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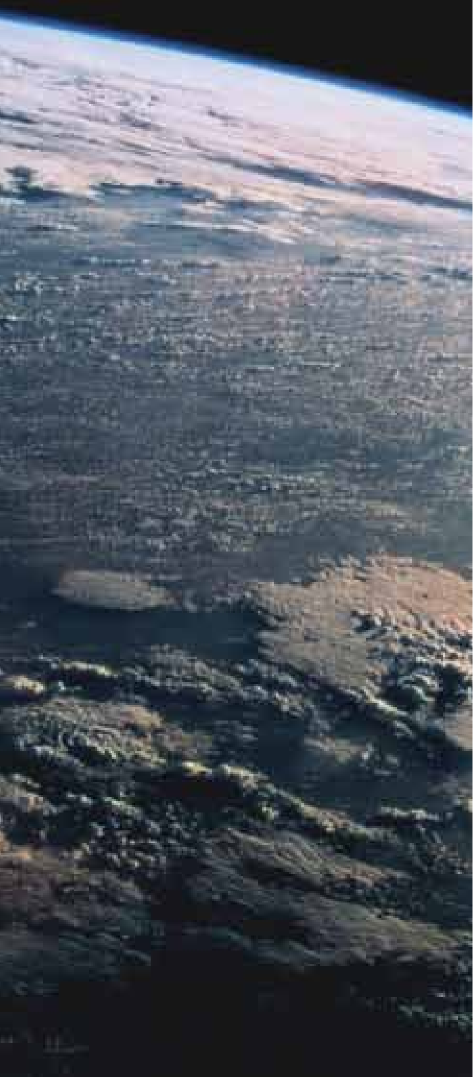

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Carbon Sequestration in British Columbia's Forests and Management Options

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EXECUTIVE SUMMARY OF FUTURE RESEARCH NEEDS

Policies are required that direct research towards aiding both short-term and long-term adaptive management for increasing forest carbon (C) storage and sequestration rates and mitigating greenhouse gas (GHG) emissions. It will need to recognize the economic importance of forests so that increased C sequestration and continuous timber supplies will have to be considered together. The following are highly recommended research areas:

- Research in coastal BC shows that fertilization of high-productivity forest sites not only can provide economic returns in terms of harvested wood, but also can increase C sequestration and reduce GHG global warming potential (GWP). However, research is required on the effect of N fertilization on soil C stocks because increased C inputs into the soil through litterfall and root decomposition can either speed up or slow down the decomposition of labile and recalcitrant soil organic matter. This has not yet been resolved. Furthermore, experiments need to be conducted to determine the effects of fertilization on net GHG GWP in southern interior and northern BC forests.

- As growth conditions change with climate change, the potential range of species will change. Therefore, it will be necessary to consider planting other more adaptive species following disturbance. Research is required on how different tree species (e.g., nitrogen fixers) can affect the magnitude and permanence of soil C stocks. Since variable retention harvesting is increasingly being used by BC foresters, its effects on the rate of growth of planted or naturally regenerating trees and long-term soil C stocks need to be investigated.

- Preserving old growth stands not only maintains large amounts of stored C but also research shows that they continue to sequester much more C than previously thought. However, further research is needed to determine whether the vulnerability of some of these stands to natural disturbance means that there are long-term advantages to carefully planned harvesting. The impact of the planned shift from logging old-growth stands to second-growth stands on the BC coast with the use of improved management, e.g., fertilization and thinning, will require study. In particular, a concerted research initiative is required to determine the impact of these management practices as well as climate change on soil C pools, soil respiration and soil microbial populations.

- Micrometeorological measurements of stand-atmosphere CO2 exchange are required to determine the net ecosystem productivity (NEP) (i.e., C sequestration) of major forest types in BC and its sensitivity to changing climate. Combined with remote-sensing tools, estimates of regional NEP can be obtained and used to validate large-scale C balance models such as CBM-CFS3. In addition, direct measurements of ecosystem C stocks should be made at regular (~5-year) intervals. These measurements are essential inputs to C inventory models and are required to validate process-based models.

- Research is required to determine the effects of fire suppression on the risk of intense crown fires and other types of disturbance (e.g., insect outbreak). Controlling insect infestations remains a challenge, and more research is required on emergence, survival and physiology of existing insect species and those appearing as a result of changing climate. Additional research efforts are needed to determine to what extent stand disturbance (fire, harvesting and insect outbreak) will increase runoff and ultimately affect losses of organic matter, nutrients and mineral soil. A major question that requires research is how to manage lodgepole pine stands recently attacked by mountain pine beetle. Research is urgently required to determine how to conserve secondary structure (i.e., non-pine species) and reduce damage to it during salvage logging to ensure maximum C sequestration and mid-term timber supplies.

- Research into the conversion of otherwise degradable biomass with low-temperature pyrolysis into a highly-recalcitrant form of C (biocharcoal) and produce bioenergy and other useful chemicals should be explored. The application of biochar to soil has been proposed as a long-term sink for atmospheric CO2 in terrestrial ecosystems and a valuable soil amendment. Economic analysis will be needed to determine under what conditions net environmental and economic benefits would be realized.

ABSTRACT

This White Paper describes the potential of forests in the northern hemisphere in general, and in British Columbia in particular, in sequestering atmospheric carbon dioxide and thus mitigating anthropogenic greenhouse gas emissions, apart from providing environmental and economical benefits. We first describe the extent of forest C stocks and C sequestration rates, and how they are affected by climate change and natural and human-induced disturbances. This is followed by a discussion of management for conservation and efficient utilization of forest C stocks and management options for increasing C sequestration rates. We do not attempt to compare the economics of different management options for maximum C sequestration. Rather, we focus on future research needs required for developing an appropriate adaptive management response framework.

INTRODUCTION

Forests are among the most productive terrestrial ecosystems, which along with their long-lived woody character, makes them attractive for climate change mitigation (Nabuurs et al., 2007). Forests not only store the largest fraction of terrestrial ecosystem carbon (C) stocks, recently estimated at 1,640 Pg C (Sabine et al., 2004), equivalent to about 220% of atmospheric C, but also provide commercial timber and non-timber forest products, wildlife habitat, climate regulation, soil and water protection or purification (>75% of globally usable freshwater supplies come from forested catchments (Shvidenko et al., 2005)), and recreational, cultural and spiritual benefits (Reid et al., 2005).

Forest C storage is an important ecosystem service, sequestering C that might otherwise exist in the atmosphere as carbon dioxide (CO_2), a potent greenhouse gas (GHG). In the Northern Hemisphere, forests are estimated to sequester up to 0.7 Pg C annually (Goodale et al., 2002), or nearly 10% of current global fossil fuel C emissions (IPCC 2007). Since both photosynthetic CO_2 uptake (GPP) and loss in respiration (R) vary with community composition, stand developmental stage, growing season length, precipitation, temperature and solar radiation, net C sequestration capacity of individual forest ecosystems varies a great deal. Future climate change may significantly influence forest C stocks through its impact on climate variables (e.g., precipitation), severity and frequency of disturbance events (e.g., fires and insect infestations), and forest succession. Understanding how variation in annual C storage is controlled at the ecosystem scale is central to any approach that employs forest C sequestration to mitigate anthropogenic CO_2 emissions (Birdsey et al., 2006).

