# Primary Production
## in the
# Flooded Terrestrial Ecosystems of the Columbia Basin

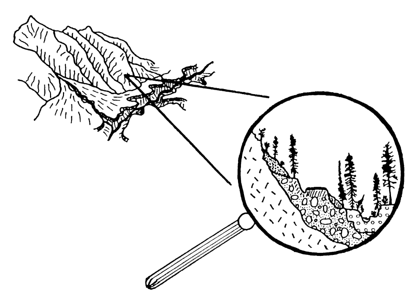
Prepared for:

**Columbia Basin Fish and Wildlife Compensation Program Nelson, B.C.**

Prepared by:


**D. MacKillop, MSc.**
**G. Utzig, P.Ag.**


**December 22, 2005**




*Kutenai Nature Investigations Ltd.*

602 Richards Street, Nelson, B.C. CANADA V1L 5K5 TEL: (250)352-5288 FAX: (250)352-6430 E-MAIL: g13utzig@telus.net

## Table of Contents



## List of Appendices

## List of Tables



## List of Figures

# Introduction

Productivity estimates were derived for terrestrial ecosystems within the Columbia Basin dam impacts footprint area using a series of models. Ecosystem mapping was developed for the affected area in a previous project (Ketcheson et al. 2004). The basic site types (site series, non-forested areas, and deciduous leading stands) identified in that project were used as the basic modelling variable for assessing terrestrial productivity. For each forested ecosystem, typical tree species composition was determined and used to look up site indices (a measure of tree productivity based on potential height growth) in the Ministry of Forests and Range (MoFR) Site Index estimation by BEC (SIBEC) reports (Ministry of Forests and Range 2005). This information was used to develop volume-over-age curves using the MoFR Variable Density Yield Projection (VDYP) forest yield model (Ministry of Forests 2002). VDYP provided yield curves (expected merchantable timber volume over time) that were used as input in the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3). CBM-CFS3 was then used to estimate net primary productivity (NPP), net ecosystem productivity (NEP), and carbon storage in live biomass and dead organic matter (Kull et al. pers comm 2005). The modelling approach used here was necessary given that the ecosystem characteristics of the sites in question have been severely altered, making remote sensing and field measurement approaches impossible.

Unlike aquatic systems where productivity is generally consistent over time, terrestrial productivity measures are very sensitive to changes in ecological succession and must be considered within a temporal context. In most boreal and montane ecosystems, NPP is low at stand initiation (e.g., following a wild fire), then peaks in early successional stages. Following maximum rates (around 30-50 years), NPP typically declines to an approximate equilibrium state. NEP follows a similar, but lower pattern, beginning in a negative state as post fire deadwood decays. Timing of peaks is generally the same for NPP and NEP, although NEP typically equilibrates at levels closer to zero (equal carbon production to release ratios).

While maximum productivity occurs in early seral stages, carbon storage in a terrestrial ecosystem usually peaks in older forests as biomass accumulates (Kurz et al. 2002, Smithwick et al. 2002). Following wild fire and other natural disturbances, carbon storage is high in dead organic matter (largely snags and logs) and low in biomass. Over time, deadwood decays to an approximate steady state in most systems. Meanwhile, biomass accumulates rapidly during the stages in which NPP and NEP are highest, then levels out when production is matched by decay. By comparison, carbon storage in soils is relatively constant over time.

The patterns presented above are simplified, while in reality the patterns tend to vary across ecosystems with different climatic, topographic, and nutrient regimes. The patterns also vary between types of natural disturbances and the variability in resulting parameters of secondary succession. Patterns differ for anthropogenic activities such as harvesting (Kurz et al. 2002), and for catastrophic disturbances that lead to primary succession. Dam creation and subsequent flooding tend to produce primary successional impacts in that much of the growing area (soil) is removed from the land (IPPC 2003). Given this assumption, terrestrial productivity levels (NPP and carbon accumulation) in the Columbia Basin dam impacts footprint area would have been reasonably high prior to flooding, but are currently very low.

The primary result of this project consists of a series of databases that summarise terrestrial productivity, timber volume, and carbon storage by ecosystem and successional state (structural stage). The data can be used to determine terrestrial productivity (NPP or NEP) and carbon storage (biomass and dead organic matter) estimates by ecosystem type, reservoir and stream reach, or for the entire footprint area. Values for each structural stage allow users to calculate estimates over a variety of scenarios including carbon storage and production at the time of flooding, under natural conditions (using the range of natural variability in disturbance for each ecosystem type), or under maximum potential scenarios.

# Background: Measures of Terrestrial Productivity

Scientists, forest managers, wildlife biologists, reservoir managers, fisheries biologists, and the public tend to think of terrestrial productivity in many different ways. To reflect this range in perspectives, we chose to model terrestrial productivity losses using several metrics. The following section provides background information on the definition, application, and assumptions associated with the metrics selected.

## *Mean Annual Increment*

Mean annual increment (MAI) is commonly used in forestry to determine optimal harvest rotations and to evaluate relative growth potential. It refers to the average merchantable volume growth, per year, of a tree or stand of trees over a given time period and is calculated by dividing merchantable volume by age ($m^3$/yr). Maximum MAI, or culmination, is the point at which average yearly growth no longer increases with time.

Annual increment (or yearly volume growth) can be measured for any given year (current annual increment – CAI) or for a specified period of time (periodic annual increment – PAI; Smith et al.1997). PAI or CAI can be very high in young stands where mortality is low, while MAI tends to be low in young stands, peaking in mature stands, and declining in older stands (Figure 1).

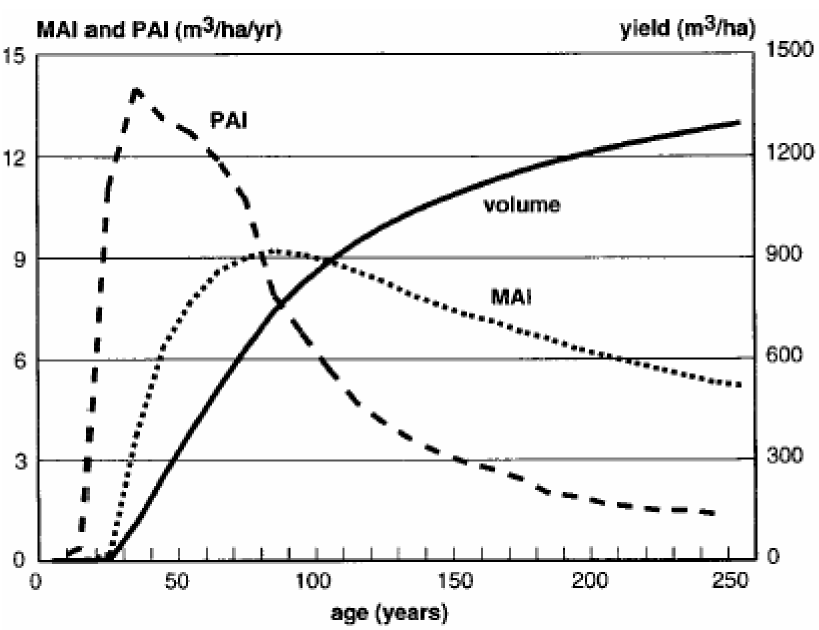



**Figure 1. Typical pattern of PAI, MAI, and Volume over time (from Cortex 2004).**

## *Site Index*

Site index is a surrogate measure of productivity that is based on the average height attained by dominant and co-dominant site trees at a fixed age (usually 50 years). It is derived from the relationship between tree age and measured height growth. To ensure that site index reflects site potential, measures are based on 'healthy' trees that are free of damage from insects, disease, weather, etc. and have not been suppressed (site trees). Site index can be measured or estimated. In older stands, where disease and damage lower growth rates, indirect estimates are often the preferred means of determining site index. The most common approach to estimating site index in BC is through the SIBEC program – Site

Index estimation by Biogeoclimatic Ecosystem Classification (Stearn-Smith 2001). The SIBEC database provides site index estimates by species for most site series (Ministry of Forests and Range 2005).

## *Carbon Pools - Biomass, Soils, Dead Organic Matter*

Carbon accounting has gained considerable attention with the rising concern over global climate change and both federal and provincial commitments under the Kyoto Protocol (Environment Canada 2005). Carbon models tend to focus on carbon pools, sinks, and sources. According to the Canadian Forest Carbon Accounting Program[1], a *carbon pool* is “a system having the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, soils, snags, logs, and the atmosphere”. Similarly, a *carbon sink* is a carbon pool in which more atmospheric carbon is flowing in than out over a given time interval. The opposite is true of a *carbon source*, although a forest can shift from a carbon sink to a carbon source through disturbances such as fire and logging.

The most commonly measured terrestrial carbon pools in terrestrial ecosystems are biomass, soils, and dead organic matter (including coarse woody debris, snags, and litterfall). Biomass refers to the “total mass of living organisms in a given area or volume” and reflects the “standing crop”, “carbon stock”, or amount of carbon present at a given time (NRCAN 2005a). Forest biomass is largely comprised of aboveground and belowground live tree elements such as stems, branches, leaves, and roots, as well as shrubs, mosses, lichens, fungi, and herbs (Canadian Forest Carbon Accounting Program, NRCAN 2005a). In forests, animals generally comprise a small portion of the total biomass.

Measures of biomass are usually given as dry weights or volumes. In terrestrial ecosystems, dry weight biomass is often converted to carbon measures using a mass fraction of 0.5 for woody components and 0.45 for grass and foliage, although in mixed sites an average ratio of 0.475 g C per 1 g biomass is often used (Olson et al. 2001). Biomass can also be converted to (and from) merchantable or wholestem volume through modelling. The CBM-CFS3 model uses merchantable volume estimates to determine full stem, foliage, and belowground biomass estimates (Kull et al. pers comm 2005).

