



A 100-year conservation experiment: Impacts on forest carbon stocks and fluxes



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ABSTRACT

Forest conservation is an important climate change mitigation strategy. National parks in Canada's Rocky and Purcell Mountains offer a rare opportunity to evaluate the impacts of a century of conservation on forest carbon (C) stocks and fluxes. We studied forest ecosystem C dynamics of three national parks in the Rocky and Purcell Mountains of British Columbia – Yoho, Kootenay, and Glacier National Parks – over the period 1970–2008 using the CBM-CFS3 inventory-based forest C budget model. We hypothesized that parks and protected areas would contain higher forest C density and have lower CO₂ uptake rates compared to their surrounding reference areas because of the exclusion of timber harvesting and resulting predominance of older, slower growing forest stands. Results for Glacier National Park relative to its reference area were consistent with our hypothesis. Forests in Kootenay National Park were substantially younger than those in its reference area despite the exclusion of harvesting because natural disturbances affected large areas within the park over the past century. Site productivity in Kootenay National Park was also generally higher in the park than in its reference area. Consequently, Kootenay National Park had both higher C density and higher CO₂ uptake than its reference area. Yoho National Park forests were similar in age to reference area forests and more productive, and therefore had both higher C stocks and greater CO₂ uptake. C density was higher in all 3 parks compared to their surrounding areas, and parks with younger forests than reference areas had higher CO₂ uptake. The results of this study indicate that forest conservation in protected areas such as national parks can preserve existing C stocks where natural disturbances are rare. Where natural disturbances are an important part of the forest ecology, conservation may or may not contribute to climate change mitigation because of the risk of C loss in the event of wildfire or insect-caused tree mortality. Anticipated increases in natural disturbance resulting from global warming may further reduce the climate change mitigation potential of forest conservation in disturbance-prone ecosystems. We show that managing for the ecological integrity of landscapes can also have carbon mitigation co-benefits.

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1. Introduction

Establishment of Canada's national park system began over one hundred and twenty-five years ago. Several national parks were established in the Rocky Mountains and nearby Purcell Mountains between 1885 and 1920. The development of trans-continental rail lines brought these landscapes to the attention of the Canadian public, and law makers soon protected them from resource extraction activities that were rapidly expanding throughout the Canadian West. National parks are dedicated to the people of Canada

for their education and enjoyment so they will be left unimpaired for future generations. As mandated by the Canada National Parks Act in 2001, maintenance of ecological integrity¹ has become the first priority of the Parks Canada Agency (Woodley, 2009).

The contribution of these parks to wildlife conservation and biodiversity protection has been intensively studied by conservation biologists. The largely intact nature of the ecosystems conserved by the collection of Canadian and US protected areas in what is termed the Yellowstone to Yukon corridor make these parks important components of continental conservation

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¹ Canada National Parks Act defines ecological integrity as “a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes”.

strategies seeking to maintain all the original top predators and key species for the region while addressing issues of landscape and habitat connectivity and climate change adaptation.

More recently, the potential contribution of these parks to climate change mitigation has become a question of policy and management interest. Protected areas are recognized worldwide as being important components of climate change mitigation and adaptation strategies because of their governance structures, permanence, and management effectiveness (Dudley et al., 2010). In developing countries, protected areas can play an important role in reducing carbon (C) emissions by reducing deforestation, i.e. the conversion of forest to non-forest land uses (Soares-Filho et al., 2010). In developed countries, where deforestation rates are generally lower, the effectiveness of conservation as a strategy for reducing C emissions or increasing C sinks is debated because the alternative to conservation is typically forest management rather than deforestation. Forests in Canada are generally not threatened by deforestation because they are predominantly on public land that is allocated for forestry and governed by legislation and codes of practice to promote sustainable forest management. It is not clear how forest C dynamics differ between forests managed for sustainable timber harvest versus those protected for conservation, particularly when both are subject to natural disturbance, as is the case in boreal forest ecosystems (Kurz and Apps, 1999; Bond-Lamberty et al., 2007; Kurz et al., 2008a,b). Some forest ecosystems lose C when converted from natural to managed disturbance regimes (Kurz et al., 1998; Trofymow et al., 2008) while others may not (Ter-Mikaelian et al., 2008).

