tif rasters of specific model results (i.e. Above ground biomass) for each timestep of the simulation period
- **ArcGIS (ArcCatalog and ArcMap) Version 10.2.1:**
    - **Contact:** ESRI Canada
    - **Description:** program to manage analyze and display geographic data—specifically for the purposes of this procedure: time series data

Procedure:

14) Recliner Input

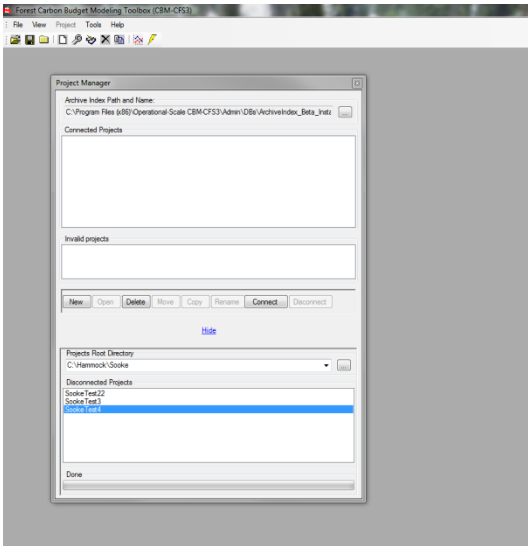
a. Inputs required for Recliner:
    i. **Spatial data file[39]** (vector or raster or both). For Vector, file can be a .shp file or a feature class within a geodatabase.

---

[39] For the Sooke Recliner run, a few small conversions had to be performed on the Sooke_forestcover_disturbance_dataset in order to have the input data in an acceptable format.

   ii. **Landscape file** (vector or raster). This file is used to define the spatial extent of the study area. If the landscape file is a raster it also identifies the starting pixel location and pixel size (you also need to select pixel area in Global setting in config file). If vector you must specify the pixel size within the Landscape section and Global setting section of the config file.
   iii. **Lookup tables** (csv or spreadsheets in a workbook (xls)) In the current form of Recliner the necessary lookup tables are:
      1. Year_Timestep – a table that specifies all years where a disturbance event occurs (no problem with putting all years of your simulation in this table).
      2. Species – table used to link Species code names within the spatial data to CBM-recognized species names.
      3. SpeciesAfter – used to identify species to be transitioned to post disturbance event. This lookup table can simply use the same table as the "Species" lookup
      4. DistType_workaround - table used to map disturbance codes within the spatial data to the "DisturbanceType" in the ArchiveIndex[40]
      5. GrowthCurves – this table is where all growth and yield curve data resides. Note: for Recliner to run properly growth and yield curves must exist for EVERY unique combination of classifiers (because of the potential for this table to be so large it is best to save this table as a .csv).

b. Create and format config.yml to map polygonal data for CBM input
   i. See "configAndComments.yml" for extensive comments on process to populate config file
   ii. Using command prompt: run recliner and point to location of config file (i.e. "C:\Hammock\bin\release\recliner.exe C:\Hammock\Sooke\config.yml"
   iii. If errors occur during Recliner run use error log file to resolve errors located at :



Archive Index Path and Name: C:\Program Files (x86)\Operational-Scale CBM-CFS3\Admin\DBs\ArchiveIndex_Beta_Insta

Projects Root Directory: C:\Hammock\Sooke

Disconnected Projects:
SookeTest22
SookeTest3
SookeTest4

---

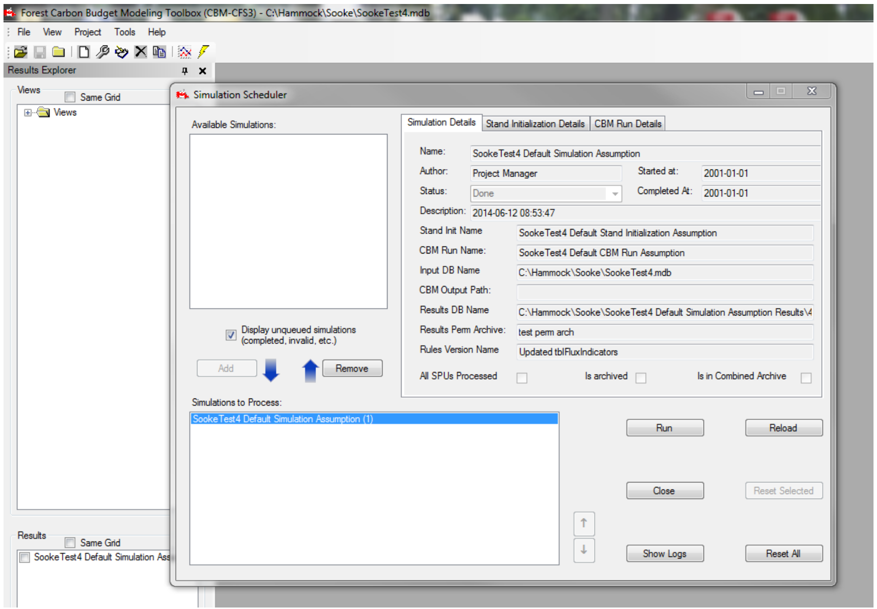
[40] The Archive Index database located within the CBM-CFS3 files at: "C:\Program Files (x86)\Operational-Scale CBM-CFS3\Admin\DBs" called "ArchiveIndex_Beta_Install.mdb" is where the Disturbance types (that are also linked to the disturbance matrices) are located

“C:\Hammock\Recliner\bin\Release\recliner-log.txt”

- iv. Recliner outputs:
  1. Parameter_groups.tif – this images groups all “like pixels” based off of disturbance date, type, and stand transition attributes and codes with a unique identifier. For the Sooke run there were 4020 parameter groups.
  2. A Microsoft Access database containing all necessary CBM-CFS3 input parameter values. This database is named based off the “ProjectDBFilePath” located in the config.yml file’s Global Setting section

15) CBM-CFS3

- a. Open CBM-CFS3 and connect to project (mdb) that was named in Recliner under “ProjectDBFilePath”. Double click on the connected project
- b. Under tools go to Simulation Scheduler and from “Simulations available” add your project to “simulations to process”. Click “Run.
- c. After the simulation is run you can explore results using the contemporary “Results Explorer”. Two CBM-CFS3 output files that contain model results must be moved to your master folder in order to run CBMPlotter. These files are: “SpatialFluxInd.out” and “spatialpool.out” located at: “C:\Program Files (x86)\Operational-Scale CBM-CFS3\Temp\CBMRun\output”



Forest Carbon Budget Modeling Toolbox (CBM-CFS3) - C:\Hammock\Sooke\SookeTest4.mdb

Simulation Scheduler

Simulation Details

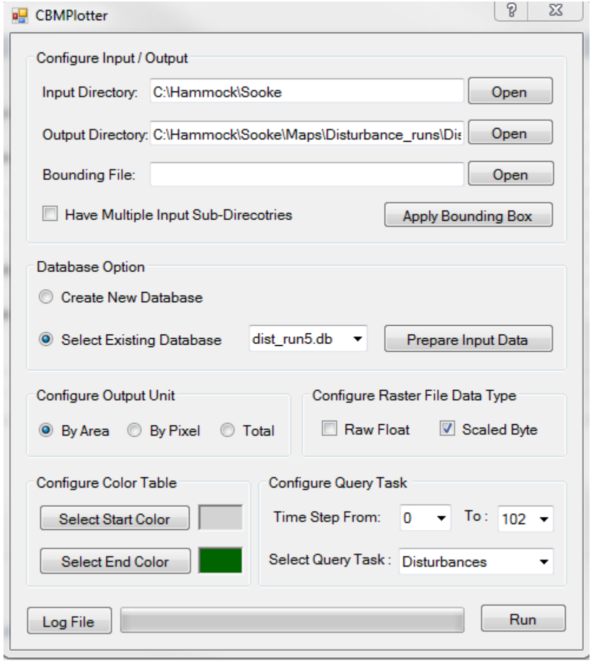
Name: SookeTest4 Default Simulation Assumption
Author: Project Manager
Started at: 2001-01-01
Status: Done
Completed At: 2001-01-01
Description: 2014-06-12 08:53:47
Stand Init Name: SookeTest4 Default Stand Initialization Assumption
CBM Run Name: SookeTest4 Default CBM Run Assumption
Input DB Name: C:\Hammock\Sooke\SookeTest4.mdb
CBM Output Path:
Results DB Name: C:\Hammock\Sooke\SookeTest4 Default Simulation Assumption Results\4
Results Perm Archive: test perm arch
Rules Version Name: Updated tblFluxIndicators
All SPUs Processed ☐ Is archived ☐ Is in Combined Archive ☐

☑ Display unqueued simulations (completed, invalid, etc.)