In northern forests, soils are a particularly important carbon pool. Carbon enters the soil through litterfall and root mortality (NRCAN 2005a), and accumulates over time. In many systems, there are larger volumes of carbon in soils than in live vegetation.

## *Net Primary Productivity*

Net primary productivity (or production; NPP) is a measure of plant growth over a given time period (usually one year). It reflects the amount of energy or carbon that a plant (or group of plants) accumulates over a specified timeframe, and is equivalent to the rate at which an ecosystem fixes carbon from the atmosphere (gross primary productivity) minus the rate that carbon is returned to the atmosphere (plant respiration; Peng and Apps 1999). In any given year, NPP reflects new foliage production as well as stem, branch and root growth. Litterfall and herbivory are also included in measures of NPP.

NPP reflects important ecosystem processes because of its influences on nutrient cycling, food web structure, disturbance regimes, species abundances, community structure, and other ecosystem functions (Hansen et al. 2000). In essence, NPP provides a measure of the carbon that is cycled through a system. From a process-perspective, NPP is highly related to photosynthesis and rates of light interception by plants, although temperature, vapour pressure, and drought also influence production rates.

It is important to note that NPP does not reflect carbon storage in an ecosystem and is not correlated with biomass measures. For example, an agricultural field may have the same NPP as a forest, but at the end of the year, the field is harvested while the forest continues to grow and accumulate carbon. As a measure of growth, the NPP for an ecosystem changes with successional patterns and ecosystem dynamics. Younger forests my have higher NPP measures than old-growth forests, but the standing crop, or total stored carbon is much greater in the old-growth forest. Measures should also be interpreted with caution since NPP is strongly linked to yearly and seasonal climatic fluctuations. Data from drought years can significantly underestimate carbon production (NPP) over an area, while the opposite is true of warm, moist years. NPP also varies geographically. Hansen et al. (2000) found that NPP shifted across elevational gradients with higher aboveground levels at lower, warmer elevations.

NPP is useful for predicting carbon dioxide uptake by plants in an area (local, regional, global), but cannot be used on its own as an estimate of carbon dynamics because it does not account for bacterial (heterotrophic) respiration by decomposers (Kurz pers comm. 2005[1]). On its own, NPP can only tell a portion of the story: total biomass, biomass increment, and other data on organic matter transfers (such as litterfall, mortality, stemflow and grazing) are needed to provide a full assessment of carbon cycling processes.

## *Net Ecosystem Productivity*

Net ecosystem productivity (NEP) is a measure of carbon uptake or release within an ecosystem. It is the amount of carbon transferred between the atmosphere and the biosphere, including measures that account for plant respiration, decomposition, and combustion (Peng and Apps 1999). Similar to NPP, NEP involves measures of total biomass produced, minus plant respiration, but NEP also accounts for measures of heterotrophic (mostly bacterial) respiration (i.e. release of carbon into the atmosphere through bacterial decomposition of dead wood) and combustion of organic matter (Grier and Logan 1977, Peng and Apps 1999, 2003, Li et al. 2003, Kurz, pers comm. 2005[3]). NEP is essentially a measure of the net carbon balance prior to disturbance. By including heterotrophic respiration, NEP provides a full picture of the flow of carbon through a system and can be used to determine whether carbon pools are sources or sinks.

NEP is measured and reported in the same units as NPP. However, NPP, by its nature, must always be a positive value. In contrast, NEP can either be positive (carbon sink), or negative (carbon source). For example, Li et al. (2003) found that NPP was positive (228 $gC/m^2/yr$) in subarctic forests, but NEP was negative (-14 $gC/m^2/yr$) because combustion (disturbance) exceeded NPP.

NEP is an important tool in carbon accounting (e.g. commitments under the Kyoto Protocol) and could be used to assess changes in carbon dynamics within the Columbia River dam impacts footprint. However it would be complex to determine the fate of the various terrestrial ecosystem carbon pools before and after flooding (e.g., some areas were logged, some areas the soils were eroded, some soils were buried by sediments).

Conceptually, NEP is a relatively simple measure. However, in practice, estimates of heterotrophic respiration are complicated and are rarely derived from empirical data. The CBM-CFS3 model emphasizes NEP measures in addition to NPP and biomass estimates.

## *Net Biome Productivity*

Net biome productivity (NBP) is a landscape-level measurement used to assess an area or region within the context of both natural and anthropogenic disturbance (Kurz, pers comm. 2005[3]). It takes estimates of NEP for a landscape over a given time period and modifies these based on actual or anticipated losses in carbon storage due to disturbance. Disturbances include fire, insects, disease, and anthropogenic changes such as forest harvesting. Some authors argue that NBP is equivalent to NEP at regional or global scales (e.g., Randerson et al. 2002).

NPB is a useful measure for determining expected changes in productivity due to natural and anthropogenic disturbance. It was not assessed in this project because the areas in question faced a

[1] W. Kurz, Senior Researcher, Canadian Forest Service

single catastrophic disturbance: flooding. Measures of NBP would be useful in determining the expected carbon dynamics for the dammed reaches had they not been flooded.

# Methods

Estimates of productivity losses in the Columbia Basin dam impacts footprint area were derived through carbon modelling exercises supplemented by literature review. Literature reviews were used to assess and cross check modelled results and to determine the most relevant metrics available for assessing productivity and carbon dynamics. This involved a review of seminal literature relating to productivity and carbon dynamics, with an emphasis on ecosystems similar to those found in the Columbia Basin. Sources included government and academic websites, as well as databases of academic journals. In total, 110 data sources were identified. Of these, 59 were reviewed and summarised in an excel-based spreadsheet (Appendix 7).

Modelled parameters include site index, annual increment, maximum mean annual increment, live biomass accumulation, carbon storage in dead organic material, net primary productivity (NPP), and net ecosystem productivity (NEP). Individual site series, non-forested sites, and deciduous leading stands, as mapped by Ketcheson et al. (2004) formed the basis for productivity assessments. Given the retrospective nature of this project, a multi-step modelling process was necessary to “reconstruct” stand types and develop estimates of associated growth patterns. This multi-step modelling process is depicted in (Figure 2) and involved:

1) identification of typical tree species composition, by site series, using the applicable BC MoF Field Guides to Site Identification and Interpretation (Meidinger et al. 1988, Lloyd et al. 1990, Braumandl and Curran 1992);
2) estimation of site index, by tree species and site series, using the Ministry of Forests and Range’s SIBEC relationships;
3) development of volume-over-age curves through the VDYP forest yield model; and
4) modelling of carbon dynamics using the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3)

Outputs from each modelling step produced both productivity estimates (e.g., site index, MAI) and inputs for subsequent models. For example, site index estimates from SIBEC were needed as input to derive volume and MAI estimates in VDYP, and volume curves from VDYP were needed as input in the CBM-CFS3 model.

Productivity estimates were complicated by several factors:

1) the project is a retrospective analysis based on ecosystems that are no longer present and cannot be field-checked;
2) terrestrial productivity and biomass accumulation are highly variable over time and change considerably with succession; and
3) most disturbances (fire, insect, harvest) are part of secondary successional processes; flooding for hydro-electric dams sets ecosystems back to a primary successional state where carbon storage and primary productivity are negligible (IPPC 2003).

With these concerns in mind, we determined that losses of “potential” productivity were more relevant than losses in “actual” productivity at the time of flooding. This assumption holds for measures of carbon accumulation, as well as productivity. For example, a young forested stand may have had low biomass at the time of flooding, but without the dams, the stand could have grown and accumulated considerably more biomass. Similarly, an old stand that was flooded may have had low measures for NPP at the time of dam construction, but given a natural disturbance such as fire, the NPP in the subsequent young stand on that site may have risen considerably.