Aimed at climate change mitigation, completing inventories of above- and below-ground C pools and temporal changes in these, i.e., rates of gains from and losses to the atmosphere, has become increasingly important. While regional inventories can provide present day C storage estimates, ecosystem-level studies provide important process-level information on C dynamics for the prediction of future carbon storage as well as local validation of regional estimates. A combination of ecological and meteorological measurements, followed by modelling, has helped us in understanding and quantifying forest C sequestration and its storage in different pools as well as influences of climate, past disturbance, stand development, and ecological succession.

BC's 62 million ha of highly diverse forests provide a wide range of social, cultural, economic and biological values and services. While lodgepole pine and spruce species dominate the BC interior with the former recently severely affected by the mountain pine beetle (MPB) infestation, the coastal temperate rainforest holds more biomass per unit area than any other ecosystem on the planet. About 95% of BC's land base is publicly owned and the managed forests on this land have been extensively studied with respect to timber supply and hence C stocks. This paper, however, discusses the role BC forests play in C sequestration for anthropogenic GHG-emission mitigation, and ways of better managing them for maximum benefits.

FOREST C STORAGE AND ITS CHANGE

While the magnitude of forest C stocks is twice that of C in the atmosphere, C fluxes out of and into the forest C pool are much smaller. Carbon stocks in BC's conifer-dominated forests are highest in the oldest stands, and have been, and are currently being, affected by disturbance and harvesting. Mean total ecosystem C stocks in mature stands in the Pacific Northwest (PNW) vary from 750 Mg ha^{-1} to 1130 Mg ha^{-1} with 30-50% being stored in the soil (Smithwick et al., 2002). In interior BC, they vary from 324 Mg C ha^{-1} to 423 Mg C ha^{-1} in old growth stands and are ~200 Mg ha^{-1} in second-growth stands (Fredeen et al., 2005). Net ecosystem productivity (NEP = GPP - R) (i.e., C sequestration) measurements in a chronosequence of coastal Douglas-fir stands since 1998 (Morgenstern et al., 2004; Humphreys et al., 2006; Jassal et al., 2008b) using the eddy-covariance (EC) technique have shown that while a clearcut-harvested stand was a net source of ~6 Mg C ha^{-1} y^{-1}, a near-end-of-rotation stand (50-60 years-old) sequestered ~4 Mg C ha^{-1} y^{-1} with the shift from a C source to C sink occurring at the age of ~17 years (Figure 1). In a wet sub-boreal interior spruce and subalpine forest east of Prince George, it took approximately 8 years to make the transition from source to sink (Fredeen et al., 2007). These transitions, however, do not take into account C stored in harvested wood products.

At larger spatial scales, remote sensing has been used in the generation of spatially explicit forest C estimates (Zheng et al., 2007), e.g., in northern BC (Janzen et al., 2006). Addition-

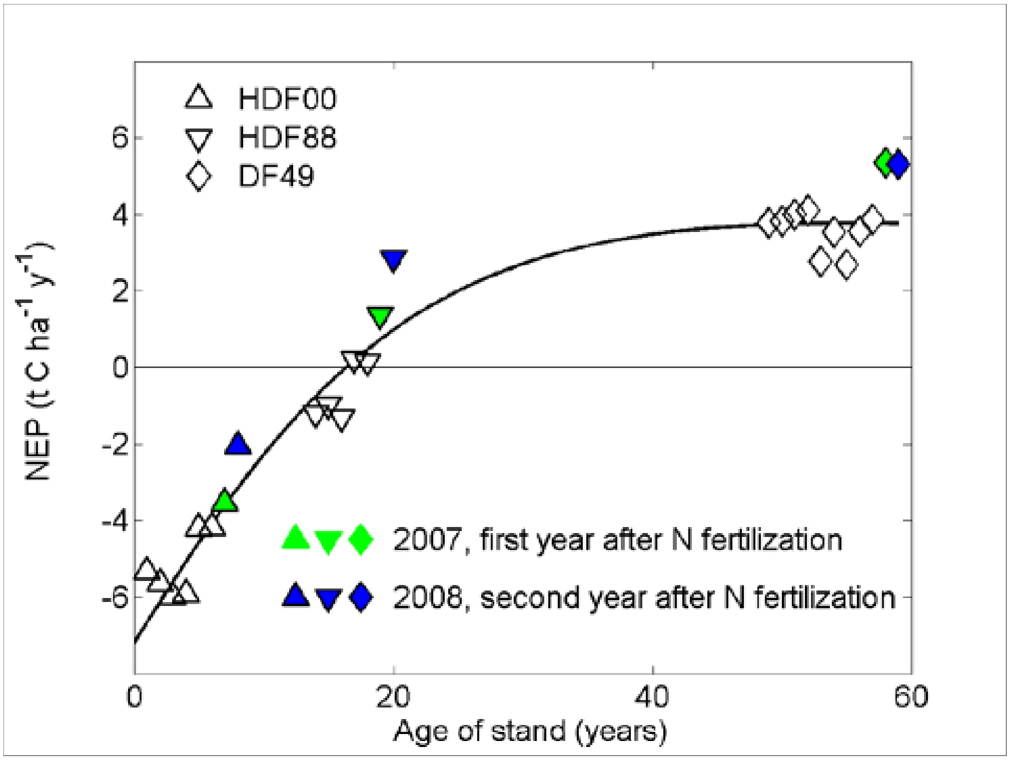

Figure 1. Effect of stand age and N fertilization on net ecosystem productivity (NEP) in a Douglas-fir chronosequence on the east coast of Vancouver Island (revised from Jassal et al., 2008b). While HDF00 and HDF88 refer to stands harvested and planted in 2000 and 1988, respectively, DF49 was planted in 1949 after forest fire several years before.

ally, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) has been used to calculate C stocks and stock changes in BC's forests (Kurz and Apps, 2006; Trofymow et al., 2008). However, confirmation of model predictions of changes in C stocks through direct C storage measurement is difficult because annual sequestration or loss is a small fraction, typically <0.2%, of the total C stored (Malhi et al., 1999).

Influences of climate change

Climate change directly affects forest growth, structure and species composition, and thus C stocks. While current species may survive, their growth rates will likely be affected and there will be competition from other species more suited to the changed climate. Changes in productivity as a result of climate change will affect rotation age, wood quality, wood volume, and size of logs (Canadell and Raupach, 2008). Boisvenue and Running (2006) found that wood-growth rates increased globally in a majority of forests over the past 55 years, possibly because of warmer air temperatures and rising CO_2. In general, there is a positive relationship between mean annual temperature and annual C storage rates, with higher temperatures extending the growing season period and consequently increasing annual photosynthetic C gains (Baldocchi et al., 2005; Black et al., 2005). However, rising air temperatures also increase C losses from ecosystem respiration, often exponentially (Law et al., 2002, Curtis et al., 2005). Global changes that include rising atmospheric CO_2, and ozone, increasing atmospheric N deposition, and changes in precipitation may affect annual forest C storage both as primary drivers and through interaction with each other (Boisvenue and Running 2006; Hyvonen et al., 2007; Magnani et al., 2007).