Simulations to Process:
SookeTest4 Default Simulation Assumption (1)

Results ☐ Same Grid
☐ SookeTest4 Default Simulation Ass

16) CBMPlotter



CBMPlotter

Configure Input / Output
Input Directory: C:\Hammock\Sooke
Output Directory: C:\Hammock\Sooke\Maps\Disturbance_runs\Di
Bounding File:
☐ Have Multiple Input Sub-Direcotries

Database Option
○ Create New Database
● Select Existing Database: dist_run5.db

Configure Output Unit
● By Area ○ By Pixel ○ Total

Configure Raster File Data Type
☐ Raw Float ☑ Scaled Byte

Configure Color Table
Select Start Color
Select End Color

Configure Query Task
Time Step From: 0 To: 102
Select Query Task: Disturbances

a. In addition to the two CBM-CFS3 output files located in your master file, the “parameter_groups.tif” must also be located here and renamed :”parameter_groups.tiff”
b. Two .xml files must be within your master folder. These two files called “query.xml” and “tasks.xml” select a predetermined set of CBM-CFS3 results and assign them to the parameter group value within the .tiff raster.
c. Select the master folder as the “Input Directory” and the location you want your output images sent as your “Output Directory”.
d. Create a new results database (.db) – this file gets created in your Input Directory, and click “Prepare Input Data”
e. Configure Output Unit:
    i. By Area: this value is generated on a per hectare basis (i.e. tons of carbon per hectare)
    ii. By Pixel: this will generate values based on the resolution of the raster (if pixels are 20m x 20m then a carbon value will be for the total within that pixel)
    iii. Total: this will generate values based on the total for individual parameter groups (this is also the value that shows up in the .csv files that are generated during any CBMPlotter run)[41]
f. Configure Query Task:
    i. Time step: select the simulation timespan you wish to created raster for
    ii. Select Query Task: determines the query you will use for your raster output (i.e. disturbance, above ground biomass, NPP, NBP, etc.)[42]

17) ArcGIS 10.2.1

a. Creating animation with complete time series (i.e. aboveground biomass, NPP, etc.)
    i. Using ArcCatalog create a mosaic dataset within the file geodatabase
    ii. Right click “Add Rasters” and select all raster from the time series generated from CBMPlotter run
    iii. After adding raster you may need to calculate statistics--- in ArcCatalog right click the mosaic dataset and under enhance, calculate statisics
    iv. Open mosaic dataset in ArcMap and add a “Time Series Attribute” to the attribute table of the mosaic dataset
    v. Under the mosaic dataset’s properties select the “Time” tab and enable time on this layer, fill in all other necessary components

---

[41] When plotting disturbances in CBMPlotter always use the Total method as the Output unit

[42] If unique or new queries are required they must be written into the tasks.xml and queries.xml scripts (consult Max Fellows and Scott Morken)

    vi. Select the “Time Slider” within the Standard Toolbar – here you can edit the playback speed, add a time display, change time display format and export the animation as an .avi file. If you want to add other map elements to the animation you must create them in layout view (as you would any other map in ArcMap) and export from layout view[43]

b. Creating animation with incomplete time series (i.e. Disturbances, etc.)[44]
    i. Convert time series rasters to integer rasters using “Int” tool in Arc[45]
    ii. Use “Reclassify” tool with lookup table to reclassify CBM output disturbance type IDs to original input disturbance types
    iii. Using ArcCatalog create a mosaic dataset within the file geodatabase
    iv. Right click “Add Rasters” and select all raster from the time series generated from CBMPlotter run
    v. In order for a time series to work in ArcGIS it must be continuous. For years where a disturbance raster does not exist you must add a blank (NoData) raster into the disturbance matrix (difference between simulation length and number or raster generated for disturbance output is the number of NoData raster that must be added to the mosaic dataset.

---

[43] It is possible to overlay layers in the same animation if they move at the same timestep

[44] Because CBM-CFS3 and Recliner require that each disturbance in a given year be unique, the process copies and assigns a new unique disturbanceID in order to allow for same disturbances in a given year with different transitions. Because of this, it may be necessary to reclassify your CBMPlotter output (specifically for disturbances) in order to symbolize disturbance according to your original disturbance types. Section 4(b) covers this process.

[45] This should be run as a python script ‘for loop’ if the simulation length (i.e. number of rasters) is large

Appendix H – DOC load model selection results (Chapter 4 appendices)

Rithet

```
LOADEST
      A Program to Estimate Constituent Loads
U.S. Geological Survey, Version for R 0.1 (June, 2013)
----------------------------------------------------
Station: Rithet
Constituent: DOC_rithet
--------------------------------------------------------------------
   Constituent Output File Part Ia: Calibration (Load Regression)
--------------------------------------------------------------------
         Number of Observations: 19
Number of Uncensored Observations: 19
         Center of Decimal Time: 2002.439
               Center of ln(Q): 2.6373
              Period of record: 1997-08-27 to 2008-11-07
Model Evaluation Criteria Based on AMLE Results
----------------------------------------------
  model   AIC  SPCC  AICc
1     1 25.62 28.45 27.22
2     2 27.38 31.16 30.24
3     3 27.62 31.39 30.47
4     4 21.18 25.90 25.79
5     5 29.37 34.10 33.99
6     6 22.26 27.92 29.26
7     7 23.18 28.84 30.18
8     8 24.24 30.85 34.42
9     9 26.11 33.66 40.51
Model # 4 selected
Selected Load Model:
--------------------
DOC_rithet ~ model(4)
where:
  DOC_rithet is the constituent load in log(kg/d)
and model 4 has these variables:
  lnQ is ln(Q) - center of ln(Q)
  sin.DECTIME is sine(2 * pi * decimal time)
  cos.DECTIME is cosine(2 * pi * decimal time)
Model coefficients:
            Estimate Std. Error   z-score p-value
(Intercept)  4.285173    0.13871 30.892265  0.0000
lnQ          1.308008    0.06458 20.253339  0.0000
sin.DECTIME -0.374030    0.13586 -2.753037  0.0053
cos.DECTIME -0.002129    0.25739 -0.008272  0.9926
AMLE Regression Statistics
Residual variance: 0.1336
R-squared: 98.34 percent
G-squared: 77.83 on 3 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9874
  p-value = 0.7905
```

```
Serial Correlation of Residuals: 0.1215
Correlation Between Explanatory Variables
----------------------------------------
        lnQ    sin.DECTIME
sin.DECTIME 0.2070
cos.DECTIME 0.7405 0.3554
Correlation Between Variable Coefficients
----------------------------------------
        lnQ     sin.DECTIME
sin.DECTIME  0.0894
cos.DECTIME -0.7293 -0.3074
Variance Inflation Factors:
         VIF
lnQ        2.232
sin.DECTIME 1.154
cos.DECTIME 2.445
Comparison of Observed and Estimated Loads
------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated loads for all dates/times within
the calibration data set. Although this comparison does not directly
address errors in load estimation for unsampled dates/times, large
discrepancies between observed and estimated loads are indicative of a
poor model fit. Additional details and warnings are provided below.
Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.
    Summary Stats: Loads in kg/d
--------------------------------------------
   Min  25% 50%  75%  90%   95%   Max
Est 1.21 60.7 240 1300 2500 16500 16500
Obs 1.12 61.6 226 1620 2820 13600 13600
Bias Diagnostics
----------------
 Bp: 11.34 percent
PLR: 1.113
  E: 0.9479
where:
   Bp Load Bias in Percent
    Positive (negative) values indicate over (under) estimation.
    ***The model should not be used when the + or - bias exceeds 25%***
  PLR Partial Load Ratio
    Sum of estimated loads divided by sum of observed loads.
    Values greater than 1 indicate over estimation.
    Values less than 1 indicate under estimation.
   E Nash Sutcliffe Efficiency Index
    E ranges from -infinity to 1.0
    E = 1; a perfect fit to observed data.
    E = 0; model estimates are as accurate as the mean of observed data.
    E < 0; the observed mean is a better estimate than the model estimates.
NOTE: Additional information on model calibration is included in the
    residual diagnostic plots. users should conduct a thorough
    residuals analysis. Example residual plots are shown in figures
    7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).
----------------------------------------------------------------------
```

```
    Constituent Output File Part Ia: Calibration (Concentration Regression)
------------------------------------------------------------------------
Model # 4 selected
Selected Concentration Model:
-----------------------------
DOC_rithet ~ model(4)
where:
   DOC_rithet is the constituent concentration in log(mg/L)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
             Estimate Std. Error   z-score p-value
(Intercept)  0.753212    0.13871  5.429987  0.0000
lnQ          0.308008    0.06458  4.769230  0.0000
sin.DECTIME -0.374030    0.13586 -2.753037  0.0053
cos.DECTIME -0.002129    0.25739 -0.008272  0.9926
AMLE Regression Statistics
Residual variance: 0.1336
R-squared: 77.16 percent
G-squared: 28.06 on 3 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9874
  p-value = 0.7905
Serial Correlation of Residuals: 0.1215
Comparison of Observed and Estimated Concentrations
--------------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated concentrations for all dates/times
within the calibration data set. Although this comparison does not directly
address errors in concentration estimation for unsampled dates/times, large
discrepancies between observed and estimated concentrations are indicative of
a poor model fit. Additional details and warnings are provided below.
Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.
      Summary Stats: Concentrations in mg/L
---------------------------------------------
     Min  25%  50%  75%  90%  95%  Max
Est 1.08 1.77 3.32 4.98 6.31 10.3 10.3
Obs 0.60 1.97 2.48 6.00 7.10  8.5  8.5
Bias Diagnostics
----------------
 Bp: 1.684 percent
PCR: 1.017
  E: 0.7549
where:
   Bp Concentration Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PCR Partial Concentration Ratio
      Sum of estimated concentrations divided by sum of observed concentrations.
```

```
     Values greater than 1 indicate over estimation.
     Values less than 1 indicate under estimation.
   E Nash Sutcliffe Efficiency Index
     E ranges from -infinity to 1.0
     E = 1; a perfect fit to observed data.
     E = 0; model estimates are as accurate as the mean of observed data.
     E < 0; the observed mean is a better estimate than the model estimates.
NOTE: Additional information on model calibration is included in the
     residual diagnostic plots. users should conduct a thorough
     residuals analysis. Example residual plots are shown in figures
     7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).
```