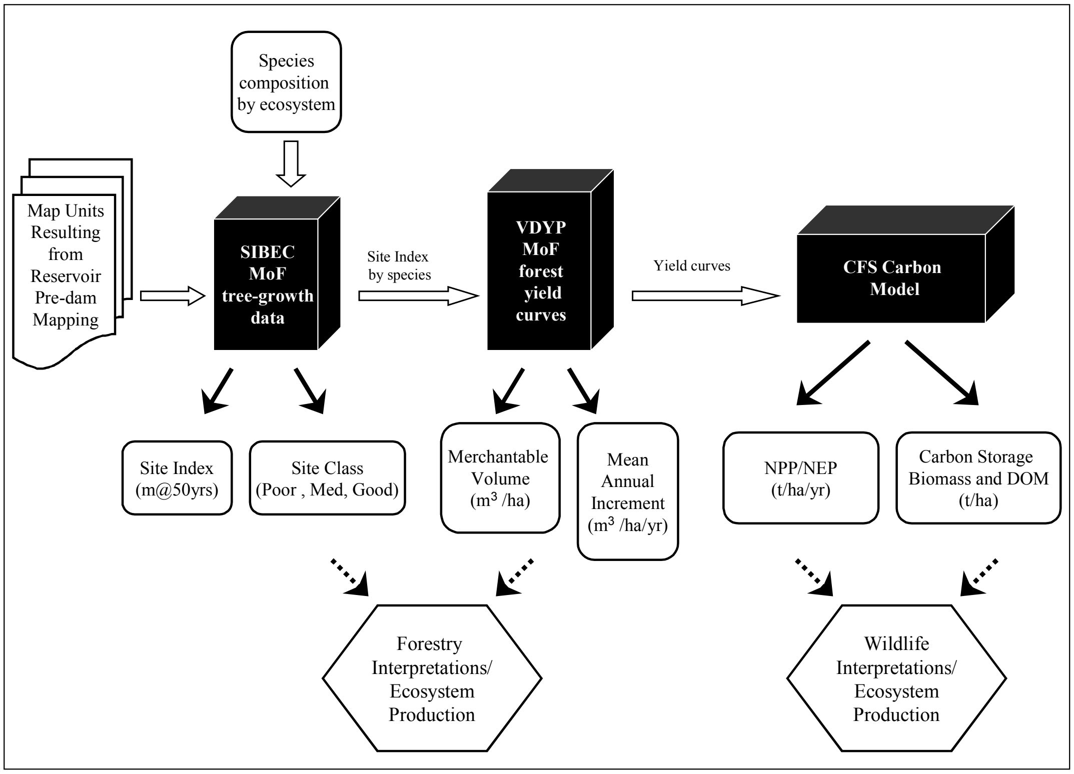



**Figure 2. Process used to model productivity in dammed areas of the Columbia Basin.**

To address the temporal (successional) fluctuations in biomass accumulation and primary productivity, we modelled productivity across the range of successional stages in each forested ecosystem using groups of structural stages (Table 1). Structural stages were grouped to reflect similarities in carbon dynamics, and were correlated with stand age (time since disturbance). This allows users to select the distribution of successional stages present in analyses of the ecosystems (e.g. actual stand inventories at time of flooding, distribution expected under the range of natural variability (RONV), maximum potential productivity on each site type, etc). Smithwick et al. (2002) took a similar approach (to the maximum potential productivity scenario) when they modelled the “potential upper bounds of carbon stores in forests of the Pacific Northwest”.

**Table 1. Structural Stage groups and associated Stand Ages**

| *Grouping* | *Structural Stages* | *Stand Ages* |
|---|---|---|
| Sparse/Bryoid-Herb | ST 1 and ST 2 | 1-9 years |
| Shrub/Herb | ST 3 | 10-30 |
| Pole/Sapling-Young Forest | ST 4 and ST 5 | 31-80 |
| Mature Forest | ST 6 | 81-200 |
| Old Forest | ST 7 | 201-349* |

*The old forest age category is truncated at 349 years based on parameters in VDYP and CBM-CFS3

To be more consistent with the reliability of the model outputs, age limits for structural stages are the same across all site types, despite known differences in successional patterns (e.g., between moist productive site series and dry, rocky site series). Summaries of mean carbon stores and NPP/NEP by seral stage are also provided for ages that are beyond those that would be expected in some ecosystems based on natural disturbance frequencies. Non-forested types were considered as disclimaxes or edaphic climaxes, and were generally limited to early seral structural stages (1-3). Age-groupings for non-forested types are summarised in Appendix 1.

## Non-forested areas

SIBEC, VDYP, and CBM-CFS3 are forest-based models that do not address agricultural or other non-forested lands. According to Kull et al. (pers comm 2005) "simple post-deforestation dynamics can be assumed" in the CBM-CFS3 model for agricultural lands. Similarly, avalanche chutes and other non-forested areas can be evaluated as if they are perpetually in an early seral state. Therefore, we followed a similar process for assessing non-forested and forested areas, but report productivity and production values from the earliest structural stages (stage 1 – sparse/bryoid, 2 – herb, and 3 – shrub/herb) for agricultural and other non-forest lands (see comments on CBM-CFS3 and understory vegetation below). The non-forested areas of the footprint are generally insignificant, representing < 7% overall, and with almost 90% of that consisting of two types: gravel bars and agricultural fields.

To differentiate between natural and managed stands, we ran an additional scenario and simulation in CBM-CFS3 for the four site series that represent the general ecosystem conditions of the majority of non-forested area: ICHmw3-01, ICHmw2-01, ICHwk1-05, and IDFdm2-01. For these simulations, we specified that stands were clearcut then slash-burned, then took average values for NPP and carbon stores based on the seral conditions estimated to approximate the non-forest ecosystems. Where disturbance patterns, management systems, or other variables differed significantly from the forested conditions assumed in the carbon model, outputs were adjusted based on expert opinion (i.e. authors' knowledge of the specific ecosystems in the study area and basic principles of soil science and forest ecology). NEP for non-forested sites was assigned a value of zero because we assumed that sites were in a relatively steady state between production and decomposition. For agriculture, we are assuming sustainable practices in which plant matter is produced then harvested over each year, with soil remaining steady due to fertilization and other inputs. For avalanche chutes, this assumption may miss a small portion of dead organic matter that accumulates in soil, but the magnitude of potential errors in this assumption is considered insignificant. A more detailed description of the assumptions and rationale for non-forested ecosystem calculations is provided in Appendix 1.

## SIBEC

We used the site series identified in the dam impacts ecosystem mapping project by Ketcheson et al. (2004) as the basis of analysis. For each site series, we determined typical species composition and stand-level crown closure. This information was derived from vegetation prominence charts and other ecosystem descriptions in the various Field Guides to Site Identification and Interpretation (Meidinger et al. 1988, Lloyd et al. 1990, Braumandl and Curran 1992), and was supplemented with expert opinion. Once stand composition was determined, we used SIBEC look-up tables to identify the typical (mean) site index for each species selected in each site series mapped. Where no data were available, values were estimated based on adjacent or similar site series. A weighted stand average, based on percent composition of each species, was determined for each site series and was used as input for VDYP.

## VDYP

The Variable Density Yield Prediction model (windows version - winVDYP ver1.1, 6.6d) developed by the BC Ministry of Forests provides estimates of the average yield, over time, from natural, unmanaged forests. It is based on thousands of plots from the temporary sample plot database and from the establishment of permanent sample plots throughout the province. The model requires measures of site index and crown closure, and is able to predict future yield curves (volume-over-age) for stands with multiple species. The maximum forest age that can be modelled is 350 years, although some tree species (e.g., western larch, Douglas-fir, western red-cedar, cottonwood) do not increase in volume past a pre-determined stand age (e.g., 250 years for Douglas-fir and western red-cedar).

VDYP uses a series of defaults and maximum allowable values for crown closure based on average growing conditions on the coast and in the interior. In this project, interior values were used for all site series. In general, default values were used for crown closure, unless the BEC Field Guide indicated that a site series is typified by open conditions. In these cases, estimates of crown closure were determined using expert opinion and the Field Guide.

The output provided by VDYP is limited to merchantable volumes with available limits of 7.5, 12.5, 17.5, or 22.5 cm dbh. We summarised culmination (maximum mean annual increment) for 7.5 cm and 12.5 cm merchantability limits, but selected growth curves with a 12.5 cm limit to conform to the specifications of the CBM-CFS3 model. Deletions due to waste and breakage can be modelled in VDYP by specifying the geographic area of concern (by PSYU), but since we were not concerned with the effects of logging residue, we did not include waste and breakage in our scenarios. However, merchantable volumes in VDYP are always net of decay.

## *CBM-CFS3*

The yield curves produced in VDYP were used as direct input into the Carbon Budget Model of the Canadian Forest Service. CBM-CFS3 is an aspatial, inventory-based carbon accounting model that uses forest inventory, growth and yield, disturbance regime, land use change (afforestation, reforestation, deforestation), and forest management activities to simulate carbon dynamics over a given time period. It determines estimates of aboveground and belowground forest biomass and dead organic matter (including soil carbon), and can assess past and future changes in carbon stocks under different scenarios. The CBM-CFS3 model also develops estimates of NPP, NEP, and NPB using tree growth (volume change), climate, and disturbance (Kull et al. pers com 2005).

The CBM-CFS3 model requires several types of input including: areas (in hectares) for the ecosystems or stand types in question; stand ages (or age classes); forest yield curves (merchantable volume-over-age; disturbance types (historic and predicted, natural and anthropogenic); and information on transitions from one ecosystem to another given a disturbance. With this data, it is possible to calculate the rate of carbon accumulation (biomass) for stemwood, bark, foliage, roots, branches, and tops of trees of merchantable size (≥12.5 cm dbh), as well as total aboveground biomass of trees of submerchantable size (Kurz and Apps 1999; Kull et al. pers comm 2005).

CBM-CFS3 does not include estimates of herbs, shrubs, mosses and lichens (consistent with carbon accounting and reporting guidelines), although these are anticipated to provide a lesser proportion of ecosystem values (Kurz, pers comm. 2005). Instead, understory dynamics are modelled for small trees (of sub-merchantable size) in the “other” carbon pool, which also includes stumps, branches, tops, and bark from merchantable-sized trees. The sapling component of the model is based on background equations in the model that are derived from the Panel on Energy Research and Development Biomass Project (Kull pers comm 2006), and is specific to ecozones, leading species, and growth curves submitted (Kurz pers comm 2005). This may reduce accuracy of biomass estimates in early seral stages and non-forested site types. However, biomass measures are generally low in these ecosystems and potential errors are considered acceptable at regional scales (Kurz pers comm 2005).

Conversions between merchantable volume and carbon measures are closely linked to assumptions in the model surrounding stand development patterns. Carbon accumulation in the soil is determined using parameter databases premised on stand dynamics, disturbance regimes, management history, mean annual temperature, biomass input from litterfall, stand mortality, decomposition, and emissions from disturbances (Kurz et al. 2002, Li et al. 2003). However, estimates of soil carbon pools tend to be the least accurate of all variables (Goodale et al. 2002). The volume of other dead organic matter, including snags (stems and branches), logs and litter, is also determined from average values, by stand age, development stage, and disturbance history, from multiple data plots. Dead organic matter is converted from biomass in the model through litterfall, stand development related mortality, and disturbance (Kurz and Apps 1999). Belowground root mortality is related to stand age as well as species composition (hardwood versus softwood) and a series of abiotic and biotic factors (Li et al. 2003). Root biomass generally represents a significant proportion of total ecosystem biomass, and is a large contributor to NPP (Li et al. 2003).