Canadian temperate and boreal forests have been recognized as important regions of C storage (Keith et al., 2009; Pan et al., 2011; Stinson et al., 2011), but projected changes in natural disturbance regimes may affect their ability to act as sustained C sinks (Kurz et al., 2008a; Scott et al., 2008; Keith et al., 2009; Metsaranta et al., 2010). The future C balance of Canada's forests is uncertain because of uncertain future impacts of natural disturbances, but the prevailing expectation amongst policy makers and managers is that forests in Canada's national parks have a role to play in climate change mitigation because protection from harvesting has resulted in greater forest C stocks (i.e., C sequestration).

The C budget of Canada's managed forests, including protected areas, is tracked by the Canadian Forest Service (Stinson et al., 2011) but there are limited data specifically about the C balance of National Park forests (Kulshreshtha et al., 2000; Scott et al., 2008). To date no studies have explicitly examined National Park forest C dynamics relative to surrounding managed forests.

In order to understand the role that Canada's national parks may play in climate change mitigation, we put forth four key questions:

1. Are forests protected by Parks currently disturbed less frequently than those in the surrounding managed forest landscape?
2. Are forests in national parks older than those in the surrounding managed forest landscape?
3. Do forests in national parks have higher C density than those in the surrounding managed forest landscape?
4. Do forests in national parks take up more atmospheric CO₂ than those in the surrounding managed forest landscape?

We chose three national parks in British Columbia, Canada (Glacier, Kootenay, and Yoho National Parks) that were established between 1885 and 1920 to estimate the impacts of a century of conservation on forest C dynamics and to quantify the past role of protected areas in climate change mitigation.

We examined the forest stand age structures and the nature and frequency of disturbances, and compared total C stocks and fluxes

in protected forest areas with surrounding forests using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, Kurz et al., 2009). We hypothesized that natural disturbances occur at a similar extent and scale inside and outside of parks. Since parks and protected areas are relatively unaffected by anthropogenic disturbances such as timber harvesting, the lower disturbance frequency should result in a higher average forest stand age in parks compared to surrounding forests. We also hypothesized that parks have higher C stocks and lower CO₂ uptake because older forest stands tend to have higher C density and lower productivity than younger forest stands (Coursolle et al., 2012).

2. Methods

2.1. Study area

Our study area (Fig. 1) is located in south-eastern British Columbia, Canada, covering a geographic area of 26,000 km², including 15,000 km² of forest. The study area boundary corresponds with the boundaries of the Invermere and Golden Timber Supply Areas (BC MFLNRO, 2012). The study area includes three national parks (Yoho, Kootenay and Glacier), numerous provincial protected areas, large publicly owned managed forests (Crown Timber Supply Area (TSA) and Tree Farm License (TFL) lands) and a few small privately owned forests and woodlots.

In the center of this area lies the Rocky Mountain Trench – a broad, flat valley through which the Kootenay River flows south and the Columbia River flows north. The trench is straddled by two mountain ranges – Rocky Mountains to the east and Purcell Mountains to the west. The area contains 6 biogeoclimatic zones (Meidinger and Pojar, 1991). Glacier National Park covers portions of three zones: Alpine Tundra (AT), Engelmann Spruce Subalpine Fir (ESSF) and Interior Cedar Hemlock (ICH). Kootenay National Park includes AT, ESSF, and Interior Douglas-fir (IDF) zones while Yoho National Park includes AT and Montane Spruce (MS) biogeoclimatic zones (Fig. 1).

Natural disturbances have a strong influence on forest ecology throughout the study area (Wong et al., 2003). Wildfire is the dominant stand-replacing disturbance at the landscape scale, while other disturbances such as avalanche and wind throw are locally important. Fires regularly occur during the hot, dry summer months and many dominant tree species have developed specific adaptations to this fire regime. Fires are generally confined by topography to the mountain valley in which they ignited. Large areas of forest can burn in one valley during a bad fire year while a nearby valley remains unburned, even with similar fuel loadings and fire weather conditions.