While warming, particularly in high altitude ecosystems can result in increased ecosystem C uptake (Nemani et al., 2003), an increase in C uptake during early spring (Black et al., 2000) can be cancelled out with decreased uptake during hotter and drier summers (Angert et al., 2005). A global synthesis of northern ecosystems has shown that 90% of the increased CO_2 uptake as a result of spring warming (~0.73 Pg CO_2 $°C^{-1}$) is offset by increased losses due to autumn warming (Piao et al., 2007). In BC's coastal forest, hotter summers resulted in faster decomposition of soil organic matter leading to reduced NEP (Morgenstern et al., 2004), while hotter and drier summers caused reductions in ecosystem respiration that exceeded the reduction in C uptake, thereby increasing NEP (Jassal et al., 2008a). Effects of drought on forests include mortality, potential reduction in resilience and alteration in major biotic feedbacks (e.g., Ciais et al., 2005). Drought-conditions further interact with disturbances such as insect attacks (Fleming et al., 2002) or fire (Flannigan et al., 2000).

The climate of the PNW is changing and according to the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2007) the change will continue at an even faster rate (www.PacificClimate.org). Changes in temperature and precipitation during the past several decades in the PNW have exceeded global averages (Mote, 2003), with summers becoming drier and winters wetter. Northern and southern BC will be warming even more and becoming somewhat wetter. Summertime water-deficit has resulted in decreased productivity of coastal Douglas-fir forests (e.g., Gessel et al., 1990; Jassal et al., 2008c; Spittlehouse, 1985). While forest-productivity losses are expected to occur in the drier and warmer regions, modest increases are expected in the north (Spittlehouse, 2003). However, while a longer growing season due to climate change will enhance photosynthesis in the spring, respiration will likely be increased in the warmer autumn (Piao et al., 2007). The balance of these effects has not been determined for northern BC forests.

Effects of Disturbance

Exchange of C between forests and the atmosphere is being influenced by human-caused and natural disturbances. Understanding and quantifying the impacts of disturbances are prerequisites to selecting forest management options aimed at enhancing C sinks and reducing C sources, while maintaining other ecological, social, and economic benefits of the forest. A recent FLUXNET synthesis found that disturbance was the primary mechanism that changes ecosystems from C sinks to sources (Baldocchi et al., 2008a). Simulations using CBM-CFS3 have shown that future disturbances by fires and large insect outbreaks will likely convert the managed forests of Canada from a sink to a source during the first Kyoto Protocol commitment period, 2008–2012 (Kurz et al., 2008a). Where forests regenerate after disturbances, periods with above-average emissions are often followed by periods of above-average C uptake (Gough et al., 2008). For some years after a disturbance, the net C balance of a stand is negative (C stocks are declining) as C release from decomposition exceeds C uptake by new tree growth (Figure 1). Eventually, the stand-level C balance will become positive as trees remove more C from the atmosphere than is released from decay.

Globally, deforestation and forestry still account for 10-20% of the rise in GHG's (IPCC, 2007) and while vigorous young stands have high NEP, they never achieve the C stocks that were contained in original primary and old-growth forest (e.g. Janzen 2006, Smithwick et al. 2002). This is particularly important where natural disturbances are infrequent and rarely stand destroying, such as coastal BC.

The current age distribution of forests in BC is skewed towards old trees, which for drier interior forests results in increased sensitivity to disturbance by fires and pests. Climate change will likely increase the number and intensity of storms (Spittlehouse, 2007) in coastal BC, thereby increasing wind-throw damage. Also, drier areas of the Southern Interior may experience regeneration problems due to increased summer droughts. Future forest C storage also will depend on ecological changes that result from ongoing forest disturbance and succession.

Fire has always played an integral role in the structure and function of forest ecosystems, especially in seasonally dry forests in the BC Interior. Although fires destroy part of the stored C, they shift the wood biomass from live C pools to dead C pools, some as highly recalcitrant charcoal. Fires can also open seed cones for some species often allowing the emergence of naturally regenerated trees. Each year, wildfires burn thousands of hectares of forestland in BC with the mean annual area burnt over the last decade being 75,000 ha and about 13,000 ha burnt in the current year (2008) (www.bcwildfire.ca). Forest fires cause a loss of C stocks that varies with fire severity but historically (1959-1999) have been estimated to be 0.5 Tg y^{-1} as direct C emissions for BC forests, mostly in the drier interior (Amiro et al., 2001). There will be some post-fire losses from fire-killed biomass but the magnitude is poorly known with few direct measurements, though, however, charcoal formed as a result of fire is highly recalcitrant.

Insect infestations can cause defoliation, partial or total tree mortality, reductions in forest CO_2 uptake in photosynthesis, and increases in emissions from the decay of biomass. Periodic insect and disease infestations have always been part of the natural cycles of growth, self-thinning, death, and rejuvenation of forest stands in BC, especially in the interior. BC is currently experiencing the largest recorded MPB outbreak in North America (Taylor et al., 2006). This epidemic has resulted in widespread mortality of lodgepole pine, the BC interior's most abundant tree species. As MPB populations increase in southern BC as well as at higher elevations there is also increasing mortality of both ponderosa and whitebark pine (Taylor et al., 2006). Climate change, mainly warmer winters, has contributed to the unprecedented extent and severity of this outbreak (Carrol et al., 2006). Insect outbreaks such as this represent an important mechanism by which climate change may undermine the ability of northern forests to take up and store atmospheric CO_2. Using CBM-CFS3 for simulating future net biome production (NBP), Kurz et al. (2008b) have estimated that the MPB outbreak will result in a cumulative loss of 270 Pg C (or 0.36 t C m^{-2} ha^{-1} on average over 374,000 km^2 of forest) during 2000–2020. EC flux research in MPB-affected stands in northern BC is now providing empirical evidence that such models may need to be refined to adequately account for the compensatory growth of sub-canopy, understory and non-attacked trees and species, shrubs and ground vegetation post-attack (Brown et al., 2008).

MANAGEMENT OF FOREST C STOCKS

Forest products remain British Columbia's most important export commodity (BC Stats 2006). Forests and forest management can also contribute toward reducing future atmospheric GHG concentrations (Nabuurs et al., 2007; House et al., 2002). While reducing deforestation may be more beneficial than afforestation in the short run, sustainable forest management aimed at maintaining or increasing forest C stocks could generate the largest sustained mitigation benefits (Nabuurs et al., 2007). Canadell and Raupach (2008) point out that the overall potential of management activities to increase C density can be substantial and comparable to that of reforestation. Forests often store C at rates well below their potential and thus could be responsive to management for enhanced C sequestration. In Canada, an additional C sequestration potential of about 3.9 and 2.6 Mg CO_2 ha^{-1} y^{-1} exists on 2-3% of total forest area through thinning and fertilization, respectively (Nabuurs et al., 2000). However, forests in southern and coastal BC may offer greater potential since longer growing seasons may support higher average C storage rates. Industrial timberlands may be managed both for forest products and C sequestration to offset anthropogenic CO_2 emissions (Birdsey et al., 2006). However, conventional forest management is mainly concerned with the volume and value of the stem wood product, and shows little regard for woody debris, litter or soil C stocks, which, comprising more than 50% of the C stock in a stand, can be particularly vulnerable to management operations (Cannell et al., 1993).