As an inventory-based model, the CBM-CFS3 is likely to have more accurate and precise results than a remote-sensing model that uses satellite imagery to interpret estimates of PAR interception (e.g., ECOLEAP; Bernier et al. 1999, NRCAN 2005b), but the scale at which vegetation relationships are determined is still reasonably coarse. The model relies on growth curves and inventory data, but relationships and assumptions are applied across broad areas. For example, data for the Columbia Basin are assessed using relationships defined for the entire Montane Cordillera Ecozone, which includes all of central and southern interior British Columbia (Environment Canada 2003).

Conversion parameters and equations, such as volume:biomass functions and root:shoot ratios are critical to the assumptions of the CBM-CFS3. The assumptions and default values behind these equations are premised on numerous field plots from across Canada, summarised by Ecozone. Details on these relationships have been documented for earlier versions of the CBM-CFS model, and are expected to be released in early 2006 (Kurz, pers comm. 2005). The most recent references on assumptions can be found in Kurz et al. (2002) and Li et al. (2003). Relationships and assumptions can be modified if users have more detailed information for a particular ecosystem (e.g., mean snag volumes, decay rates, etc.), but were not changed for use in this project. Data from yield curves, in conjunction with the base assumptions, formed the main driver of the model.

Yield curves are an important component of the CBM-CFS3 model for several reasons. In addition to providing the basis for volume:biomass conversions, yield curves help drive changes between carbon dynamics in the four phases of stand development recognized in the model: regeneration, immature growth, mature growth, and overmature/ old growth (Kurz and Apps 1999). Growth during the early stage follows a linear pattern, but increases to a logistic growth model (sigmoidal) in immature stands, levels off in mature stands, and, if field-based data for an Ecozone warrant, declines in the overmature stage (Kurz and Apps 1999). Where stand break up does not occur, the overmature stage is not modelled and the 'steady state' of mature stands continues through older ages.

Most users of the CBM-CFS3 model use inventory data and anticipated disturbance (usually harvest) as their primary inputs. In this project, we identified one stand type for each site series, then used SIBEC and VDYP to define stand growth and yield rates (as described above). Because of our interest in "potential" rather than "current" productivity at a given point in time, we developed a hypothetical inventory then calculated carbon data on a per hectare basis for each site type and each structural stage grouping. We also initiated all stands in all site series at age zero, which allowed us to use CBM-CFS3 to model a pseudo-chronosequence of carbon dynamics over time. In using this approach, we did not add any planned anthropogenic or natural disturbances to the scenarios, and we assumed that all forested stands developed following wildfire[2]. As described above, non-forested stands were modelled using the same approach, but clearcut harvest followed by slash-burning was identified as the stand initiating disturbance, and output data was limited to the annual values for only the early seral stages.

Specific output categories from CBM-CFS3 are summarised in Table 2. These measures were calculated for each site series assuming conifer stands, and additionally for cottonwood dominated stands in the ICHmw1/07, ICHmw2/07, ICHmw3/08, and IDFdm2/04. Stands in the PPdh2-03, PPdh2-04, and ICHwk1-07 are typically deciduous leading, and were only modelled as such. Results are summarised in an associated database (Appendix 2) that provides values (tonnes/ha, tonnes/ha/yr) for each ecosystem type, by structural stage. These values can be summed, by area, for the entire flooded area, by reach, by ecosystem, or by a range of structural stage distributions.

**Table 2. Parameters estimated in CBM-CFS3.**

| *Carbon stocks (t/ha):* | *Productivity (t/ha/yr):* |
|---|---|
| Total Ecosystem Carbon | NPP |
| Total Biomass | NEP |
| Aboveground biomass | |
| Belowground biomass | |
| Total Dead Organic Matter (DOM) | |
| Aboveground DOM | |
| Belowground DOM | |
| Deadwood (logs and snags) | |
| Litter | |
| Soil Carbon | |

[2] A stand-origin disturbance is required in CBM-CFS3 to determine estimates of soil and other dead wood carbon pools. For most of the stands in the study area, wildfire is the most common natural stand-replacing disturbance, and most of the stands flooded were likely from this origin.

# Results

Modelled output from SIBEC, VDYP, and CBM-CFS3 covered a range of site types based on site types, including site series, deciduous leading stand types, and non-forested areas.

**Table 3. Site Types modelled within the Columbia Basin Dam Footprint.**

| *Site Type** | *Site Type** | *Site Type** |
|---|---|---|
| ICHdw1-01a | ICHmw3-04 | IDFdm2-07 |
| ICHdw1-01b | ICHmw3-05 | IDFdm2-07-Ac7 |
| ICHdw1-02 | ICHmw3-06 | IDFun-02 |
| ICHdw1-03 | ICHmw3-07 | IDFun-03 |
| ICHdw1-04 | ICHmw3-08 | IDFun-04 |
| ICHmm-01 | ICHmw3-08-Ac10 | IDFun-05 |
| ICHmm-02 | ICHmw3-08-Ac8 | IDFun-06 |
| ICHmm-03 | ICHmw3-09 | PPdh2-01 |
| ICHmm-04 | ICHvk1-01 | PPdh2-02a |
| ICHmm-05 | ICHvk1-03 | PPdh2-02b |
| ICHmm-06 | ICHvk1-04 | PPdh2-03 |
| ICHmm-07 | ICHvk1-05 | PPdh2-03-At |
| ICHmm-08 | ICHvk1-06 | PPdh2-04 |
| ICHmw1-01 | ICHwk1-01 | SBSdh1-01 |
| ICHmw1-02 | ICHwk1-02 | SBSdh1-06 |
| ICHmw1-04 | ICHwk1-04 | SBSdh1-07 |
| ICHmw1-05 | ICHwk1-05 | SBSdh1-08 |
| ICHmw1-07 | ICHwk1-06 | Avalanche Chute |
| ICHmw1-07-Ac8 | ICHwk1-07 | Avalanche Runout |
| ICHmw2-01 | ICHwk1-08 | Agriculture |
| ICHmw2-02 | ICHwk1-09 | Orchard |
| ICHmw2-03 | ICHxw-01 | Expose Soil |
| ICHmw2-04 | ICHxw-02 | Gravel Bar |
| ICHmw2-05 | ICHxw-03 | Gravel Pit |
| ICHmw2-06 | ICHxw-05 | Mining |
| ICHmw2-07 | IDFdm2-01 | Rock Outcrop |
| ICHmw2-07-Ac8 | IDFdm2-02 | Talus |
| ICHmw2-08 | IDFdm2-03 | Human Settlement |
| ICHmw2-09 | IDFdm2-04 | |
| ICHmw3-01 | IDFdm2-05 | |
| ICHmw3-02 | IDFdm2-06 | |

* Site series followed by Ac or At refer to deciduous leading stands (AC = black cottonwood; At = trembling aspen). The number following the Ac or At designation refers to the stand composition, by decile.

For each site type, summary values were derived for species composition, site index, culmination MAI, merchantable volume, NPP, NEP, carbon accumulation in biomass (above and below ground), and carbon storage in dead organic matter (deadwood, litter, soil – above and below ground). All values are provided in a series of digital appendices to this report.

Species composition, site index, and VDYP yield curve data are provided in Appendix 3 and include volume estimates in 10 year time steps for 'typical' stands in each site type (site series, non-forest, deciduous types) for ages 0 – 350 (Figure 3). This data can be used to determine the potential or actual (estimated) merchantable volume (12.5 cm dbh limit) of the area at the time of flooding or for any other projected time period. The data can also be used to frame potential timber supply losses.

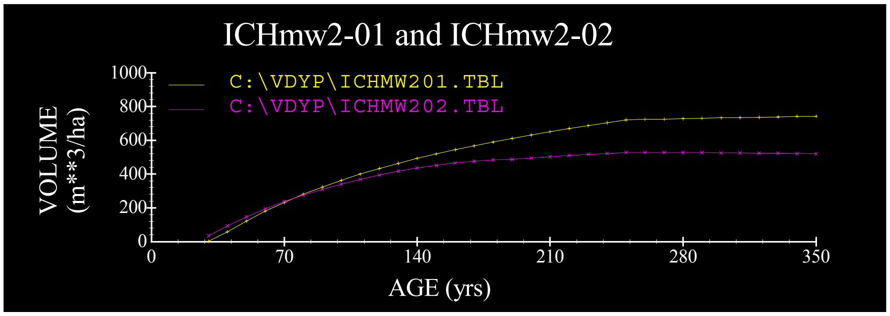



**Figure 3. Sample output from VDYP showing volume-over-age data for the ICHmw2-01 and ICHmw2-02 site series.**

Carbon accumulation, NPP/NEP values, and culmination age, volume and MAI are provided for each site type in Appendix 2. Culmination values provide the year of maximum MAI and the associated volume. Foresters use this information to determine rotation lengths that optimize potential fiber supply over time. In the above example (Figure 3), the culmination age at a merchantable limit of 12.5 cm dbh for the ICHmw2-01 is 105 years with a MAI of 3.63 $m^3$/ha/yr and a standing volume of 381.3 $m^3$/ha (merchantable). Similarly, the same values for the ICHmw2-02 are culmination at 85 years, with 3.44 $m^3$/ha/yr, and 292.5 $m^3$/ha of timber.