When forest stands are not burned and the trees are able to grow old, they often become more susceptible to attack by insects or disease, and uneven-age stand structures develop as individuals or groups of trees are killed. Periodically, outbreaks of bark beetles or other insects cause widespread tree mortality (Safarynik et al., 2004). In order to restore ecological integrity to forests that have been affected by fire suppression, Parks Canada has recently begun prescribed burning in many of its national parks including Kootenay and Yoho but these have been limited to small areas and were not considered in this study.

The size of the forested valleys in our study area is relatively small, and our study period is relatively short within the context of the natural history and life-cycle of disturbance and regeneration in these forests. The forests in one valley could have been younger than those in a neighbouring valley 100 years ago (before park establishment) simply as a result of random chance (e.g., lightning happened to ignite fires in one valley but not the other). The C dynamics of the forests we see today are strongly influenced

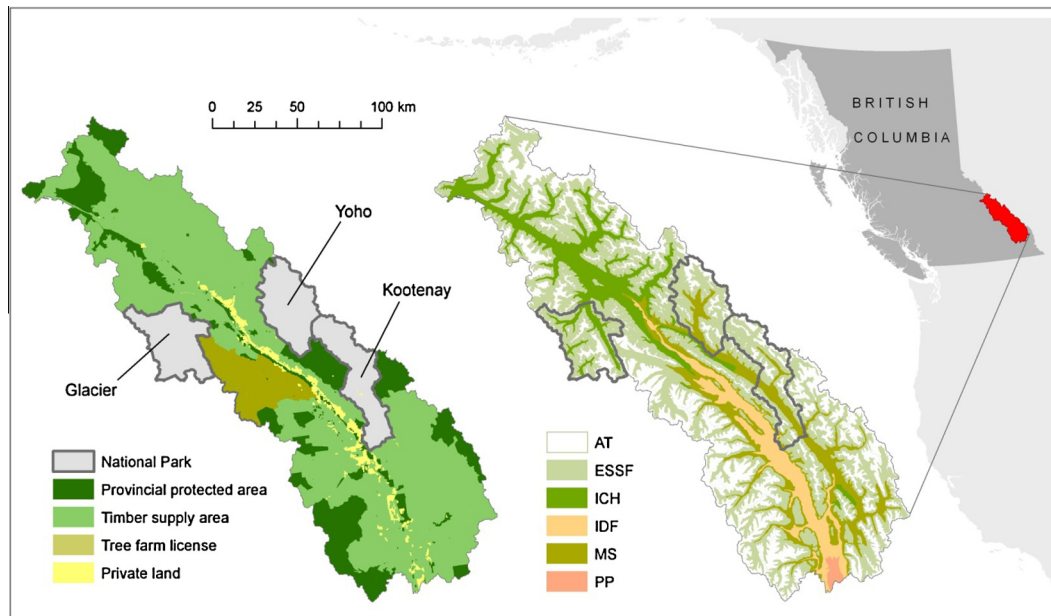


Fig. 1. Study area.

by the legacy effects of past disturbances, even as long as 100 years ago. The disturbance history of each mountain valley is unique, and therefore no two valleys have identical forests, even when they share common ecological characteristics and natural history.

In our study, we compared forests under different management histories (conservation versus no conservation) and similar ecology and natural history, but our design cannot fully control for disturbance history because of the stochastic nature and spatial scale of forest disturbance in our study area, where two different forest areas can be subject to the same disturbance regime, yet have different disturbance histories.