Judge

```
LOADEST
      A Program to Estimate Constituent Loads
U.S. Geological Survey, Version for R 0.1 (June, 2013)
----------------------------------------------------

Station: judge
Constituent: DOC_daily

--------------------------------------------------------------------
   Constituent Output File Part Ia: Calibration (Load Regression)
--------------------------------------------------------------------

          Number of Observations: 14
Number of Uncensored Observations: 14
          Center of Decimal Time: 2002.929
                Center of ln(Q): 2.6467
               Period of record: 1997-10-09 to 2008-11-07

Model Evaluation Criteria Based on AMLE Results
---------------------------------------------

  model   AIC  SPCC  AICc
1     1 24.96 26.88 27.36
2     2 24.92 27.47 29.36
3     3 25.69 28.24 30.13
4     4 14.73 17.92 22.23
5     5 23.64 26.84 31.14
6     6 13.42 17.25 25.42
7     7 15.68 19.52 27.68
8     8 11.35 15.82 30.01
9     9 13.07 18.18 41.87
Model # 8 selected

Selected Load Model:
--------------------

DOC_daily ~ model(8)

where:
  DOC_daily is the constituent load in log(kg/d)
and model 8 has these variables:
  lnQ is ln(Q) - center of ln(Q)
```

```
   lnQ2 is ln(Q) - center of ln(Q))^2
   DECTIME is decimal time - center of decimal time
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
            Estimate Std. Error z-score p-value
(Intercept)   5.1634    0.19791 26.0896  0.0000
lnQ           1.0179    0.08154 12.4826  0.0000
lnQ2          0.1181    0.05523  2.1393  0.0118
DECTIME       0.0534    0.03249  1.6434  0.0436
sin.DECTIME  -0.4759    0.11787 -4.0378  0.0001
cos.DECTIME  -0.2378    0.26736 -0.8895  0.2505

AMLE Regression Statistics
Residual variance: 0.08478
R-squared: 96.03 percent
G-squared: 45.16 on 5 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9681
  p-value = 0.3241
Serial Correlation of Residuals: -0.194

Correlation Between Explanatory Variables
---------------------------------------

            lnQ     lnQ2    DECTIME sin.DECTIME
lnQ2         0.0000
DECTIME     -0.2541 -0.2890
sin.DECTIME  0.0326 -0.1200 -0.1929
cos.DECTIME  0.3031 -0.0020  0.0284  0.0408

Correlation Between Variable Coefficients
---------------------------------------

            lnQ     lnQ2    DECTIME sin.DECTIME
lnQ2         0.0941
DECTIME      0.2914  0.3329
sin.DECTIME  0.0516  0.1914  0.2452
cos.DECTIME -0.3247 -0.0452 -0.1308 -0.0633

Variance Inflation Factors:
              VIF
lnQ         1.204
lnQ2        1.141
DECTIME     1.267
sin.DECTIME 1.082
cos.DECTIME 1.121

Comparison of Observed and Estimated Loads
----------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated loads for all dates/times within
the calibration data set. Although this comparison does not directly
```

```
address errors in load estimation for unsampled dates/times, large
discrepancies between observed and estimated loads are indicative of a
poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Loads in kg/d
-------------------------------------------
     Min  25% 50% 75%  90%  95%  Max
Est 37.3 74.7 156 238  906 1370 1370
Obs 31.8 82.2 149 230 1020 1340 1340

Bias Diagnostics
----------------
 Bp: 0.2758 percent
PLR: 1.003
  E: 0.9857

where:
   Bp Load Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PLR Partial Load Ratio
      Sum of estimated loads divided by sum of observed loads.
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

----------------------------------------------------------------------
    Constituent Output File Part Ia: Calibration (Concentration Regression)
----------------------------------------------------------------------

Model # 8 selected

Selected Concentration Model:
----------------------------

DOC_daily ~ model(8)

where:
   DOC_daily is the constituent concentration in log(mg/L)
and model 8 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   lnQ2 is ln(Q) - center of ln(Q))^2
```

```
   DECTIME is decimal time - center of decimal time
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
            Estimate Std. Error z-score p-value
(Intercept)  1.62204    0.19791  8.1958  0.0000
lnQ          0.01786    0.08154  0.2190  0.7723
lnQ2         0.11815    0.05523  2.1393  0.0118
DECTIME      0.05340    0.03249  1.6434  0.0436
sin.DECTIME -0.47592    0.11787 -4.0378  0.0001
cos.DECTIME -0.23783    0.26736 -0.8895  0.2505

AMLE Regression Statistics
Residual variance: 0.08478
R-squared: 78.89 percent
G-squared: 21.77 on 5 degrees of freedom
P-value: 0.0006
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9681
  p-value = 0.3241
Serial Correlation of Residuals: -0.194


Comparison of Observed and Estimated Concentrations
--------------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated concentrations for all dates/times
within the calibration data set. Although this comparison does not directly
address errors in concentration estimation for unsampled dates/times, large
discrepancies between observed and estimated concentrations are indicative of
a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Concentrations in mg/L
---------------------------------------------
     Min  25%  50%  75%  90%  95%  Max
Est 3.11 3.28 5.27 6.36 10.2 11.3 11.3
Obs 2.80 3.50 4.65 9.70 10.4 11.1 11.1

Bias Diagnostics
----------------
 Bp: -0.3179 percent
PCR: 0.9968
  E: 0.7914

where:
   Bp Concentration Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PCR Partial Concentration Ratio
      Sum of estimated concentrations divided by sum of observed concentrations.
```

```
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).
```