BC's forests are a large and long-term store of C with the net stocks fluctuating due to wild fires and insect outbreaks. Human activities also have a significant impact, and there are opportunities for increasing C sequestration and GHG-emissions mitigation. Mitigation of GHG-emissions demands conserving, enhancing and efficiently using forest C stocks. However, before we consider various options, it is important to continue to refine and expand our knowledge of inventories of above- and below-ground C-stocks using a combination of ecological, meteorological and remote sensing techniques. This will help to identify the location of C pools that are more vulnerable to natural and silvicultural disturbances as a result of climate change. While there is need to continue to improve models and the inventory information required to run them, empirical mechanistic and process-level information will ultimately be required to better predict future C stocks.

Conservation of forest C stocks

Conservation of forest C stocks involves reducing slash burning, suppressing fires and using pest control in sensitive areas, redirecting logging from old-growth to second-growth stands and increasing rotation length, salvage logging of fire- or beetle-killed stands for lumber and biofuel, and using wood for long-lasting products. In the short term, GHG mitigation benefits of reducing deforestation are greater than the benefits of reforestation (Canadell and Raupach, 2008). Contrary to earlier beliefs that old-growth forests cease to accumulate C (Kira and Sihedie, 1967; Odum, 1969), a recent meta-analysis of 519 stands of up to 800 years old from around the globe has shown that old-growth forests continue to accumulate significant amounts of C (Luyssaert et al., 2008), also borne out in BC studies, e.g. sub-boreal spruce and fir stands (Janzen 2006). This emphasizes the importance of maintaining and increasing the protected areas of old-growth forests on the central and northern coast. A policy of net-zero deforestation needs to be followed in letter and spirit, i.e., whenever forestland is converted to other uses, an equivalent non-forest area must be planted elsewhere, preferably on marginal land.

Forest protection regulations should be further strengthened such that tree-farm licenses should have attached conditions on rotation-age and logging residue. Similarly reduced-impact logging techniques that not only increase soil-C storage over traditional logging but also are cost effective, need to be reinforced. Logging residue should not be burnt but either left on-site to act as an organic amendment likely to increase soil C or used in non-timber services, e.g., bioenergy.

Increased awareness is required in controlling wild fires and insect infestations, especially in light of climate change, by reducing fuel load and restoring landscape heterogeneity, respectively. However, all-out fire suppression may lead to situations ripe for stand-destroying events such as more intense fires (e.g. the Yellowstone Park fire in 1988) or widespread unstoppable insect attacks (e.g. bark beetles). A greater understanding of the trade-offs between fire suppression and long-term forest C storage are needed.

Increasing the length of the harvest-rotation period ensures a longer time for undisturbed soil conditions, which helps maintain soil organic matter (Grant et al., 2007). However, a better understanding and predictive tools are needed to estimate optimum rotation-age for different forest species for maximum economic returns and GHG emission mitigation. This is particularly important with respect to climate change and management options like fertilization, which can alter previous knowledge regarding optimum rotation-age.

Afforestation has the potential to increase C sequestration through increased biomass and litterfall over many years. High initial costs of afforestation with decades of delay in returns, however, may be offset by erosion control and other non-consumptive uses and ecosystem services of forests. Sites disturbed by harvesting, wildfires and insect damage, etc. should be reforested promptly and with more than one species to assure fast but long-term C storage. Urban afforestation with perennial shrubs and trees in backyards, schools and hospital grounds, civic parks, parking lots, campuses and other public spaces should be enhanced. However, little information is available on the role of urban forestation in C sequestration and GHG-emissions mitigation.

Efficient use of C stocks and fossil fuel substitution

Manufactured wood products can store C for decades, e.g., in buildings and furniture. Incentives should be provided to encourage mitigation activities involving C retention in wood products, and emissions reduction by using them to replace emissions-intensive and C-poor products such as steel, aluminum, concrete and plastic (Harmon et al., 1990; Hennigar et al., 2008). Harmon et al. (1990), using a non-linear difference model of temporal dynamics of PNW Douglas-fir, determined that 42% of harvested timber entered wood products with a life span of greater than 5 years. Construction of apartment buildings using wooden frames instead of concrete frames reduces life-cycle C emissions by 110-470 kg CO_2 m^{-2} floor area (Gustavsson and Sathre, 2006). Net GHG-emissions mitigation will be further increased if wood is first used for construction and then recycled or used as biofuel after building disposal (Eriksson et al., 2007).

Biomass can be used to produce heat and electricity, solid, liquid and gaseous fuels, and other products. Using biomass from waste wood (e.g. MPB-killed wood) and forest residues is a better choice than using agricultural crops for fuel, particularly when grains are used as opposed to cellulosic materials (www.fao.org).

ENHANCEMENT OF FOREST C SEQUESTRATION

Enhancement of C sequestration in forests can be accomplished through management practices like thinning and fertilization that result in increased mean annual increment, and reforestation. Forest thinning has been known to enhance total wood yield over a rotation and augment soil C pools (Selig et al., 2008). However, the MPB attack has been found to be more severe in thinned stands of lodgepole pine in the BC interior (Taylor et al., 2006). This suggests the need to further investigate and understand such interactions.

Forest fertilization

Despite earlier reports to the contrary (Nadelhoffer et al., 1999), recent research has shown that net C sequestration in temperate and boreal forests has increased in response to elevated N deposition (Magnani et al., 2008; Pregitzer et al., 2008). Observations from free–air CO_2 enhancement (FACE) experiments have suggested that there may be no growth enhancement by CO_2 fertilization unless additional N is available (Canadell et al., 2007). With annual N deposition of <2 kg N ha^{-1} (Galloway et al., 2004) and soils deficient in N, BC's coastal forests (Chapin et al., 2002), respond to N fertilization. Forest fertilization is already a widespread silvicultural practice in the PNW (Chappell et al., 1991). Canary et al. (2000) observed that fertilization of 3-40 year-old Douglas-fir stands in western Washington at ~1000 kg N ha^{-1} spread over 16 years resulted in an additional increase in C sequestration at an average of 1 t C ha^{-1} y^{-1} over 24 years. By contrast, fertilization of lodgepole pine stands in the BC Interior has resulted in no response to a small response (Amponsah et al., 2004, 2005). With the MPB affecting BC's central interior, the BC Ministry of Forests and Range policies seek to increase the productivity of second-growth coastal forests through N fertilization in order to maintain employment in the forest products sector and provide the potential benefit of reducing GHG emissions through increased C sequestration (BCMFR, 2007).

The BC Climate Action Team Report (2008) further recommends enhancing forest management practices that make forest ecosystems more resilient to stresses caused by climate change. As these practices are promoted through monetary incentives, they have the potential to be rapidly implemented. However, the full impacts of the practices promoted are poorly understood from the perspective of C sequestration and climate change. Thus it is essential to quantify the C costs of management and to consider how such practices may compromise other ecosystem goods and services (Sonne, 2006). Fertilization of a near-end-of-rotation coastal Douglas-fir stand with 200 kg N ha^{-1} resulted in a nearly 60% increase in NEP, from 3.3 to 5.3 t C ha^{-1} y^{-1} (Figure 1), but resulted in ~5% of applied N lost in highly potent N_2O in the first year after fertilization (Jassal et al., 2008b). Calculations showed that after accounting for N_2O emissions and CO_2 emissions associated with manufacturing, transport and application of fertilizer (Kongshaug, 1998), fertilization resulted in decreased net change in GHG global warming potential (GWP) in the first year. A similar increase in NEP but with no N_2O emissions in the second year suggests the viability of N fertilization in increasing C sequestration for GHG mitigation. The results showed that N fertilization of a near-end-of-rotation coastal Douglas-fir stand at a cost (including fertilizer and its aerial application) of \$300 ha^{-1} resulted in an additional sequestration of 7.3 Mg CO_2 ha^{-1} y^{-1} (~7.5 m^3 wood ha^{-1} y^{-1}) in the first two years (Jassal et al., 2008d), which is well within the IPCC estimates of \$100 per Mg CO_2 (Nabuurs et al., 2007). It is likely that larger effects of fertilization are observed in young stands while older stands may show smaller or no effects (Jandl et al., 2006; Jassal et al., 2008d). However, there is a need to conduct similar experiments in the BC interior on lodgepole pine and spruce stands, and apply rigorous and full GHG accounting when making decisions.