Carbon accumulation and NPP/NEP values are provided as tonnes per hectare and are also available in Appendix 4 and Appendix 5 with annual estimates for each variable in each site type. These appendices include a series of excel files that show exported CBM-CFS3 output for each site type analysed. CBM-CFS3 provided NPP and NEP estimates such as those shown in Figure 4 and Figure 5. We chose to stratify analyses by site series (or site type) to match with the reservoir mapping outputs, but it is possible to model groups of site series, such as a BEC variant, in CBM-CFS3.

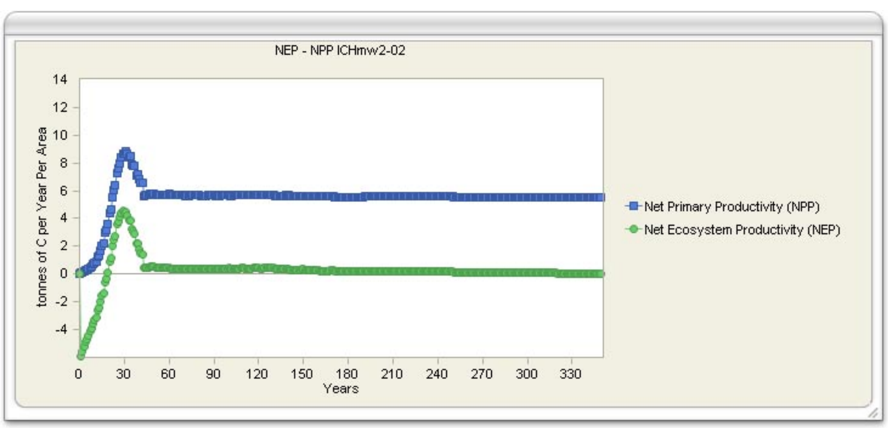



**Figure 4. Sample output from CBM-CFS3 showing a chronosequence of NPP and NEP for ICHmw2-02 sites that originated following wildfire (time since disturbance = 0 – 349 years).**

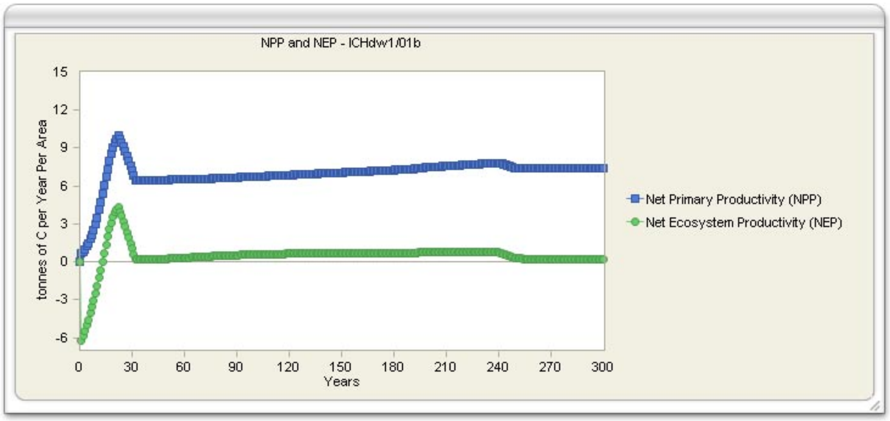



**Figure 5. Sample output from CBM-CFS3 showing a chronosequence of NPP and NEP for ICHdw1-01b sites that originated following wildfire (time since disturbance = 0 – 349 years).**

Carbon stocks were also summarised by site series with output for biomass accumulation (Figure 6), and dead organic matter, by carbon pool (Figure 6 and Figure 7). These could also be summarised by BEC variant or other combination using CBM-CFS3, or with the raw data in Appendix 4 or the summarised data in Appendix 2. In addition to above and below ground estimates of biomass and dead organic matter, CBM-CFS3 can provide estimates of carbon in merchantable and sub-merchantable trees, foliage, fine and coarse roots, stems and tops, softwood or hardwood snags, or a series of carbon pools defined by their decomposition rate (very fast, fast, slow, medium). These were not assessed in this project, but could be modelled using the same input data used in the CBM-CFS3 simulations and scenarios used here (Appendix 6).

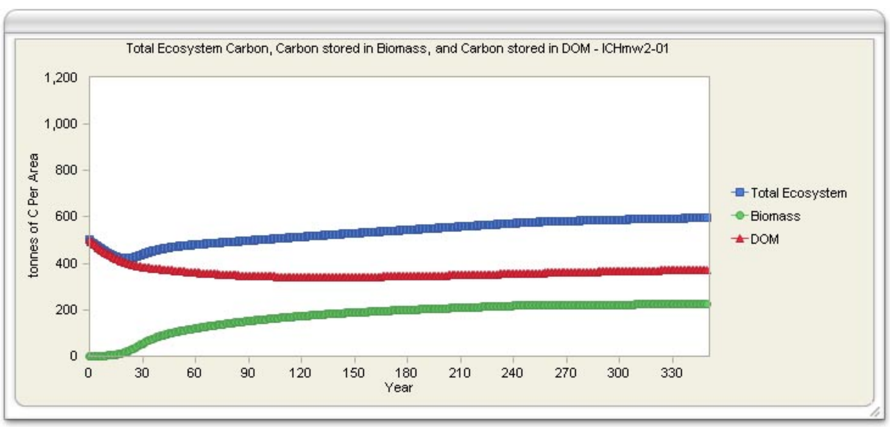



**Figure 6. Sample output from CBM-CFS3 showing a chronosequence of carbon stores in biomass, dead organic matter and the total ecosystem for ICHmw2-01 sites originating following wildfire (time since disturbance = 0 – 349 years).**

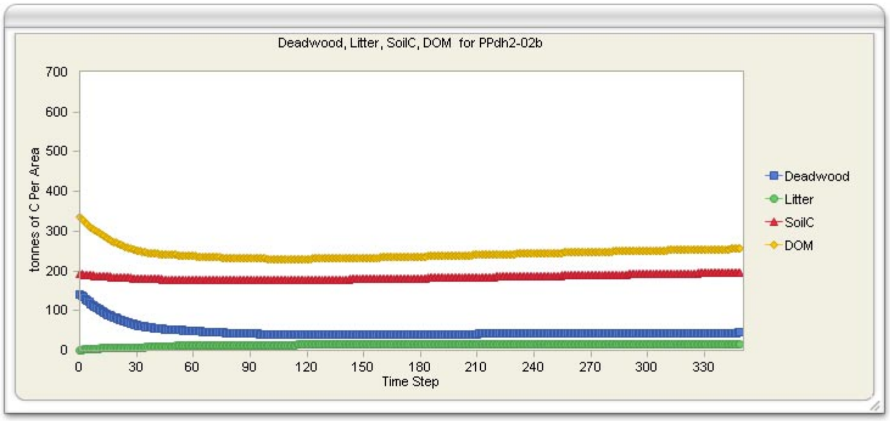



**Figure 7. Sample output from CBM-CFS3 showing a chronosequence of carbon stores in deadwood (snags and logs), litter, soil, and total dead organic matter for PPdh2-02b sites originating following wildfire (time since disturbance = 0 – 349 years).**

The graphs above show carbon stocks and productivity on an annual basis. However, the main output from this modelling exercise is a series of summary tables with mean values for each group of structural stages (based on the structural stage groupings in Table 1; Appendix 2). These values can be summed across the entire footprint area, individual reaches, or other geographic combinations, and can be used to model dynamics based on a range of age class or seral stage distributions.

# Application of the Results

All the results for the study area are summarized by site series and non-forested types that have been identified as individual map units by Ketcheson et al. (2004). Values are also provided by structural stage groupings for each of the forested map units. By combining the estimated values for each of the map units from this study with the GIS spatial representation of the map units from the Ketcheson et al. (2004) mapping, it is possible to spatialize any of the productivity or carbon pool estimates. Through the use of the structural stages it is also possible to examine how values change temporally, or to predict values for any particular point in time. Of the many ways the data could be summarized spatially or temporally, three potentially options have been selected for illustration and are described below.

Through use of a series of lookup tables or linked databases, values for NPP, NEP and carbon pool information from this report can be directly assigned to all of the GIS-based terrestrial ecosystem polygons provided by Ketcheson et al. (2004) for the study area. To make complete use of the NPP, NEP and carbon pool information provided by this report will require use of the following variables in the GIS data base: BEC variant, site series alpha, site series number, structural stage, forest type and cottonwood presence. For each of the options described below the data can be summarized for the whole study area, by individual reservoir or by other ecological unit.

## *NPP, NEP and Carbon Pools at the Time of Flooding*

The mapping provided by Ketcheson et al. (2004) assigns map unit (site series) and structural stage (which can be used as an age surrogate) to each of the terrestrial ecosystem polygons. The structural stages reflect the state of the ecosystems at the time of the aerial photography used for mapping (generally[3] just prior to flooding). By linking the values for NPP, NEP and carbon pools to the site series, structural stages and cottonwood presence values presented in the Ketcheson et al. (2004) mapping, a

[3] Although the date of aerial photography varies, this may not be a significant variable given the general nature of the structural stages. However if the date of aerial photography significantly pre-dates the flooding, this could be corrected by aging the stands in those areas and adjusting the structural stages accordingly.

summary of the conditions for any of the variables can be displayed spatially or summarized by area for the time immediately prior to flooding. This represents values at a single point in time.

The values presented in the database are derived with the assumption that all forested stands developed following a stand-replacing wild fire. Dynamics of harvested stands differ from natural stands, particularly in early seral stages when deadwood values are high for natural sites and litter (logging debris) is high for harvested sites. The data presented here should be applied with some caution to harvested sites, although over time scenarios become similar in the CBM-CFS3 model. Note: older "intermediate-utilization" logging typical of the pre-dam era may be more similar to wild fires than current harvesting techniques. This is particularly true for quantities of large deadwood left on site.