Council

```
LOADEST
       A Program to Estimate Constituent Loads
U.S. Geological Survey, Version for R 0.1 (June, 2013)
----------------------------------------------------

Station: Council
Constituent: DOC_council

--------------------------------------------------------------------
    Constituent Output File Part Ia: Calibration (Load Regression)
--------------------------------------------------------------------

           Number of Observations: 12
Number of Uncensored Observations: 12
           Center of Decimal Time: 2001.259
                  Center of ln(Q): 2.7359
                 Period of record: 1997-10-09 to 2004-11-25

Model Evaluation Criteria Based on AMLE Results
---------------------------------------------

  model   AIC  SPCC  AICc
1     1 17.73 19.18 20.73
2     2 19.66 21.60 25.38
3     3 19.65 21.59 25.36
4     4 13.78 16.20 23.78
5     5 21.62 24.05 31.62
6     6 15.75 18.66 32.55
7     7 15.78 18.68 32.58
8     8 17.75 21.14 45.75
9     9 14.45 18.33 62.45
Model # 4 selected

Selected Load Model:
--------------------

DOC_council ~ model(4)

where:
   DOC_council is the constituent load in log(kg/d)
and model 4 has these variables:
```

```
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
            Estimate Std. Error z-score p-value
(Intercept)   4.9761     0.2766  17.991  0.0000
lnQ           1.2261     0.1403   8.738  0.0000
sin.DECTIME  -0.3361     0.1604  -2.095  0.0220
cos.DECTIME  -0.4535     0.4238  -1.070  0.2051

AMLE Regression Statistics
Residual variance: 0.1203
R-squared: 95.37 percent
G-squared: 36.86 on 3 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9721
  p-value = 0.4792
Serial Correlation of Residuals: 0.4412

Correlation Between Explanatory Variables
---------------------------------------

            lnQ     sin.DECTIME
sin.DECTIME -0.3120
cos.DECTIME  0.6584  0.0064

Correlation Between Variable Coefficients
---------------------------------------

            lnQ     sin.DECTIME
sin.DECTIME  0.4202
cos.DECTIME -0.6952 -0.2963

Variance Inflation Factors:
              VIF
lnQ         2.144
sin.DECTIME 1.214
cos.DECTIME 1.935

Comparison of Observed and Estimated Loads
------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated loads for all dates/times within
the calibration data set. Although this comparison does not directly
address errors in load estimation for unsampled dates/times, large
discrepancies between observed and estimated loads are indicative of a
poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Loads in kg/d
```

```
-------------------------------------------
     Min  25% 50% 75% 90% 95% Max
Est 13.5 48.6 176 572 577 638 638
Obs 19.1 47.2 167 449 663 955 955

Bias Diagnostics
----------------
 Bp: -2.773 percent
PLR: 0.9723
  E: 0.8063

where:
   Bp Load Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PLR Partial Load Ratio
      Sum of estimated loads divided by sum of observed loads.
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

----------------------------------------------------------------------
    Constituent Output File Part Ia: Calibration (Concentration Regression)
----------------------------------------------------------------------

Model # 4 selected

Selected Concentration Model:
----------------------------

DOC_council ~ model(4)

where:
   DOC_council is the constituent concentration in log(mg/L)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
            Estimate Std. Error z-score p-value
(Intercept)   1.3455     0.2766   4.864  0.0000
lnQ           0.2261     0.1403   1.612  0.0662
sin.DECTIME  -0.3361     0.1604  -2.095  0.0220
cos.DECTIME  -0.4535     0.4238  -1.070  0.2051
```

```
AMLE Regression Statistics
Residual variance: 0.1203
R-squared: 59.86 percent
G-squared: 10.95 on 3 degrees of freedom
P-value: 0.012
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9721
  p-value = 0.4792
Serial Correlation of Residuals: 0.4412


Comparison of Observed and Estimated Concentrations
--------------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated concentrations for all dates/times
within the calibration data set. Although this comparison does not directly
address errors in concentration estimation for unsampled dates/times, large
discrepancies between observed and estimated concentrations are indicative of
a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Concentrations in mg/L
---------------------------------------------
     Min  25%  50%  75%  90%  95%  Max
Est 1.71 2.28 3.41 4.06 5.01 5.59 5.59
Obs 1.70 2.35 2.60 3.95 7.00 7.50 7.50

Bias Diagnostics
----------------
 Bp: -1.308 percent
PCR: 0.9869
  E: 0.6313

where:
   Bp Concentration Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PCR Partial Concentration Ratio
      Sum of estimated concentrations divided by sum of observed concentrations.
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).
```

Appendix I – DOC load model selection statistics

Rithet

```
LOADEST
      A Program to Estimate Constituent Loads
U.S. Geological Survey, Version for R 0.1 (June, 2013)
----------------------------------------------------

Station: Rithet
Constituent: DOC_rithet

----------------------------------------------------------------------
   Constituent Output File Part Ia: Calibration (Load Regression)
----------------------------------------------------------------------


          Number of Observations: 19
Number of Uncensored Observations: 19
          Center of Decimal Time: 2002.439
                Center of ln(Q): 2.6373
               Period of record: 1997-08-27 to 2008-11-07

Model Evaluation Criteria Based on AMLE Results
----------------------------------------------

  model   AIC SPCC
1     4 21.18 25.9
Model # 4 selected

Selected Load Model:
--------------------

DOC_rithet ~ model(4)

where:
   DOC_rithet is the constituent load in log(kg/d)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
             Estimate Std. Error   z-score p-value
(Intercept)  4.285173    0.13871 30.892265  0.0000
lnQ          1.308008    0.06458 20.253339  0.0000
sin.DECTIME -0.374030    0.13586 -2.753037  0.0053
cos.DECTIME -0.002129    0.25739 -0.008272  0.9926

AMLE Regression Statistics
Residual variance: 0.1336
R-squared: 98.34 percent
G-squared: 77.83 on 3 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
```

```
  r = 0.9874
  p-value = 0.7905
Serial Correlation of Residuals: 0.1215

Correlation Between Explanatory Variables
---------------------------------------

           lnQ    sin.DECTIME
sin.DECTIME 0.2070
cos.DECTIME 0.7405 0.3554

Correlation Between Variable Coefficients
---------------------------------------

           lnQ     sin.DECTIME
sin.DECTIME  0.0894
cos.DECTIME -0.7293 -0.3074

Variance Inflation Factors:
            VIF
lnQ         2.232
sin.DECTIME 1.154
cos.DECTIME 2.445

Comparison of Observed and Estimated Loads
------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated loads for all dates/times within
the calibration data set. Although this comparison does not directly
address errors in load estimation for unsampled dates/times, large
discrepancies between observed and estimated loads are indicative of a
poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

     Summary Stats: Loads in kg/d
-------------------------------------------
    Min  25% 50%  75%  90%   95%   Max
Est 1.21 60.7 240 1300 2500 16500 16500
Obs 1.12 61.6 226 1620 2820 13600 13600

Bias Diagnostics
----------------
 Bp: 11.34 percent
PLR: 1.113
  E: 0.9479

where:
   Bp Load Bias in Percent
     Positive (negative) values indicate over (under) estimation.
     ***The model should not be used when the + or - bias exceeds 25%***
  PLR Partial Load Ratio
     Sum of estimated loads divided by sum of observed loads.
```

```
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

----------------------------------------------------------------------
    Constituent Output File Part Ia: Calibration (Concentration Regression)
----------------------------------------------------------------------

Model # 4 selected

Selected Concentration Model:
----------------------------

DOC_rithet ~ model(4)

where:
   DOC_rithet is the constituent concentration in log(mg/L)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
             Estimate Std. Error   z-score p-value
(Intercept)  0.753212    0.13871  5.429987  0.0000
lnQ          0.308008    0.06458  4.769230  0.0000
sin.DECTIME -0.374030    0.13586 -2.753037  0.0053
cos.DECTIME -0.002129    0.25739 -0.008272  0.9926

AMLE Regression Statistics
Residual variance: 0.1336
R-squared: 77.16 percent
G-squared: 28.06 on 3 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9874
  p-value = 0.7905
Serial Correlation of Residuals: 0.1215


Comparison of Observed and Estimated Concentrations
-------------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated concentrations for all dates/times
within the calibration data set. Although this comparison does not directly
address errors in concentration estimation for unsampled dates/times, large
```

```
discrepancies between observed and estimated concentrations are indicative of
a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Concentrations in mg/L
----------------------------------------------
     Min  25%  50%  75%  90%  95%  Max
Est 1.08 1.77 3.32 4.98 6.31 10.3 10.3
Obs 0.60 1.97 2.48 6.00 7.10  8.5  8.5

Bias Diagnostics
----------------
 Bp: 1.684 percent
PCR: 1.017
  E: 0.7549

where:
   Bp Concentration Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PCR Partial Concentration Ratio
      Sum of estimated concentrations divided by sum of observed concentrations.
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).
```