Thinning

Thinning of overstocked stands is one of the basic tools of silviculture. Though thinning may result in less on-site C, it accelerates tree growth, ensures long-term forest health, and promotes strong, well-structured trees leading to higher annual increment and quality of wood. Forest thinning can also, under certain circumstances, decrease the severity and rate of spread of wild fires (Jandl et al., 2006). Despite concerns about increased soil respiration over the short term, thinning leads to less logging residues at harvest substantially reducing subsequent decomposition losses. Thus, there is some room for improved silviculture to enhance C sequestration, particularly if commercially thinned trees could be utilized to offset stand-tending operations, e.g., to provide bioenergy.

Role of secondary structure in MPB-affected stands

Management responses to MPB-affected lodgepole pine stands vary from complete removal of the pine canopy and secondary structure (SS) (saplings, seedlings, shrubs and herbaceous plants) to selective removal of MPB-affected trees with varying degrees of SS retention, to completely non-invasive strategies, i.e., allowing SS to grow undisturbed in a dead stand. Poor choice of management approach could have several negative consequences: the regenerative potential of forest soils could be compromised; drainage to surrounding watersheds could be increased in response to the drop in evapotranspiration; and, snow melt could occur earlier in the spring, causing spring floods and influencing stream flow during the remainder of the growing season.

Surveys of pine-leading (>50% pine overstory) forests in north-central BC have indicated that while 20-25% of pine-leading plots had such poor SS that total salvage-logging and planting was the best way to mitigate timber losses, 40-50% of surveyed plots had sufficient SS to be stocked without any substantial intervention. Of the stands surveyed in the Nadina, Vanderhoof and Prince George Forest Districts, about 60% of pine-leading plots had SS with volumes equivalent to or greater than a 20-year-old spruce plantation, while close to 30% were equivalent to a 30-year-old spruce stand following clearcutting (Coates et al., 2006). Thus, opportunities for mid-term timber harvest, preservation of biodiversity and habitat, and hydrologic recovery would be ensured by strategically protecting SS during salvage-logging operations (Burton, 2008). This will ensure continuous short-term C sequestration and long-term C storage. EC measurements in MPB-attacked stands in the BC interior with and without significant SS have shown that the growing season CO_2 uptake by the SS made the former a very weak C source of 0.25 t C ha^{-1} y^{-1} compared to the latter as a medium source of 1.25 t C ha^{-1} y^{-1}, thereby showing the importance of SS in sequestering C (Brown et al., 2008).

MANAGEMENT RESPONSE FRAMEWORK AND FUTURE RESEARCH NEEDS

The foregoing discussion can help generate policies to direct research towards aiding both short-term and long-term adaptive management for increasing forest C storage and sequestration rates and mitigating GHG-emissions. Use of policy analysis or growth and yield models (e.g., *Tipsy* (Mitchell et al., 2000)) and forest management models (e.g., *Remsoft Spatial Planning System* (Hennigar et al., 2008)) can be made to optimise for maximum C sequestration. However, a good management adaptive framework will need to recognize the economic importance of forests so that increased C sequestration and continuous timber supplies will have to be considered together. We recommend that C stored in the protected areas of old-growth forest should also be factored in any framework adopted to enhance long-term C storage. However, to determine the true forest contribution to GHG-emissions mitigation, C stored in wood products, and in landfills, as well as that saved by replacing them with other emissions-intensive products, along with energy used in the forest products sector and management activities must also be included.

We have seen that fertilization of high-productivity forest sites can not only provide economic returns in terms of harvested wood, but also can increase C sequestration and reduce GHG GWP. However, more research is required on the effect of N fertilization on soil C stocks as enhanced tree growth, which increases C inputs into the soil through litterfall and root decomposition, can either speed-up or slow-down the decomposition rate of labile and recalcitrant organic matter in the soil. The latter is a question not yet resolved. It appears that the enhancement of C sequestration with fertilization may have greater potential at lower latitudes due to a longer growing season, but experiments need to be conducted to determine the effect of fertilization on net GHG GWP in southern interior and northern BC forests, and the influence of soil texture.

Tree-species selection can modify soil C stocks, e.g., N-fixing species can be especially effective in increasing soil C (Jandl et al., 2006). However, permanence of such C sequestration has not been duly investigated. As growth conditions change under climate change, the potential range of species will change and species will migrate northward and to higher elevations. Therefore, we have to consider planting other more adaptive species following disturbance. Also, as variable retention harvesting is increasingly used by BC foresters as an environmentally responsible way to manage forest lands, its role in C sequestration in planted or naturally regenerating trees and in long-term soil C stocks needs to be investigated.

If mature stands are, in general, more vulnerable to natural disturbance, then increased harvest may reduce risk of natural disturbance (Routledge, 1980). The BC action plan for coastal forestry envisages shifting logging from old-growth to second-growth trees, which will be prepared for cutting through better management, e.g., fertilization and thinning. However, caution may have to be exercised as this quick turn-over amounts to a shorter rotation age for coastal forests. Simulations with a process-based ecosystem model *ecosys* showed that over 240 years, 60-year-rotations compared to 120-year-rotations increased wood production but decreased soil C stocks (Grant et al., 2007). A balance sheet of C pools based mainly on measurements showed a decrease of 0.5 t C ha^{-1} y^{-1} in soil C for a near-end-of-rotation coastal Douglas-fir stand. These results have serious ramifications for long-term forest C stocks. With soil C being the largest pool in terrestrial ecosystems, and models based on historical data incapable of tracking temporal changes in it, concerted research efforts are required to estimate soil C pools as well as heterotrophic and rhizospheric components of soil respiration, and to understand the effects of climate change on these. The models need to be refined to account for short-term changes in these C pools before they can be employed to forecast future long-term trends.

Additional EC flux measurements in carefully selected representative stands for BC's major ecosystems are required to understand the processes in the short-term and develop relationships to determine the sensitivity of NEP to climate change in the long-term. For example, measurements on a coastal Douglas-fir chronosequence have shown a decrease in NEP in warmer summers but an increase in NEP in drier summers. EC flux measurements have the advantage of integrating net primary productivity and heterotrophic respiration, which is necessary to improve the management of forest ecosystems for C sequestration, especially under changing climate (Baldocchi, 2008b). Furthermore, direct measurements of ecosystem C storage are essential to inventory C stocks of BC forests (e.g., in National Forest Inventory plots) as inputs to C inventory models. These should be made at regular (~5-year) intervals to provide independent estimates of C sequestration rates to compare with EC measurements and help validate process-based models. Of particular importance is increasing efforts to quantify changes in soil organic matter in the forest floor and mineral layers.