## *Estimated Long-term Averages of "Natural" Conditions*

To better understand the long-term changes to productivity and carbon pools it may be useful to construct an estimated mean of the "range of natural variability" (RONV) for comparison, rather than using a single point in time. This would require defining natural disturbance units (groups of ecosystems with similar stand-replacing return intervals) for the study area, and calculating estimated long-term average percentages of seral/structural stages for each of those units (based on return intervals and the exponential equation). These percentages could then be used to set structural stage values for each mapping unit, with the data summarized over the study area based on the RONV values, rather than the structural stage values that existed just prior to flooding.

This type of summary would not provide detailed spatial locations for the various structural stages at any given point in time, but rather an estimate of their average amounts over the long-term. However if the data was linked to a spatial timber supply model or other disturbance simulator, various potential spatial patterns could be simulated.

## *Potential Productivity and Carbon Storage Under Specified Management Regimes*

Natural resource managers generally are attempting to manage areas for production of a particular product, and will attempt to maximize that production through various management strategies and treatments. For example, sustained yield forest management attempts to replace natural stand-replacing disturbance regimes with clearcut harvesting at culmination age to maximize fibre production. To estimate potential forest productivity lost due to flooding, one could assign the MAI at culmination age to each of the mapping units and summarize the lost productivity in $m^3$/ha/yr. To better simulate present management, one would have to place some environmental and social constraints on the maximizing fibre scenario.

Given the present concerns over carbon storage, one may choose to explore the forgone opportunities to maximize active carbon storage by assigning the maximum NEP for each mapping unit and assume a resource management scenario that had selected maximizing carbon storage as its objective (alternatively one could explore the age class distribution that would maximize the stored pools).
This type of summary would not provide detailed spatial locations for the various structural stages at any given point in time, but rather an estimate of their average amounts over the long-term. However if the data was linked to a spatial timber supply model or other disturbance simulator, various potential spatial patterns could be simulated.

# Discussion

Under ideal circumstances, productivity estimates would be generated using field data collected from the site types within the study area. However, given that the sites in question no longer exist in their 'natural' state, some degree of extrapolation is required. A viable alternative would be to use data from similar (nearby) sites to directly quantify productivity values for each site type, but this data does not exist and would be time-consuming and expensive to collect. Very few complete, field-based carbon-budget studies have been published for temperate forests, and where studies have occurred in the past, many present incomplete data that focuses on a subset of total ecosystem processes (Vogt 1991). With this in mind, modelling is the most accurate means of assessing losses in terrestrial productivity for these areas, although we expect precision to decline commensurate with the assumptions and generalizations at each stage in the modelling process.

We chose to use SIBEC, VDYP, and CBM-CFS3, but we also recognize that there are alternative sets of models that could have been applied. FORECAST, a primary productivity model developed at UBC provides similar outputs without having to extrapolate from timber volumes. FORECAST also produces measures of understory (herb, shrub, moss) productivity. However, calibration processes are somewhat cumbersome and were well beyond the scope of this project. Within the CBM-CFS3 framework, we could have used different growth and yield models such as TIPSY (for managed stands) or PROGNOSIS$^{BC}$ (for individual tree growth projections). VDYP was selected because it is premised on volume output for natural, unmanaged stands, typical of those flooded under the reservoirs.

The results presented in the accompanying databases provide "best-available" information, but are likely to err at site-specific scales. Some of this error can be explained by the generalizations inherent in modelling exercises. Most of the site index estimates provided in SIBEC are not accompanied by reliability estimates. The few that report mean values and standard deviations from field samples typically have standard deviations in the range of 0.5-2.5 site index points. Neither VDYP nor CBM-CFS3 provide reliability estimates for their modelling results, although a summary of assumptions behind CBM-CFS3 is expected in 2006 (Kurz, pers comm. 2005).

VDYP and CBM-CFS3 do not recognize low intensity disturbances such as those found in fire-maintained ecosystems, like the IDF, PP, and drier site series in the ICHdw1 and ICHxw. Instead, both models show a steady increases in growth and yield, which likely over-estimates total stand biomass and under-estimates carbon release from low intensity fires that kill off understory herbs, shrubs, and saplings with minimal mortality among canopy trees. This problem is partially addressed by specifying low stand densities for these sites, but it is not clear that CBM-CFS3 accurately models these grassland/shrub ecosystems. The lack of inclusion of mosses lichens and other herbaceous understory in the modelling also likely leads to some error in the predictions, but they are likely minor compared with the overall levels of predicted values.

While it is difficult to test the accuracy of model predictions as applied to the footprint area, a cursory comparison between the modelled results of this project and other published values (see data in Appendix 7) indicates that the modelled values are comparable to those reported in other studies. For example, Hansen et al. (2000) examined aboveground NPP in the Greater Yellowstone Ecosystem and found that the highest values were in cottonwood, Douglas-fir, and aspen stands, followed by intermediate values in a range of lodgepole pine seral stages. The lowest NPP values were found in grasslands and sagebrush ecosystems. Similarly, the highest biomass values (in old forest structural stages) were found in cedar-hemlock-spruce (or Douglas-fir) stands in the ICHmw3-07 and ICHmw2-06, ICHdw1-04, and ICHwk1-05. The lowest values were from dry ponderosa pine sites in the PP and IDF BEC zones. High NPP values were calculated for in the ICHwk1-04, ICHmw3-01, and ICHmw2-05 (in the shrub/herb stage), while low values were found in black spruce dominated stands in the SBSdh1-08 and ICHmm-07, and open stands in the ICHwk1-09 and IDFdm2-06. Lodgepole pine sites, such as the ICHmw2-02 and ICHmw1-02 had intermediate biomass and NPP.

Considerable attention has been paid to Douglas-fir stands in Oregon and Washington (e.g., Long and Turner 1975, Harmon et al. 1990, Runyon et al. 1999, Smithwick et al. 2002). While much of the research has been in coastal areas, Runyon et al. (1999) reported values along a coast-interior transect. NPP values ranged from 3.0 t/ha/yr in Juniper stands of eastern Oregon to 22.5 t/ha/yr in mature, low elevation hemlock-Douglas-fir stands in western Oregon. Biomass was lowest in the juniper stands (10.8 t/ha ±2.8 t/ha), but was moderate in the hemlock-fir stands (408.3 t/h ±31 t/h) and highest in old growth hemlock-sitka spruce forests (710 t/ha ±114 t/ha). More recently, Smithwick et al. (2002) reported biomass values of 1127 t/ha for old-growth hemlock-sitka spruce forests and 829 t/ha for hemlock-fir stands. Both Runyon et al. (1999) and Smithwick et al. (2002) report biomass values for ponderosa pine. Runyon et al. (1999) reported 14.9 t/ha in young ponderosa pine stands, while Smithwick et al. (2002) reported 195 t/ha for 300-500 year old stands. Runyon et al. (1999) also estimated NPP in the young stands at 3.2 t/ha/yr.

The most comprehensive study of productivity to take place within the Columbia Basin was conducted by Comeau and Kimmins (1989) in 70-78 year old pine stands in the Montane Spruce (MS) zone near Canal Flats. They reported NPP values between 7.9 and 9.6 t/ha/yr for xeric sites and 11.9 t/ha/yr for mesic sites, with 55.1% of the total resulting from belowground NPP. Although outside of the footprint area, these sites in the MS are likely similar to IDF sites in the East Kootenay. Modelled NPP values for structural stage 4-5 xeric IDF sites in this study ranged from 4.2 – 6.0 t/ha/yr. NPP on dry ICH sites was between 6.0 and 6.9 t/ha/yr. These values are more similar to those found in a study of mature lodgepole pine and white spruce stands in the Rocky Mountains of southwestern Alberta where NPP rates ranged from 4.4 – 5.3 t/ha/yr (Prescott et al. 1989). Mesic IDF sites (structural stage 4-5) in this study were also lower than those in Comeau and Kimmins' (1989) MS sites with values around 6.3 t/ha/yr. Comeau and Kimmins (1989) found that approximately 25% of stand biomass was belowground in xeric stands compared to 20% in mesic stands. However, comparisons with biomass figures in the present study are confounded because the output from CBM-CFS3 reports *carbon* stores in biomass while Comeau and Kimmins (1989) and Prescott et al. (1989) report dry weight biomass.

As noted throughout this report, values for NPP and carbon stores must be interpreted within the temporal and site-specific contexts. We addressed the temporal concerns by providing values for the range of structural stages in the footprint ecosystem map (Ketcheson et al. 2004). Differences in site productivity potential were addressed by analysing each site series/site type separately. However, the models that we used have a poor ability to differentiate between stand densities over time. For example, VDYP models stands with the same percent cover for all time steps. We addressed some of this concern by assigning a lower crown closure to open stand types (e.g. ICHwk1-09), but default crown closure values were used for most sites. Litton et al. (2003) found considerable differences in biomass accumulation between varying densities of young lodgepole pine stands in Yellowstone National Park. Low density sites (<1000 sph) had biomass values ranging from 222-935 kg/ha, while moderate density stands (7,000 – 40,000 sph) had 3808-12,523 kg/ha, and high density stands had 8874-13,685 kg/ha.

Comparisons of modelled results for agricultural lands and other non-forested site types, suggest that results from CBM-CFS3 are also within an expected range. Assessments of NPP for agriculture lands across the world generally report values between 0.8 and 5.0 t/ha/yr (e.g., Potter et al. 1993, Malstrom et al. 1997), which are consistent with our value of approximately 1.5 t/ha/yr for agricultural fields. Hansen et al. (2000) have reported values for ponderosa pine grasslands and sagebrush types in the Greater Yellowstone Ecosystem with aboveground values of 1.9-2.1 t/ha/yr, which are roughly consistent with this report's values for avalanche tracks (1.3-1.6t/ha/yr).