Judge

```
LOADEST
       A Program to Estimate Constituent Loads
U.S. Geological Survey, Version for R 0.1 (June, 2013)
-------------------------------------------------------

Station: Judge
Constituent: DOC_daily

----------------------------------------------------------------------
    Constituent Output File Part Ia: Calibration (Load Regression)
----------------------------------------------------------------------


           Number of Observations: 14
Number of Uncensored Observations: 14
           Center of Decimal Time: 2002.929
                  Center of ln(Q): 2.6467
```

```
      Period of record: 1997-10-09 to 2008-11-07

Model Evaluation Criteria Based on AMLE Results
-----------------------------------------------

  model   AIC  SPCC
1     4 14.73 17.92
Model # 4 selected

Selected Load Model:
--------------------

DOC_daily ~ model(4)

where:
   DOC_daily is the constituent load in log(kg/d)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
            Estimate Std. Error z-score p-value
(Intercept)   5.2127    0.21934 23.7650  0.0000
lnQ           0.9792    0.09081 10.7837  0.0000
sin.DECTIME  -0.5466    0.13206 -4.1388  0.0002
cos.DECTIME  -0.1795    0.30857 -0.5819  0.4948

AMLE Regression Statistics
Residual variance: 0.1149
R-squared: 93.27 percent
G-squared: 37.78 on 3 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9705
  p-value = 0.3734
Serial Correlation of Residuals: -0.1132

Correlation Between Explanatory Variables
-----------------------------------------

            lnQ    sin.DECTIME
sin.DECTIME 0.0326
cos.DECTIME 0.3031 0.0408

Correlation Between Variable Coefficients
-----------------------------------------

            lnQ     sin.DECTIME
sin.DECTIME -0.0212
cos.DECTIME -0.3022 -0.0325

Variance Inflation Factors:
              VIF
lnQ         1.102
```

```
sin.DECTIME 1.002
cos.DECTIME 1.102

Comparison of Observed and Estimated Loads
------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated loads for all dates/times within
the calibration data set. Although this comparison does not directly
address errors in load estimation for unsampled dates/times, large
discrepancies between observed and estimated loads are indicative of a
poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Loads in kg/d
--------------------------------------------
     Min  25% 50% 75%  90%  95%  Max
Est 30.6 90.1 160 354  798 1160 1160
Obs 31.8 82.2 149 230 1020 1340 1340

Bias Diagnostics
----------------
 Bp: -5.01 percent
PLR: 0.9499
  E: 0.9397

where:
   Bp Load Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PLR Partial Load Ratio
      Sum of estimated loads divided by sum of observed loads.
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

-------------------------------------------------------------------------
    Constituent Output File Part Ia: Calibration (Concentration Regression)
-------------------------------------------------------------------------

Model # 4 selected

Selected Concentration Model:
----------------------------
```

```
DOC_daily ~ model(4)

where:
   DOC_daily is the constituent concentration in log(mg/L)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
            Estimate Std. Error z-score p-value
(Intercept)  1.67136    0.21934  7.6198  0.0000
lnQ         -0.02077    0.09081 -0.2287  0.7870
sin.DECTIME -0.54658    0.13206 -4.1388  0.0002
cos.DECTIME -0.17955    0.30857 -0.5819  0.4948

AMLE Regression Statistics
Residual variance: 0.1149
R-squared: 64.23 percent
G-squared: 14.39 on 3 degrees of freedom
P-value: 0.0024
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9705
  p-value = 0.3734
Serial Correlation of Residuals: -0.1132


Comparison of Observed and Estimated Concentrations
--------------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated concentrations for all dates/times
within the calibration data set. Although this comparison does not directly
address errors in concentration estimation for unsampled dates/times, large
discrepancies between observed and estimated concentrations are indicative of
a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Concentrations in mg/L
----------------------------------------------
     Min  25%  50% 75%   90%   95%   Max
Est 3.13 3.84 6.13 7.9  8.63  9.23  9.23
Obs 2.80 3.50 4.65 9.7 10.40 11.10 11.10

Bias Diagnostics
----------------
 Bp: -0.6134 percent
PCR: 0.9939
  E: 0.5926

where:
   Bp Concentration Bias in Percent
```

```
    Positive (negative) values indicate over (under) estimation.
    ***The model should not be used when the + or - bias exceeds 25%***
  PCR Partial Concentration Ratio
    Sum of estimated concentrations divided by sum of observed concentrations.
    Values greater than 1 indicate over estimation.
    Values less than 1 indicate under estimation.
   E Nash Sutcliffe Efficiency Index
    E ranges from -infinity to 1.0
    E = 1; a perfect fit to observed data.
    E = 0; model estimates are as accurate as the mean of observed data.
    E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
    residual diagnostic plots. users should conduct a thorough
    residuals analysis. Example residual plots are shown in figures
    7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).
```

Council

```
  LOADEST
     A Program to Estimate Constituent Loads
U.S. Geological Survey, Version for R 0.1 (June, 2013)
----------------------------------------------------

Station: Council
Constituent: DOC_council

--------------------------------------------------------------------
   Constituent Output File Part Ia: Calibration (Load Regression)
--------------------------------------------------------------------

          Number of Observations: 12
Number of Uncensored Observations: 12
          Center of Decimal Time: 2001.259
                Center of ln(Q): 2.7359
               Period of record: 1997-10-09 to 2004-11-25

Model Evaluation Criteria Based on AMLE Results
---------------------------------------------

  model   AIC SPCC
1     4 13.78 16.2
Model # 4 selected

Selected Load Model:
--------------------

DOC_council ~ model(4)

where:
   DOC_council is the constituent load in log(kg/d)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)
```

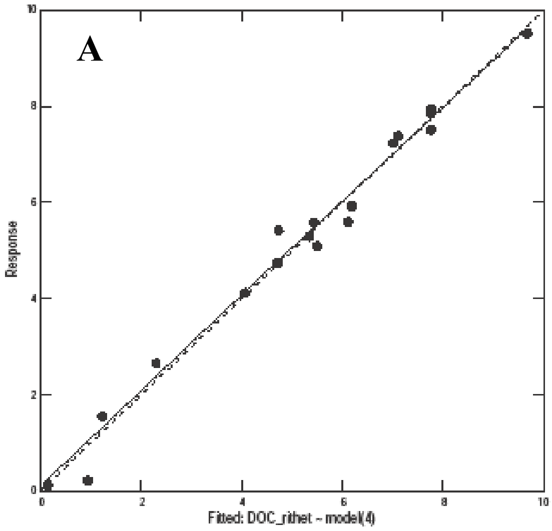
```
Model coefficients:
            Estimate Std. Error z-score p-value
(Intercept)   4.9761     0.2766  17.991  0.0000
lnQ           1.2261     0.1403   8.738  0.0000
sin.DECTIME  -0.3361     0.1604  -2.095  0.0220
cos.DECTIME  -0.4535     0.4238  -1.070  0.2051

AMLE Regression Statistics
Residual variance: 0.1203
R-squared: 95.37 percent
G-squared: 36.86 on 3 degrees of freedom
P-value: <0.0001
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9721
  p-value = 0.4792
Serial Correlation of Residuals: 0.4412

Correlation Between Explanatory Variables
---------------------------------------

            lnQ     sin.DECTIME
sin.DECTIME -0.3120
cos.DECTIME  0.6584  0.0064

Correlation Between Variable Coefficients
---------------------------------------

            lnQ     sin.DECTIME
sin.DECTIME  0.4202
cos.DECTIME -0.6952 -0.2963

Variance Inflation Factors:
              VIF
lnQ         2.144
sin.DECTIME 1.214
cos.DECTIME 1.935

Comparison of Observed and Estimated Loads
----------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated loads for all dates/times within
the calibration data set. Although this comparison does not directly
address errors in load estimation for unsampled dates/times, large
discrepancies between observed and estimated loads are indicative of a
poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Loads in kg/d
------------------------------------------
     Min  25% 50% 75% 90% 95% Max
Est 13.5 48.6 176 572 577 638 638
Obs 19.1 47.2 167 449 663 955 955
```