While reduced slash burning will likely help in conserving forest soil C stocks, knowledge of its short-term impacts on ease of planting and herbicide application, and microclimate, and long-term impacts on C in recalcitrant charcoal is urgently needed.

Climate change will increase the stresses on many forests, which in turn will limit our ability to suppress natural disturbances. The policy of fire suppression can delay, but cannot prevent wildfires altogether over the long term. Also, continued fire suppression can bring about other changes, such as arrested forest successional cycling, aging of the forests, or accumulation of woody biomass, that can lead to increased risk of other disturbance types (e.g., insects) or to more intensive disturbances (e.g., crown fire). Fire reduction policies that require the removal of undergrowth and occasional thinning could contribute to the production of bioenergy, which in turn could replace fossil fuel use. Controlling insect infestations and fires remains a challenge, and more research is required on emergence, survival and physiology of old and new species of insects with ecosystems shifting northwards with climate change. Furthermore, the decomposition rate of highly recalcitrant charcoal formed as a result of fire, vis-à-vis its contribution to long-term C sequestration remains to be quantified (Preston and Schmidt, 2006).

The net effect of removing forest cover through harvesting, fire or defoliation is an increase in the water content of the soil, an increase in the amount of water available for runoff (Winkler et al. 2005; Jassal et al., 2008c), and a change in the timing of snow melt (Winkler et al. 2005). Additional research efforts are needed to determine how increased runoff will affect losses of nutrients, organic matter and soil and diminish C accumulation in the long-term.

Care needs to be taken to conserve SS and reduce collateral damage of other species during salvage logging in pine-beetle-affected areas. This would require the use of innovative salvage-logging techniques and equipment.

While afforestation will increase C sequestration and thus GHG-emissions mitigation, excessive afforestation in northern BC may result in decreased albedo and increased evapotranspiration with the latter adversely affecting stream flows. Positive forcing induced by decreased albedo can increase climate change rather than mitigating it (Betts, 2000).

New frontiers in research and development envisage conversion of otherwise degradable biomass with low-temperature pyrolysis into a highly-recalcitrant form of C (biocharcoal or biochar) and, at the same time, produce bioenergy or other useful chemicals, which might provide the ideal GHG mitigation solution for BC's forestry land uses. The application of biochar to soil has been proposed as a novel approach to establish a significant long-term sink for atmospheric CO_2 in terrestrial ecosystems, and to act as a valuable soil amendment with immediate benefits through improved soil fertility and increased productivity (Lehman et al., 2006). However, full C accounting and economic analyses are needed to determine those situations where net environmental and economic benefits will be realized.

REFERENCES

Amiro BD, Todd JB, Wotton BM, Logan KA, Flannigan MD, Stocks BJ, Mason JA, Martell DL, Hirsch KG. 2001. Direct carbon emissions from Canadian forest fires, 1959-1999. *Canadian Journal of Forest Research* 31, 512-525.

Amponsah IG, Lieffers VJ, Comeau PG, Brockley RP. 2004. Growth response and sapwood hydraulic properties of young lodgepole pine following repeated fertilization *Tree Physiology* 24, 1099-1108.

Amponsah IG, Comeau PG, Brockley RP, Lieffers VJ. 2005. Effects of repeated fertilization on needle longevity, foliar nutrition, effective leaf area index, and growth characteristics of lodgepole pine in interior British Columbia, Canada. *Canadian Journal of Forest Research* 35, 440-451.

Angert A, Biraud S, Bonfils C, Henning CC, Buermann W, Pinzon J, Tucker CJ, Fung I. 2005. Drier summers cancel out the CO_2 uptake enhancement induced by warmer springs. *PNAS* 102, 10823-10827.

Baldocchi D. 2008a. Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. *Australian Journal of Botany* 56, 1-26.

Baldocchi D. 2008b. Fluxnet: Quo vadis. *FluxLetter* 1, 4-5.

Baldocchi D, Black TA, Cur PS, Falge E, Fuentes JD, Granier A, Gu L, Knohl A, Pilegaard K, Schmid HP, Wilson R, Wofsy S, Xu L, Yamamoto S. 2005. Predicting the onset of net carbon uptake by deciduous forests with soil temperature and climate data: A synthesis of FLUXNET data. *International Journal of Biometeorol* 49, 377-387.

BCMFR. 2008. 2007/08 Annual Service Plan Report. B.C. Ministry of Forests and Range, Victoria, BC, Canada, 71 p.

BCMFR. 2007. Coastal Forest Action Plan. B.C. Ministry of Forests and Range, Victoria, BC, Canada, 9 p.

Betts RA. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* 408, 187-190.

Birdsey R, Pregitzer K, Liicier A. 2006. Forest carbon management in the United States: *Journal of Environmental Quality* 35, 1461-1469.

Black TA, Gaumont-Guay D, Jassal RS, Amiro BD, Jarvis PG, Gower ST, Kelliher FM 2005. Measurement of carbon dioxide exchange between the boreal forest and the atmosphere. In *Carbon Balance of Forest Biomes*, Griffiths H, Jarvis P (eds.), BIOS Scientific Publishers, U.K., pp 151-186.

Black TA, Chen WJ, Barr AG, Arain MA, Chen Z, Nesic Z, Hogg EH, Neumann HH, Yang PC. 2000. Increased carbon sequestration by a boreal deciduous forest in years with a warm spring. *Geophysical Research Letters* 27, 1271–1274.

Boisvenue C, Running SW. 2006. Impacts of climate change on natural forest productivity: Evidence since the middle of the 20th century. *Global Change Biology* 12, 862-882.

Brown M, Black TA, Nesic Z, Fredeen A, Jackson P, Burton P, Trofymow T, Spittlehouse D, Grant N, Eggington V. 2008. Impact of the mountain pine beetle on the carbon balance of lodgepole pine stands in western Canada. 28th Conference of Agricultural and Forest Meteorology of the American Meteorol Society, Orlando, FL, April 2008.

Burton PJ. 2008. The potential role of secondary structure in forest renewal after mountain pine beetle. *Canadian Silviculture* May 2008, 26-29.

Canary JD, Harrison RB, Compton JE, Chappel HN. 2000. Additional carbon sequestration following repeated urea fertilization of second-growth Douglas-fir stands in western Washington. *Forest Ecololgy and Management* 138, 225-232.

Canadell JG, Kirschbaum M, Kurz WA, Sanz M-J, Schlamadinger B, Yamagata Y. 2007. Factoring out natural and indirect human effects on terrestrial carbon sources and sinks. *Environmental Science and Policy* 10, 370–384.

Canadell JG, Raupach MR. 2008. Managing forests for climate change mitigation. *Science* 320, 1456-1457.

Cannell MGR, Dewar RC, Pyatt DG. 1993. Conifer plantations on drained peatlands in Britain: A net gain or loss of carbon? *Forestry* 66, 353-369.

Chappell HN, Cole DW, Gessel SP, Walker RB. 1991. Forest fertilization research and practice in the Pacific Northwest. *Fertilizer Research* 27, 129-140.

Chapin, FS, Matson PA, Mooney HA. 2002. Principles of terrestrial ecosystem ecology. New York, NY, USA: Springer-Verlag.