2.2. Study design

The study consisted of two components – (i) characterizing and comparing the forest stand age structure and disturbance regimes inside and outside of parks, and (ii) assessing and comparing the carbon stocks and fluxes, impacted by these disturbances, inside and outside of parks. To make comparisons inside and outside of the national parks, each park's forests were compared with the managed forests in its immediate surroundings, which we termed 'reference areas' (Table 1 and Fig. 2). Some surrounding areas were adjacent to more than one park and thus contributed to more than one reference area. We did not account for C dynamics of non-forest ecosystems; only forested lands in the parks and their reference

areas were considered. Because of the rugged, mountainous landscape, only approximately half of the study area supports forest. Results were aggregated and summarized for 8 geographic units which included the three national parks (Glacier, Kootenay, Yoho) individually, all provincial parks and protected areas combined together into one category ('ProtArea'), as well as four Reference areas (Glacier_Ref, Kootenay_Ref, Yoho_Ref, and ProtArea_Ref).

2.3. CBM-CFS3 model

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) was used to estimate the C stocks and changes during the period 1970–2008 in annual time steps. CBM-CFS3 is a forest C dynamics model that operates at scales from individual stands to nations (Kurz et al., 2009). The model uses empirical yield functions to describe stand-level forest growth rates. It converts estimates of volume per hectare into aboveground biomass components using a library of stand-level volume to biomass conversion equations (Boudewyn et al., 2007). Below-ground biomass in fine and coarse roots is estimated from stand-level equations for softwood and hardwood species (Li et al., 2003). The model simulates dynamics of dead organic matter and soil C in 11 pools, including standing dead trees, coarse woody debris, fine woody debris, litter and humified organic matter in the forest floor and mineral soil (Kurz et al., 2009). Here in this paper, we refer to all these dead organic matter and soil C pools collectively as DOM.

The CBM-CFS3 accounts for continuous processes (growth, decomposition) that occur in all forest stands in all years, and disturbances that occur in some stands in some years. Disturbances represented in the model include fires, insects, and human activities such as clearcut, partial cut and salvage harvesting (Kurz et al., 2009). Disturbances affect the distribution and quantity of C in all pools and can transfer C to the atmosphere (e.g. in the case of fire) and to the forest product sector (e.g. in the case of harvesting). Disturbances can also affect stand age, and the post-disturbance yield trajectory. Following international reporting conventions, here we assumed that all C contained in wood harvested and removed from the forest is subject to instantaneous oxidation and release to the atmosphere. While it is understood that harvested wood products in use and in landfills store C for

Table 1
Parks and protected areas, and their respective reference areas.

Geographic unit	Geographic area (km ²)	Forest area (km ²)
Yoho National Park	1310	665
Yoho_Ref	7505	4622
Kootenay National Park	1406	818
Kootenay_Ref	8514	5920
Glacier National Park	1349	373
Glacier_Ref	8998	5046
ProtArea	4730	2233
ProtArea_Ref	15,274	9659
Overall study area	26,307	15,055

Note that some of the reference areas are overlapping, such that the sum of the areas of the geographic units analyzed is greater than the overall study area.