# Literature Cited

Bernier, P.Y., Fournier, R., Ung, C.-H., Robitaille, G., Larocque, G., Lavigne, M.B., Boutin, R., Raulier, F., Paré, D., Beaubien, J., and Delisle, C. 1999. Linking ecophysiology and forest productivity: an overview of the ECOLEAP project. For. Chron. 75:417-421.

Braumandl, T.F. and M.P. Curran. 1992. A field guide for site identification and interpretation for the Nelson Forest Region. BC Min. For. Research Branch, Victoria, B.C., Land Manage. Handb. No 20.

Comeau P.G., and J.P. Kimmins (1989) Above-ground and below-ground biomass and production of lodgepole pine on sites with differing soil-moisture regimes. Canadian J. Forest Research 19, 447-454.

Environment Canada. 2003. Pacific and Yukon Ecozones and Ecoregions. Available online at: http://www.ecoinfo.ec.gc.ca/ecozones/ecozones_e.cfm

Environment Canada. 2005. Climate Change Overview. Website: http://www.ec.gc.ca/climate/kyoto-e.html Updated December 2, 2005; visited December 15, 2005.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, GH. Kohlmaier, W. Kurz, S.Liu, G.-J. Nabuurs, S. Nilsson, and A.Z. Shvidenko. 2002. Ecological Applications 12(3): 891–899.

Grier, C. C., and R. S. Logan. 1977. Old-growth Pseudotsuga Menziesii communities of a western Oregon watershed: biomass distribution and production budgets. Ecological Monographs 47:373-400.

Hansen AJ, Rotella JJ, Kraska MPV, and Brown D. 2000. Spatial patterns of primary productivity in the Greater Yellowstone Ecosystem. Landscape Ecology 15, 505-522.

Harmon, M. E., W. K. Ferrell, and J. F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699–702.

Intergovernmental Panel on Climate Change (IPPC). 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Chapter 3, section 3.5.2.2 Change in carbon stocks in land converted to flooded land (Reservoirs). Available online at: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.htm

Ketcheson, M.V., K. Misurak, V. Lipinski, G. Kernaghan, K. Lessard, T. Dool, L. Bradley and E. White. 2005. Columbia Basin BC Hydro Footprint Mapping: BC Hydro Reference Number DFIM040. Report prepared for CBFWCP, Nelson, BC.

Kull, S., Kurz, W.A., Rampley, G., Banfield, E., Schivatcheva, T. and M.J. Apps. Natural Resources Canada, Canadian Forest Service, September 30, 2005. Operational Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.0: Draft User's Guide.

Kurz, W.A. and M.J. Apps. 1999. "A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector." Ecological Applications, 9(2):526-547.

Kurz, W.A.; M. Apps; E. Banfield; and G. Stinson. 2002. Forest carbon accounting at the operational scale. The Forestry Chronicle 78(5):672–679.

Li, Z., Kurz, W.A., Apps, M.J., and Beukema, S.J. 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvement and implications for the estimation of NPP and NEP. Canadian Journal of Forest Research 33: 126-136.

Litton, C.M., M.G. Ryan, D.B. Tinker, and D.H. Knight. 2003. Belowground and aboveground biomass in young postfire lodgepole pine forests of contrasting tree density. Canadian Journal of Forest Research 33:351-363.

Lloyd, D., K. Angove, G. Hope and C. Thompson. 1990. A guide to site identification and interpretation for the Kamloops Forest Region. BC Min. For. Research Branch, Victoria, B.C., Land Manage. Handb. No 23.

Long, J. N., and J. Turner. 1975. Aboveground biomass of understorey and overstorey in an age sequence of four Douglas-fir stands. Journal of Applied Ecology 12:179–188.

Malmstrom, C., M. Thompson, G. Juday, S. Los, J. Randerson and C. Field. 1997. Interannual variation in global-scale net primary production: testing model estimates. Global Biogeochemical Cycles 11:367-392.

Meidinger, D., A. McLeod, A. MacKinnon, C. DeLong and G. Hope. 1988. A field guide for site identification and interpretation of ecosystems of the Rocky Mountain Trench, Prince George Forest Region. BC Min. For. Research Branch, Victoria, B.C., Land Manage. Handb. No 15.

Ministry of Forests. 2002. Variable Density Yield Predictions. Research Branch, Victoria, BC. Available online at: http://www.for.gov.bc.ca/hre/gymodels/VDYP/features.htm

Ministry of Forests and Range. 2005. Site Index estimates by Site Series (SIBEC) – Second approximation. Research Branch, Victoria, BC. Available online at: http://www.for.gov.bc.ca/hre/sibec/SIBEC_RDM_Section_6.htm

Natural Resources Canada. 2005a. Forest Carbon Accounting, a webpage of the Canadian Forest Service. Website: http://carbon.cfs.nrcan.gc.ca/index_e.html#ref. Updated October 24, 2005; visited November/December 2005.

Natural Resources Canada (NRCAN) 2005b. ECOLEAP Project. Available online at: http://ecoleap.cfl.scf.rncan.gc.ca/accueil_e.html. Updated December 5, 2005; visited November/December 2005.

Olson, R.J., K.R. Johnson, D.L. Zheng, and J. M.O. Scurlock. 2001. Global and Regional Ecosystem Modeling: Databases of Model Drivers and Validation Measurements. Report published by the Environmental Sciences Division. Oak Ridge National Laboratory for NASA.

Peng, C., and M.J. Apps. 1999. Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes. Ecological Modelling 122:175–193.

Potter, C., J. Randerson, C. Field, P. Matson, P. Vitousek, H. Mooney, and S. Klooster. 1993. Terrestrial ecosystem production: a process model based on global satellite surface data. Global Biogeochemical Cycles 7(4): 811-841.

Prescott, C. E., P. Corbin, and D. Parkinson. 1989. Biomass, productivity, and nutrient-use efficiency of aboveground vegetation in four Rocky Mountain coniferous forests. Canadian Journal of Forest Research 19:309-317.

Randerson, J.T., F.S. Chapin, III, J.W. Harden, J.C. Neff, and M.E. Harmon. 2002. Net ecosystem production: A comprehensive measure of net carbon accumulation by ecosystems. Ecological Applications, 12(4):937–947.

Runyon, J., R. H. Waring, S. N. Goward, and J. M. Welles. 1994. Environmental limits on net primary production and light-use efficiency across the Oregon transect. Ecological Applications 4: 226-237.

Smith, D.M., B.C. Larson, M.J. Kelty, P.M.S Ashton. 1997. The practice of silviculture: Applied forest ecology, 9th edition. John Wiley & Sons, Inc., New York. 537 p.

Smithwick, E.A.H., M.E. Harmon, S.M. Remillard, S.A. Acker, and J.F. Franklin. 2002. Potential upper bounds of carbon stores in forests of the Pacific Northwest. Ecological Applications, 12(5):1303–1317. (Data available at: http://www.esapubs.org/archive/appl/A012/012/appendix-A.htm)

Stearns-Smith, S. 2001. Making sense of site index estimates in British Columbia: A quick look at the big picture. B.C. Journal of Ecosystems and Management 1(2):1-4.

Vogt, K. 1991. Carbon budgets of temperate forest ecosystems. Tree Physiol. 9:69–86.

# Appendices

**Appendix 1. Assumptions for non-forested types**

| Type | Description | NPP | NEP | Carbon storage* | Rationale |
|---|---|---|---|---|---|
| **CF** | Cleared fields: hayfields and other croplands; may be subject to fertilization and irrigation | Average of years 6-15 of a clearcut scenario for ICHmw3-01 and IDFdm2-01; NPP likely variable | 0 | Biomass is average of year 10 of ICHmw3-01 and IDFdm2-01 clearcut scenario; soil and litter is 50% of minimum; DOM-ag is 5% of DOM-tot | Most of the CF types are mapped in the IDFdm2 and ICHmw3 (the remainder are distributed in slightly dryer and wetter BEC units); hay and other cereal crops are similar to the early seral herb structural stage present in early years after disturbance; most agriculture is on medium textured mesic soils typical of SS 01 and likely included some irrigation and fertilization; sustainable annual management is assumed to maintain these anthropogenic disclimax ecosystems in a near equilibrium state and therefore NEP is near zero; the lack of trees, plowing and annual cropping is reflected by the reduced soil and litter carbon; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |
| **CO** | Orchards: small to moderate-size deciduous trees with hay or other herbaceous ground cover | Average of years 11-20 of a clearcut scenario for ICHmw3-01 | 0 | Biomass is year 15 of ICHmw3-01 clearcut scenario; soil and litter is 50% of minimum; DOM-ag is 5% of DOM-tot | Orchards are similar to the early to mid seral tall shrub/herb structural stage present in years 11-20 after disturbance; most agriculture is on medium textured mesic soils typical of SS 01; most orchards were mapped in the West Kootenays; sustainable annual management is assumed to maintain these anthropogenic disclimax ecosystems in a near equilibrium state and therefore NEP is near zero; the lack of large trees, pruning and annual cropping is reflected by the reduced soil and litter carbon; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |
| **GB** | Gravel bar: non-vegetated to sparsely vegetated exposed gravelly to cobbly areas in rivers or along lakeshores | 50% of the average of years 1-5 of a clearcut scenario for ICHwk1-05 | 0 | Biomass is 50% of year 5 of ICHwk1-05 clearcut scenario; soil and litter is 5% of minimum; DOM-ag ground is 5% of DOM-tot | Areas are typically unstable and flooded for a significant portion of the growing season; they are perpetually maintained as very sparsely vegetated early seral communities typified by years 1-5 years after disturbance; the relatively stable disclimax ecosystems are assumed to be near equilibrium and therefore NEP is near zero; the lack of trees, flooding and annual disturbance is reflected by the severely reduced soil and litter carbon; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |