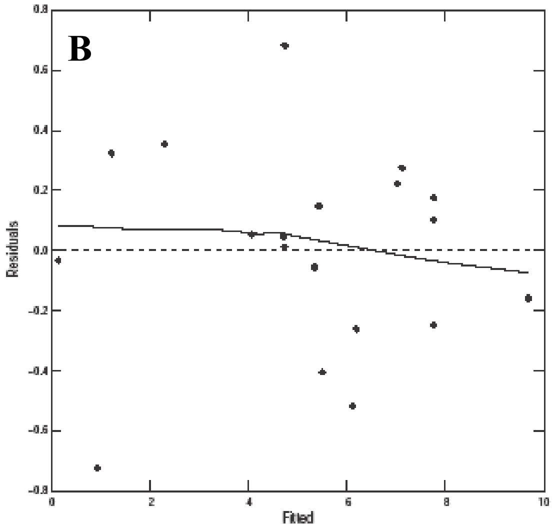
```
Bias Diagnostics
----------------
 Bp: -2.773 percent
PLR: 0.9723
  E: 0.8063

where:
   Bp Load Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PLR Partial Load Ratio
      Sum of estimated loads divided by sum of observed loads.
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

----------------------------------------------------------------------
    Constituent Output File Part Ia: Calibration (Concentration Regression)
----------------------------------------------------------------------

Model # 4 selected

Selected Concentration Model:
----------------------------

DOC_council ~ model(4)

where:
   DOC_council is the constituent concentration in log(mg/L)
and model 4 has these variables:
   lnQ is ln(Q) - center of ln(Q)
   sin.DECTIME is sine(2 * pi * decimal time)
   cos.DECTIME is cosine(2 * pi * decimal time)

Model coefficients:
             Estimate Std. Error z-score p-value
(Intercept)   1.3455     0.2766   4.864  0.0000
lnQ           0.2261     0.1403   1.612  0.0662
sin.DECTIME  -0.3361     0.1604  -2.095  0.0220
cos.DECTIME  -0.4535     0.4238  -1.070  0.2051

AMLE Regression Statistics
Residual variance: 0.1203
R-squared: 59.86 percent
G-squared: 10.95 on 3 degrees of freedom
```

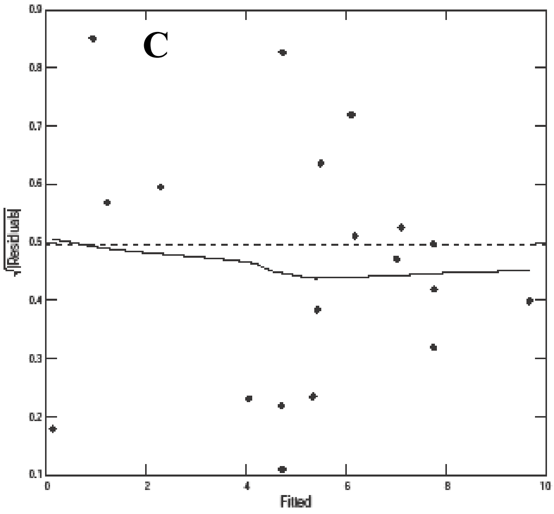
```
P-value: 0.012
Prob. Plot Corr. Coeff. (PPCC):
  r = 0.9721
  p-value = 0.4792
Serial Correlation of Residuals: 0.4412


Comparison of Observed and Estimated Concentrations
--------------------------------------------------
  The summary statistics and bias diagnostics presented below are based
on a comparison of observed and estimated concentrations for all dates/times
within the calibration data set. Although this comparison does not directly
address errors in concentration estimation for unsampled dates/times, large
discrepancies between observed and estimated concentrations are indicative of
a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the
detection limit when an observation is censored. The summary stats and
bias diagnostics are therefore slightly inaccurate for censored datasets.

      Summary Stats: Concentrations in mg/L
---------------------------------------------
     Min  25%  50%  75%  90%  95%  Max
Est 1.71 2.28 3.41 4.06 5.01 5.59 5.59
Obs 1.70 2.35 2.60 3.95 7.00 7.50 7.50

Bias Diagnostics
----------------
 Bp: -1.308 percent
PCR: 0.9869
  E: 0.6313

where:
   Bp Concentration Bias in Percent
      Positive (negative) values indicate over (under) estimation.
      ***The model should not be used when the + or - bias exceeds 25%***
  PCR Partial Concentration Ratio
      Sum of estimated concentrations divided by sum of observed concentrations.
      Values greater than 1 indicate over estimation.
      Values less than 1 indicate under estimation.
    E Nash Sutcliffe Efficiency Index
      E ranges from -infinity to 1.0
      E = 1; a perfect fit to observed data.
      E = 0; model estimates are as accurate as the mean of observed data.
      E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the
      residual diagnostic plots. users should conduct a thorough
      residuals analysis. Example residual plots are shown in figures
      7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).
```

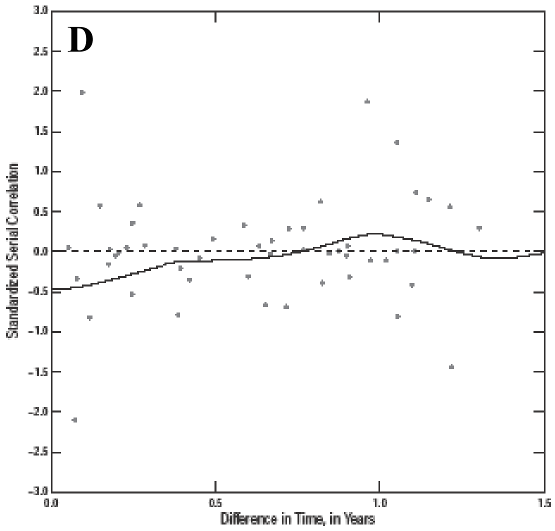
Appendix J – DOC load model diagnostic plots

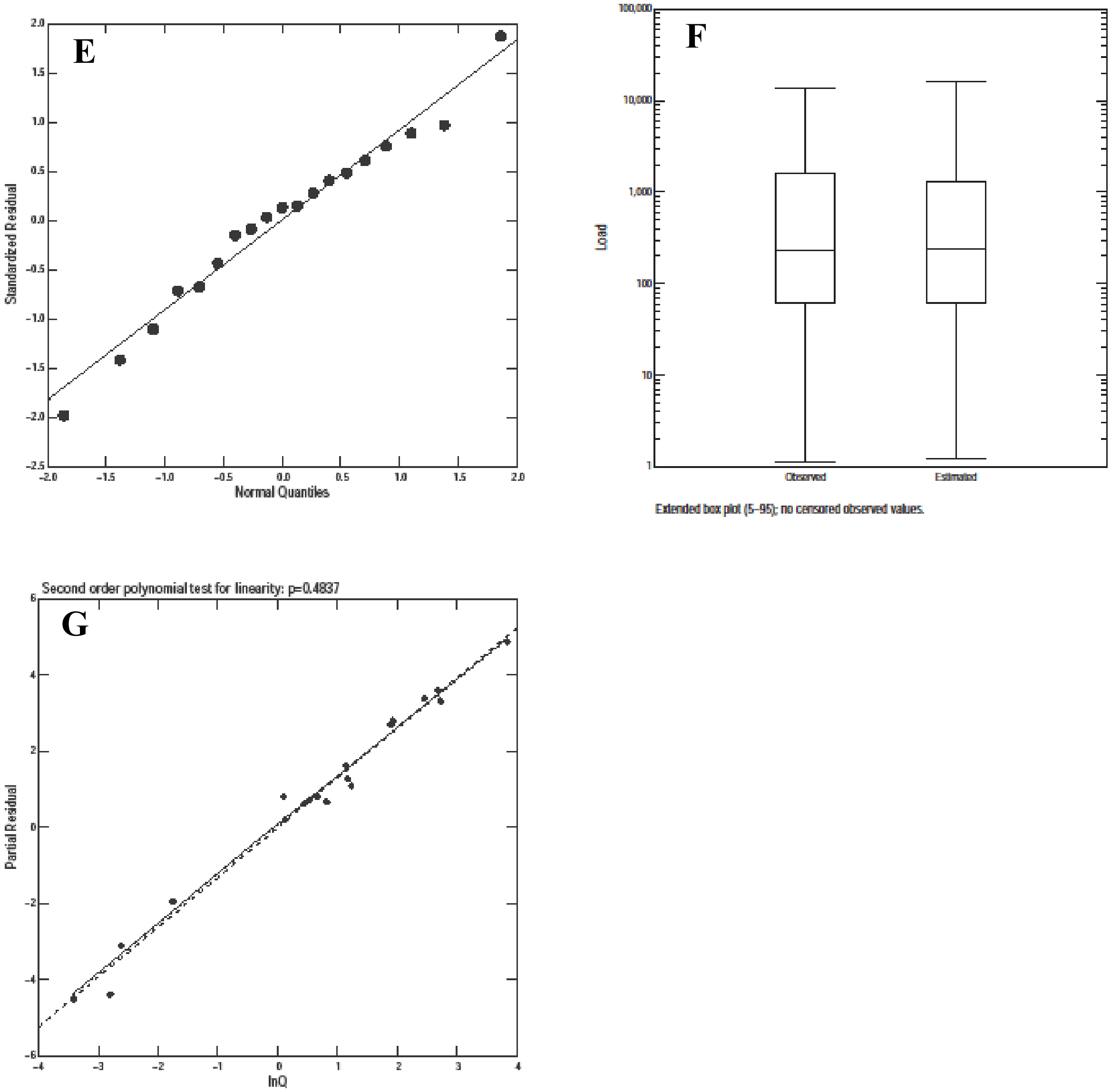
Rithet (plot descriptions below)