Ciais P, Janssens I, Shvidenko A, Wirth C, Malhi Y, Grace J, Schulze E-D, Heimann M, Phillips O, Dolman AJ. 2005. The potential for rising CO2 to account for the observed uptake of carbon by tropical, temperate and boreal forest biomass. In The Carbon Balance of Forest Biomes, Griffith H and Jarvis PG (Eds.), Taylor and Francis, pp 109–150.

Coates KD, DeLong C, Burton PJ, Sachs DL. 2006. Abundance of secondary structure in lodgepole pine stands affected by the mountain pine beetle. Report for the Chief Forester, May 2006. Bulkley Valley Centre for Natural Resources Research and Management. Unpublished report, 17 p.

Curtis PS, Vogel CS, Gough CM, Schmid HP, Su H-B, Bovard BD. 2005. Respiratory carbon losses and the carbon-use efficiency of a northern hardwood forest, 1999-2003. *New Phytologist* 167, 437-456.

Eriksson E, Gillespie AR, Gustavsson L, Langvall O, Olsson M, Sathre R, Stendahl J, 2007. Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forest Research* 37, 671–681.

Fredeen AL, Waughtal JD, TG Pypker. 2007. When do replanted sub-boreal clearcuts become net sinks for CO2? *Forest Ecology and Management* 239, 210-216.

Fredeen AL, Bois CH, Janzen DT, Sanborn PT. 2005. Comparison of coniferous forest carbon stocks between old-growth and young second-growth forests on two soil types in central British Columbia, Canada. *Canadian Journal of Forest Research* 35, 1411-1421.

Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger RP, Asner GP, Cleveland CC, Green PA, Holland EA, Karl DM, Michaels AF, Porter JH, Townsend AR, Vorosmarty CJ. 2004. Nitrogen cycles: past, present, and future. *Biogeochemistry* 70, 153–226.

Gessel SP, Millar RE, Cole DW. 1990. Relative Importance of Water and Nutrients on the Growth of Coastal Douglas–Fir in the Paciic Northwest. *Forest Ecology and Management* 30, 327–340.

Goodale CL, Apps MJ, Birdsey RA, Field CB, Heath LS, Houghton RA, Jenkins JC, Kohlmaier GH, Kurz W, Liu S, Nabuurs GJ, Nilsson S, Shvidenko AZ. 2002. Forest carbon sinks in the Northern Hemisphere. *Ecological Applications* 12: S9I-899.

Gough CM, Vogel CS, Schmid HP, Curtis PS. 2008a. Controls on Annual Forest Carbon Storage: Lessons from the Past and Predictions for the Future. *BioScience* 58, 609-622.

Grant RF, Black TA, Humphreys ER, Morgenstern, K. 2007. Changes in net ecosystem productivity with forest age follow clear-cutting of a coastal Douglas-fir forest: testing a mathematical model with eddy covariance measurements along a forest chronosequence. *Tree Physiology* 27, 115–131.

Gustavsson L, Sathre R. 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. *Building and Environment*, 41, pp. 940-951.

Harmon ME, Ferrell WK, Franklin JF. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247, 699-702.

Hennigar CR, MacLean DA, Amos-Binks LJ. 2008. A novel approach to optimize management strategies for carbon stored in both forests and wood products. *Forest Ecology and Management* 256: 786–797

House JI, Prentice IC, LeQuere C. 2002. Maximum impacts of future reforestation or deforestation on atmospheric CO_2. *Global Change Biology* 8, 1047-1052.

Humphreys ER, Black TA, Morgenstern K, Cai T, Drewitt GB, Nesic Z, Trofymow JA. 2006. Carbon dioxide fluxes in coastal Douglas-fir stands at different stages of development after clearcut harvesting. *Agricultural and Forest Meteorology* 140, 6-22.

Hyvonen R, Ågren GI, Linder S, Persson T, Cotrufo MF, Ekblad A, Freeman M, Grelle M, Janssens IA, Jarvis PG, Kellomäki S, Lindroth A, Loustau D, Lundmark T, Norby RJ, Oren R, Pilegaard K, Ryan MG, Sigurdsson BD, Strömgren M, van Oijen M, Wallin G. 2007. The likely impact of elevated CO_2, nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: A literature review. *New Phytologist* 173, 463-480.

IPCC (Intergovernmental Panel on climate Change). 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press. (www.ipcc.ch/ipccreports/ar4-wgl.htm).

Jandl R, Rasmussen K, Tome M, Johnson D.W. 2006. The role of forests in carbon cycles, sequestration and storage: 4. Forest management and carbon sequestration. www.iufro.org/science/task-forces/carbon-sequestration/

Janzen DT. 2006. The impacts of forest management activities on carbon stocks and sequestration in the Aleza Lake Research Forest. M.Sc. Thesis, UNBC, Prince George, BC.

Janzen DT, Fredeen AL, RD Wheate. 2006. Radiometric correction techniques and accuracy assessment for Landsat TM data in remote forested regions. *Canadian Journal of Remote Sensing*. 32, 330-340.

Jassal RS, Black TA, Novak MD, Gaumont-Guay G, Nesic Z. 2008a. Effect of soil water stress on soil respiration and its temperature sensitivity in an 18-year-old temperate Douglas-fir stand. *Global Change Biology 14*, 1-14.

Jassal RS, Black TA, Chen B, Real R, Nesic Z, Spittlehouse D, Trofymow, AJ. 2008b. N_2O emissions and carbon sequestration in a nitrogen-fertilized Douglas-fir stand. *Journal of Geophysical Research-Biogeosciences*, doi:10.1029/2008JG000764.

Jassal RS, Black TA, Spittlehouse D, Brummer C., Nesic Z. 2008c. Evapotranspiration and water use efficiency in Pacific Northwest Douglas-fir stands of different ages following clearcut harvesting. *Agricultural and Forest Meteorology*, AGRFORMET-D-08-00277.

Jassal RS, Black TA, Chen B, Bruemmer C, Spittlehouse DL, Nesic Z. 2008d. Enhancement of carbon sequestration in west coast Douglas-fir forests with nitrogen fertilization. *AGU Fall Meeting*, Paper # B31G-0383.

Kira T, Sihdei T. 1967. Primary production and turnover of organic matter in different forest ecosystems of the western pacific. *Japan Journal of Ecology* 17, 70–87.

Kongshaug G. 1998. Energy consumption and greenhouse gas emissions in fertilizer production. The International Fertilizer Industry Association (IFA) Technical Conference, 28 September-1 October, Marrakeck, Morocco.

Kurz WA, Stinson G, Rampley GJ, Dymond CC, Neilson, ET. 2008a. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *PNAS* 105, 1551–1555.

Kurz WA, Dymond CC, Stinson W, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L. 2008b. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452, 987-990.

Kurz WA, Apps MJ. 2006. Developing Canada's national forest carbon monitoring, accounting and reporting system to meet the reporting requirements of the Kyoto protocol. *Mitigation and Adaptation Strategies for Global Change* 11, 33–43.