| Type | Description | NPP | NEP | Carbon storage* | Rationale |
|---|---|---|---|---|---|
| **AC** | Snow avalanche chute: areas where periodic snow avalanching prevents forest development | Average of years 6-15 of a clearcut scenario for ICHmw3-01; NPP likely variable | 0 | Biomass is year 15 of ICHmw3-01 clearcut scenario; soil and litter is 50% of minimum; DOM-ag is 5% of DOM-tot | Periodic snow avalanching perpetually maintains herb, shrub or mixed herb/shrub communities typical of structural stages 2 or 3 typified by years 6-15 years after disturbance in a normal seral sequence; the relatively stable disclimax ecosystems are assumed to be near equilibrium and therefore NEP is near zero; the lack of trees is reflected by the reduced soil and litter carbon; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |
| **AR** | Snow avalanche run-out zone: toe-slope and/or riparian areas where snow avalanching prevents forest development | Average of years 6-15 of a clearcut scenario for ICHwk1-05; NPP likely variable | 0 | Biomass is year 15 of ICHwk1-05 clearcut scenario; soil and litter is 75% of minimum; DOM-ag is 5% of DOM-tot | Periodic snow avalanching perpetually maintains relatively moist herb, shrub or mixed herb/shrub communities typical of structural stages 2 or 3 typified by years 6-15 years after disturbance in a normal seral sequence; the relatively stable disclimax ecosystems are assumed to be near equilibrium and therefore NEP is near zero; the lessor reduction in soil and litter carbon reflects the balance between the lack of trees and slower decomposition due to a shorter season and cooler soils; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |
| **RO, TA** | Rock outcrops and talus: non-vegetated to sparsely vegetated areas if rock or coarse colluvium | 50% of the average of years 1-5 of a clearcut scenario for ICHmw2-02 | 0 | Biomass is 50% of year 5 of ICHmw2-02 clearcut scenario; soil and litter is 10% of minimum; DOM-ag is 5% of DOM-tot | Very dry edaphic climaxes that are perpetually maintained as sparsely vegetated early seral communities; though more sparsely vegetated, they are similar to those that are typical of years 1-5 years after disturbance on slightly moister types; the relatively stable edaphic climax ecosystems are assumed to be near equilibrium and therefore NEP is near zero; the lack of trees and very sparse vegetation is reflected by the severely reduced soil and litter carbon; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |

| Type | Description | NPP | NEP | Carbon storage* | Rationale |
|---|---|---|---|---|---|
| **ES** | Exposed soil: non-vegetated to sparsely vegetated areas resulting from erosion and/or human disturbance activities | Average of years 1-5 of a clearcut scenario for ICHmw2-02 | 0 | Biomass is year 5 of ICHmw2-02 clearcut scenario; soil and litter is 10% of minimum; DOM-ag ground is 5% of DOM-tot | Disclimaxes that are perpetually maintained as sparsely vegetated early seral communities due to periodic disturbance; the relatively stable disclimax climax ecosystems are assumed to be near equilibrium and therefore NEP is near zero; where the disturbance has ceased they are early seral types in the earliest stages of succession and NEP may have a small positive value; the lack of trees and very sparse vegetation is reflected by the severely reduced soil and litter carbon; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |
| **UR** | Urban/ residences: in this map area generally partially treed residential areas; may be subject to fertilization and irrigation | Average of years 6-15 of a clearcut scenario for ICHmw3-01 and IDFdm2-01; NPP likely variable | 0 | Biomass is average of year 15 of ICHmw3-01 and IDFdm2-01 clearcut scenario; soil and litter is 25% of minimum; DOM-ag is 5% of DOM-tot | Most of the mapped UR types are partially treed residential areas; NPP values are intended to provide an average for a type that is typified by partially forested and partially cleared municipal and rural lots, but also includes limited areas of roads, industrial lands and undeveloped mature forest lands; continuous management is assumed to maintain these anthropogenic disclimax ecosystems in a near equilibrium state and therefore NEP is near zero, although where development is increasing it may be negative; the reduced tree coverage, pruning and areas of disturbed soil are reflected by the reduced soil and litter carbon; the lack of snags/ deadwood is reflected in a reduced DOM-ag/DOM-bg ratio |
| **GP,MZ** | | 0 | 0 | 0 | Ongoing disturbance prevents or severely limits biological activity. |

* DOM-ag refers to aboveground Dead Organic Material (litter and deadwood); DOM-tot refers to both above and belowground DOM.

**Appendix 2. Productivity estimates, by site type and structural stage groupings**

**File Name:**
Terr_Prod_Summary.xls

**Data Description:**
This file contains five worksheets.

1) Info – outlines data development, assumptions, and definitions for the remaining worksheets.
2) NPP-NEP – provides output from CBM-CFS3, summarised by structural stage group for each site type.
3) Biomass-DOM – provides output from CBM-CFS3 on carbon stocks and pools, summarised by structural stage group for each site type.
4) MAI-SI – provides species composition summaries (as determined using BEC Field Guides to Site Identification and Interpretation), weighted averages for site index (from SIBEC), site class and culmination age, volume and mean annual increment (MAI) for 7.5 cm and 12.5 cm dbh merchantability limits (from VDYP).
5) Non-Forest – provides estimates of NPP, NEP, Biomass, and DOM for each of the non-forested types. This information has been summarised for each non-forest type and can be applied to a given type in all areas (all reaches) within the footprint.

**Suggested Use:**
The data provided here is the primary output from this project and can be used to determine productivity estimates for the footprint area. Data are based on individual site series/site types, and can be summed or rolled-up in a variety of ways.

1) By site type
2) By BEC unit, ecosection or other ecological boundary
3) By reach (summed by site type first)
4) At the time of flooding
5) Based on maximum potential values
6) Based on the range of natural variability (RONV)
7) Based on any other land use scenario

**Appendix 3. Species composition, SIBEC, and VDYP output**

**File Name:**
SIBEC-VDYP Output.xls

**Data Description:**
Data in this file include species composition for forested ecosystems and their associated site index values based on SIBEC, full VDYP output (includes height and diameter over time for 7.5 cm and 12.5 cm dbh limits), and summaries of the VDYP yield curves used in CBM-CFS3 (12.5 cm merchantability).

**Suggested Use:**
This information is provided as background data and could be examined for more detail on merchantable volumes, tree heights, or mean diameters at a given age, for either the 7.5 cm or 12.5 cm dbh limit.

## Appendix 4. Summary of carbon stocks in Biomass and DOM for each site type

**File Name:**
Folder: Biomass-DOM-SITES

**Data Description:**
This is a folder containing all of the exported output files from CBM-CFS3 relating to carbon stocks. It includes an individual MS Excel file for each site type analysed. Files that start with “CC” followed by the BEC unit refer to scenarios based on clearcut and slash-burning as the most recent stand disturbance. Data in all files provides annual values for all sites, and ranges from 0-349 years.

**Suggested Use:**
This is the base data used to derive the database in the Terr_Prod_Summary.xls file and is provided here as background information. It could be used to re-analyse the data using different structural stages, or to graph chronosequences of carbon stock changes over time.

## Appendix 5. Summary of NPP and NEP for each site type

**File Name:**
Folder: NPP-NEP-SITES

**Data Description:**
This is a folder containing all of the exported output files from CBM-CFS3 relating to NPP and NEP estimates. It includes an individual MS Excel file for each site type analysed. Files that start with “CC” followed by the BEC unit refer to scenarios based on clearcut and slash-burning as the most recent stand disturbance. Data in all files provides annual values for all sites, and ranges from 0-349 years.

**Suggested Use:**
This is the base data used to derive the database in the Terr_Prod_Summary.xls file and is provided here as background information. It could be used to re-analyse the data using different structural stages, or to graph chronosequences of NPP and NEP changes over time.

## Appendix 6. CBM-CFS3 model input data

**File Name:**
CBM Data Input-15Dec05-Age0.xls
CBM Data Input-20Dec05-Age0-CC.xls

**Data Description:**
These are the data files that were imported into the CBM-CFS3 model. They include specific formatting necessary for using the CBM-CFS3 model. The CBM Data Input-15Dec05-Age0.xls includes data used for forested stands and is based on wildfire as the most recent stand replacing disturbance. CBM Data Input-20Dec05-Age0-CC.xls includes the data used to model non-forested areas and is based on clearcut and slash-burn as the most recent stand replacing disturbance.

**Suggested Use:**
These files are provided in case there is a desire to create additional scenarios or future simulations in CBM-CFS3.

**Appendix 7. Literature review**

**File Name:**
Terr_Prod_Lit Review Dbase.xls
Folder: Literature

**Data Description:**
The xls file contains lists of academic and government publications referring to primary productivity, carbon stores, and biomass accumulation, as well as summaries

1) Lit List provides a list of literature found through web searches and queries on academic databases.
2) Value Summary provides a brief project description followed by a detailed summary of values for carbon stocks and/or productivity (where available).
3) NPP dbase provides a summary and overview of select literature that was reviewed. This worksheet offers more detail on project methods and general findings than the Value Summary sheet.

The folder contains digital versions of literature collected for this project (where available online). Bibliographic information is available in Lit List in the xls file.

**Suggested Use:**
Information in this database can be used in future work related to terrestrial productivity estimates.