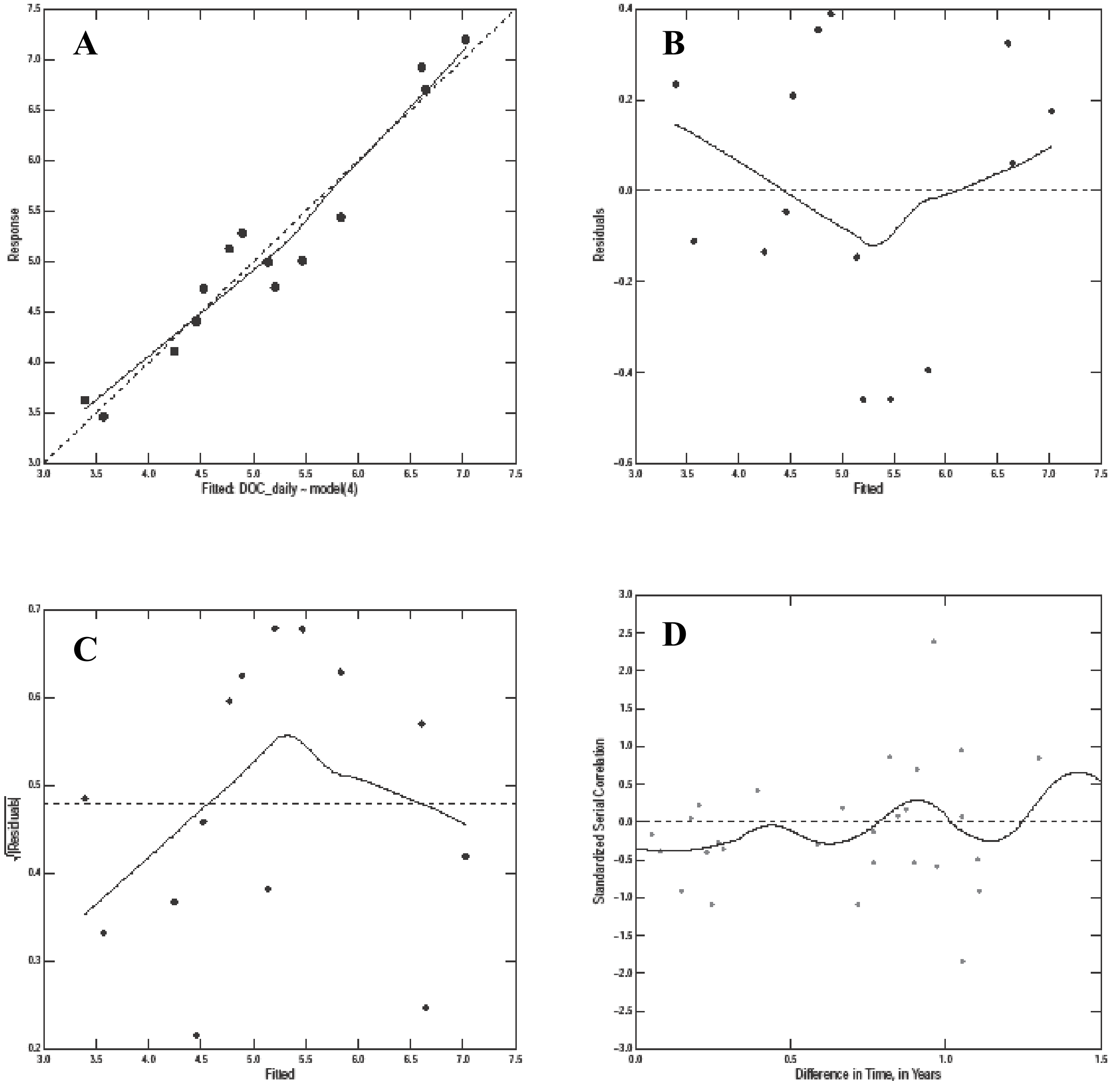


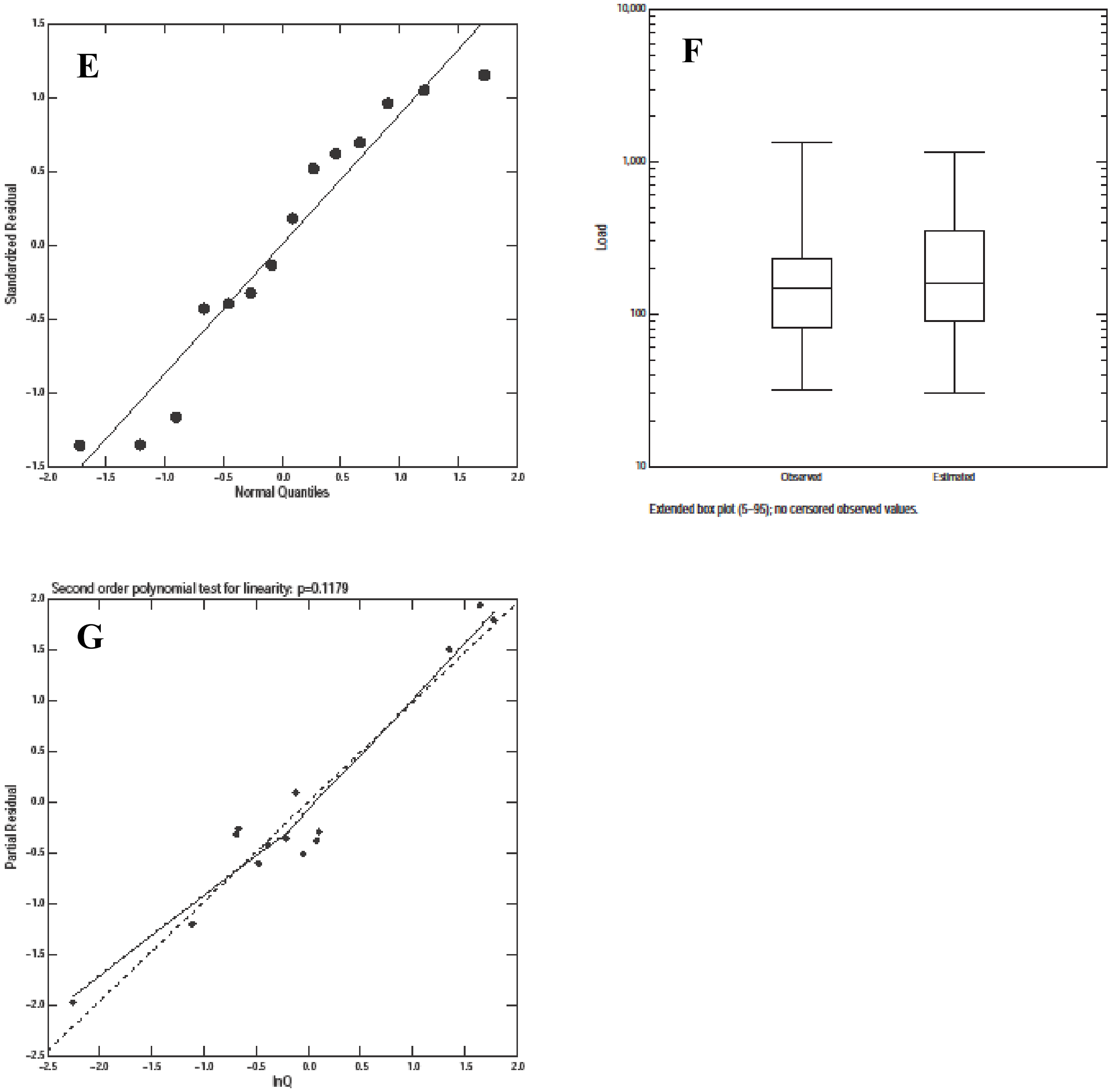


A – Rating-curve regression model (AMLE regression line as dashed line and LOWESS smooth curve as solid line)
B – The residuals versus fit for the regression model (horizontal dashed line is at zero and the solid line is the LOWESS smooth curve)
C – The scale-location graph for the regression model (horizontal dashed line is the expected value of the square root of the absolute value of the residuals and the solid line is the LOWESS smooth
D – Correlogram from the regression model (horizontal dashed line is the zero value and the solid line is a kernel fit)
E – Q-normal plot of residuals (solid line is the theoretical fit of mean of 0 and standard deviation of 1)
F – Box plot comparing estimated and observed values (<5 and >95 percentiles)
G – Partial residual plot for the stream flow with second order polynomial test for linearity