Law BE, Falge E, Gu L, Baldocchi DD, Bakwin P, Berbigier P, Davis K, Dolman AJ, Falk M, Fuentes JD, Goldstein A, Granier A, Grelle A., Hollinger D, Janssens IA, Jarvis PG, Jensen NO, Katul G, Mahli Y, Matteucci G, Meyers T, Monson R, . Munger W, Oechel W, Olson R, Pilegaard K, Paw U KT, Thorgeirsson H, Valentini R, Verma S, Vesala T, Wilson K, Wofsy

S. 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. *Agricultural and Forest Meteorology* 113, 97-120.

Lehman J, Gaunt J, Rondon M. 2006. Bio-char sequestration in terrestrial ecosystems – A review. *Mitigation and Adaptation Strategies for Global Change* 11, 403–427

Luyssaert S, Schulze E-D, Borner A, Knohl A, Hessenmoller D, Law BE, Ciais P, Grace P. 2008. Old-growth forests as global carbon sinks. *Nature* 455, 213-215.

Magnani F, mencucini M, Borghetti M, Berbigier P, Berninger F, Delzon S, Grelle A, Hari P, Jarvis PG, Kolari P, Kowlaski AS, Lankrejier H, Law BE, Lindroth A, Loustau D, Manca G, Moncrief JB, Rayment M, Tedeschi V, Velentini R, Grace J. 2007. The human footprint in the carbon cycle of temperate and boreal forests. *Nature* 447, 848-850.

Malhi Y, Baldocchi DD, Jarvis PG. 1999. The carbon balance of tropical, temperate and boreal forests. *Plant Cell and Environment* 22, 715-740.

Mitchell KJ, Stone M, Grout SE, Di Lucca CM, Nigh GD, Goudie J, Stone JN, Nussbaum AJ, Yanchuk A, Stearns-Smith S, Brockley R. 2000. TIPSY Version 3.0. British Columbia Ministry of Forests, Research Branch, Victoria, B.C.

Morgenstern K, Black TA, Humphreys ER, Griffis TJ, Cai C, Drewitt GB, Gaumont-Guay D, Nesic Z. 2004. Sensitivity and uncertainty of the carbon balance of a Pacific Northwest Douglas-fir forest during an El Niño/La Niña cycle. *Agricultural and Forest Meteorology* 123, 201-219.

Mote PW. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters* 30, 1601-1603.

Nabuurs GJ, Dolman AJ, Vrkaik E, Kuikman PJ, vanDiepen CA, Whitmore AP, Daamen WP, Oenema O, Kabat P, Mohren GMJ. 2000. Article 3.3 and 3.4 of the Kyoto Protocol: consequences for industrialized countries' commitment, the monitoring needs, and possible side effects. *Environmental Science & Policy* 3, 123-134.

Nabuurs GJ, Masera O, Andrasko K, Benitez-Ponce P, Boer R, Dutschke M, Elsiddig E, Ford-Robertson J, Frumhoff P, Karjalainen T. 2007. In *Climate Change 2007: Mitigation. Contribution of Working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (Eds.), Cambridge Univ Press, Cambridge, pp 541–584.

Nadelhoffer KJ, Emmett BA, Gundersen P, Kjùnaas OJ, Koopmansk CJ, Schleppi P, Tietemak A, Wright A. 1999. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. *Nature, 398*, 145-148.

Nemani RR, Keeling CD, Hashimoto H, Jolly WM, Piper SC, Tucker CJ, Myneni RB, Running SW. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* 300, 1560-1563.

Odum EP. 1969. The strategy of ecosystem development. *Science* 164, 262–270.

Piao S, Ciais P, Friedlingston P, Peylin P, Reichstein M, Luyssaert S, Margolis H, Fang J, Barr A, Chen A, Grelle A, Hollinger D, Lauria T, Lindroth A, Richardson AD, Vesal T. 2007. Net carbon dioxide losses of northern ecosystems in response to autumn warming. *Nature* 451, 49-53.

Pregitzer KS, Burton JA, Zak DR, Talhelm AF. 2008. Simulated chronic nitrogen deposition increases carbon storage in Northern Temperate forests. *Global Change Biology 14*, 142-153.

Preston CM, Schmidt MWI. 2006. Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. *Biogeosciences* 3, 397-420.

Reid WV, Mooney HA, Cropper A, Capistrano D, Carpenter SR, Chopra K, Dasgupta P, Dietz T, Duraiappah AK, Hassan R, Kasperson R, Leemans R, May RM, McMichael AJ, Pingali P, Samper C, Scholes R, Watson RT, Zakri AH, Shidong Z, Ash NJ, Bennett E, Kumar P, Lee M, RaudseppHearne C, Simons H, Thonell J, Zurek MB (Eds.). 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, District of Columbia, 155 pp.

Routledge RD. 1980. The effect of potential catastrophic mortality and other unpredictable events on optimal forest rotation policy. *Forest Science* 26, 389–399.

Sabine CL, Heimann M, Artaxo P, Bakker DCE, Chen CTA, Field CB, Gruber N. 2004. Current status and past trends of the global carbon cycle. In *Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, C.B. Field and M.R. Raupach, (Eds.), Island Press,Washington, Distict of Columbia, 17-44.

Selig MF, Seiler JR, Tyree MC 2008. Soil carbon and CO_2 efflux as influenced by the thinning of loblolly pine (Pinus taeda L) plantations on the piedmont of Virginia. *Forest Science* 54, 58-66.

Shvidenko A, Barber CV, Persson R. 2005. Forest and woodland systems. In *Ecosystems and Human Well-being: Volume 1: Current State and Trends*, Hassan R, Scholes R, and Ash N (Eds.), Island Press, Washington, District of Columbia, pp 585-621.

Smithwick EAH, Harmon ME, Remillard SM, Acker SA, Franklin JF. 2002. Potential upper bounds of carbon stores in forests of the Pacific Northwest. *Ecological Applications* 12, 1303–1317.

Sonne E. 2006. Greenhouse gas emissions from forestry operations: A life cycle assessment. *Journal of Environmental Quality* 35, 1439-1450.

Spittlehouse DL. 2007. Climate Change and BC's Forest and Range Management: Climate Change, Impacts & Adaptation Scenarios. Research Branch, BC Ministry of Forests and Range, Victoria, BC. Produced for the Future Forest Ecosystems Initiative. 42 p.

Spittlehouse DL. 2003. Water availability, climate change and the growth of Douglas-fir in the Georgia Basin. *Canadian Journal of Water Resources* 8, 673-688.

Spittlehouse DL. 1985. Determination of the year–to–year variation in growing season water use of a Douglas–fir stand. In *Forest Atmosphere Interaction*, B.A. Hutchison and B.B. Hicks (eds.), D. Reidel Publishing Co., Dordrecht, Holland. pp 235–254.

Taylor SW, Carroll AL, Alfaro RI, Safranyik L. 2006. Forest, climate and mountain-pine-beetle dynamics in western Canada. In *The Mountain Pine Beetle: A Synthesis of Biology, Management and Impacts in Lodgepole Pine*, Safranyik L and Wilson B (Eds.), Natural Resources Canada, Canadian Forest Service, Victoria. pp. 67–94.

Trofymow JA, Stinson G, Kurz WA. 2008. Derivation of a spatially explicit 86-year retrospective carbon budget for a landscape undergoing conversion from old growth to managed forests on Vancouver Island, BC. *Forest Ecology and Management,* in press.

Winkler RD, Spittlehouse DL, Golding DL. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in Southern British Columbia. *Hydrological Processes* 19, 51-62.

Zheng G, Chen JM, Tian Q, Ju WM, Xia X. 2007. Combining remote sensing imagery and forest age inventory for biomass mapping. *Journal of Environmental Management* 85, 616-623.

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