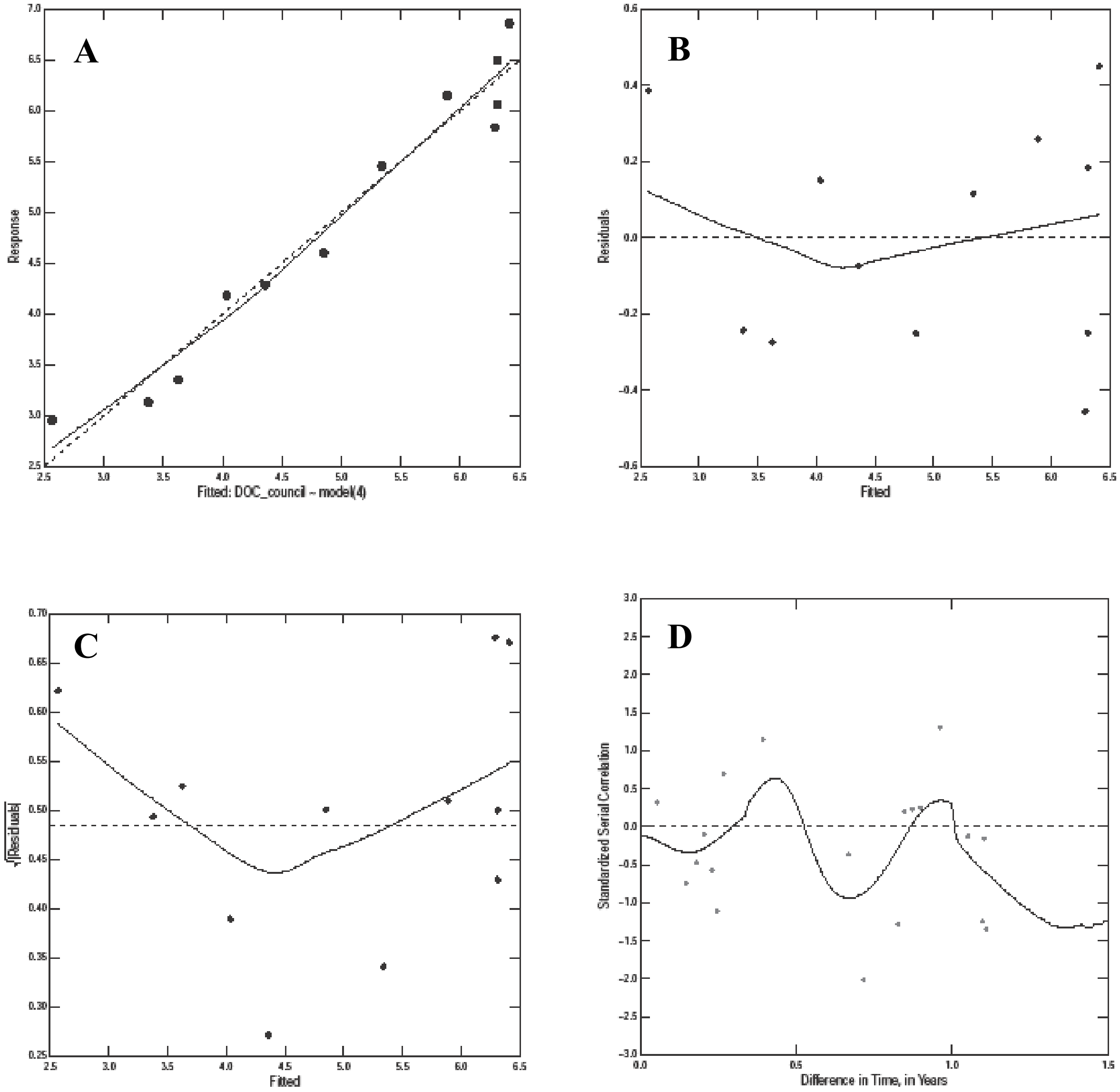
See Runkel, et al. (2004) for detailed description of diagnostic plots

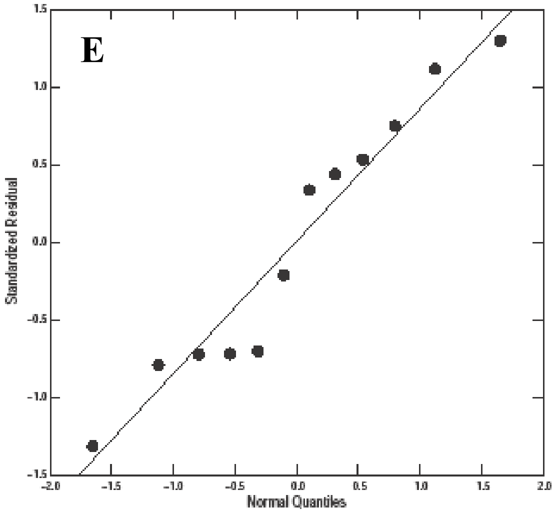
Judge

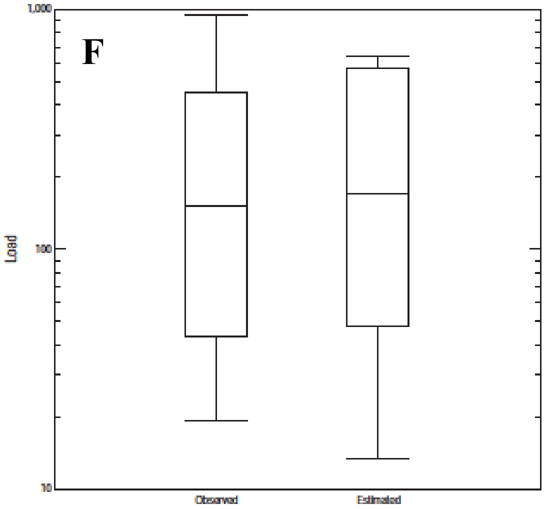

A
Response
Fitted: DOC_daily ~ model(4)
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
B
Residuals
Fitted
0.4
0.2
0.0
-0.2
-0.4
-0.6
C
√|Residuals|
Fitted
0.7
0.6
0.5
0.4
0.3
0.2
D
Standardized Serial Correlation
Difference in Time, in Years
0.0
0.5
1.0
1.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0


E
Standardized Residual
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
Normal Quantiles
F
Load
10,000
1,000
100
10
Observed
Estimated
Extended box plot (5–95); no censored observed values.
G
Second order polynomial test for linearity: p=0.1179
Partial Residual
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
lnQ

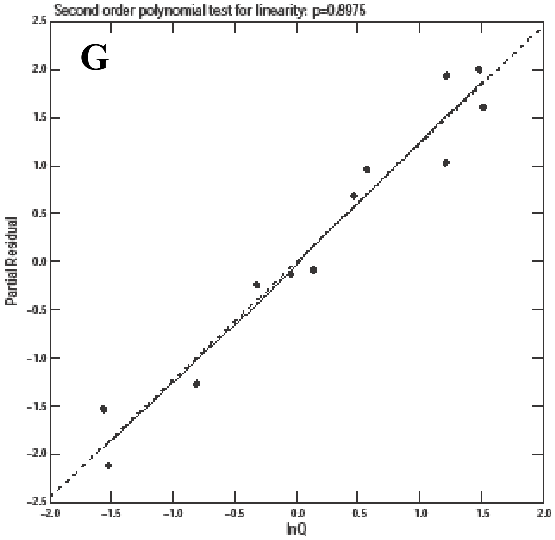
Council


A
Response
Fitted: DOC_council ~ model(4)
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5
B
Residuals
Fitted
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5
C
√|Residuals|
Fitted
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5
D
Standardized Serial Correlation
Difference in Time, in Years
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
0.0 0.5 1.0 1.5





Extended box plot (5–95); no censored observed values.


Second order polynomial test for linearity: p=0.8975