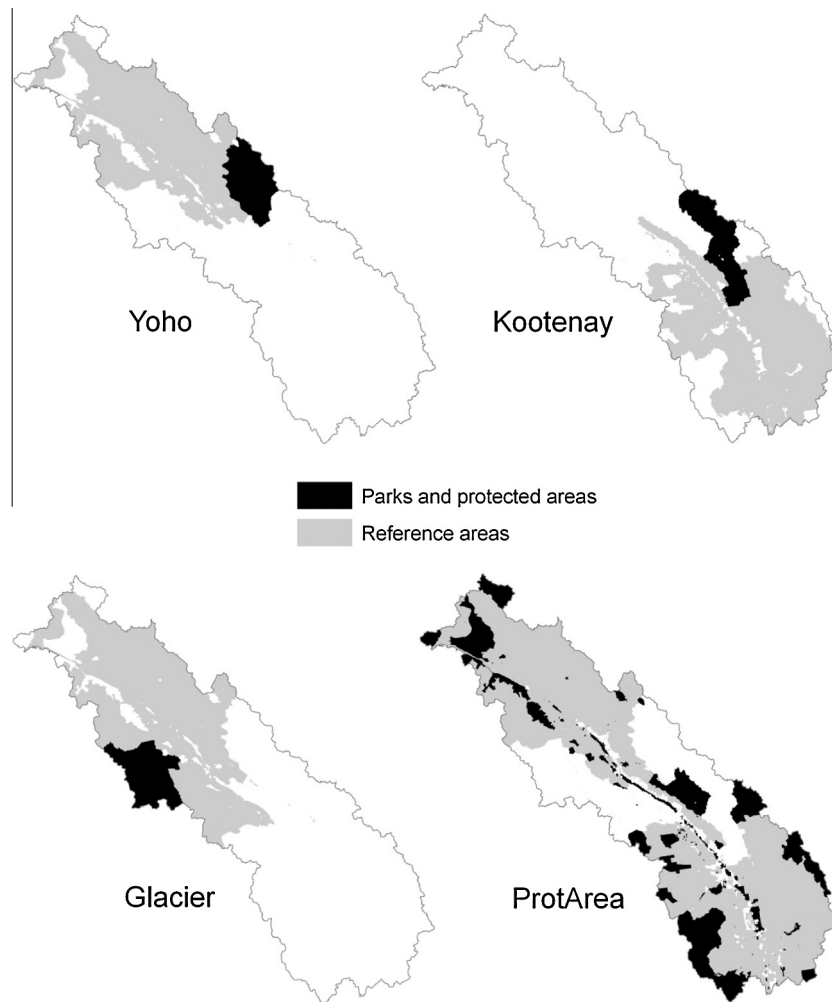


Fig. 2. National Parks, provincial protected areas (ProtArea) and their associated managed forest reference areas for forest C budget comparison purposes.

many years to decades (Apps et al., 1999; Skog, 2008), tracking the processing steps and fate of C harvested from our study areas is beyond the scope of this study. Woody biomass, slash, and roots left on site after harvesting (or other disturbances) will decompose and the release of CO₂ to the atmosphere in the years after the disturbance events is represented in the model.

The CBM-CFS3 is used widely in Canada and internationally and numerous papers describe its application at various spatial scales and for various scientific questions. Recent national-scale applications in Canada are described in Stinson et al. (2011), and Metsaranta et al. (2010) and regional-scale applications in BC include Trofymow et al. (2008) and Kurz et al. (2008b). Details on the use of the model are outlined in the model Users' Guide (Kull et al., 2011). The model and its documentation are freely available at <http://carbon.cfs.nrcan.gc.ca>.

In addition to estimates of C stocks, annual stock changes, and fluxes of CO₂, CO and CH₄, the model generates ecological indicators including estimates of total Net Primary Production (NPP), heterotrophic respiration (Rh), Net Ecosystem Production (NEP), Net Ecosystem Exchange (NEE) and Net Ecosystem Carbon Balance (NECB). Consistent with the definitions summarised by Chapin et al. (2006), NECB is defined here as Net Biome Production (NBP) integrated over space, and NEP is the net balance between gross primary production and ecosystem respiration which conceptually analogous to NPP minus heterotrophic respiration. NEE

is a measure of the vertical exchange of C between the forest and the atmosphere, as would be observed by a flux tower (e.g., Coursolle et al., 2012) or an inverse model over larger domains (Hayes and Turner, 2012). The model estimates the values of these indicators for each year in the study period, which were then used to compute mean value over the study period, standard deviation, and standard error values.

2.4. Data and assumptions

2.4.1. Forest management and natural disturbances

Natural disturbances such as wildfires and forest insects can have a significant impact on age structure and species composition in forests, and therefore on C dynamics. Typically, forest inventory data include limited information on past disturbances. Disturbance data can be obtained from historical records maintained by government agencies, where available, or can be derived from a historical time series of remote sensing data such as Landsat data (White et al., 2011; Masek et al., 2013). Records of fire history and insect outbreaks have been maintained in BC since the 1920s and these were available in a GIS database. Wildfire data were also compiled from a GIS fire history database maintained for national parks by Parks Canada and we also integrated recent mapping data from the Canadian National Burn Area Composite, a product maintained by the Canadian Forest Service (CFS) which combines provincial

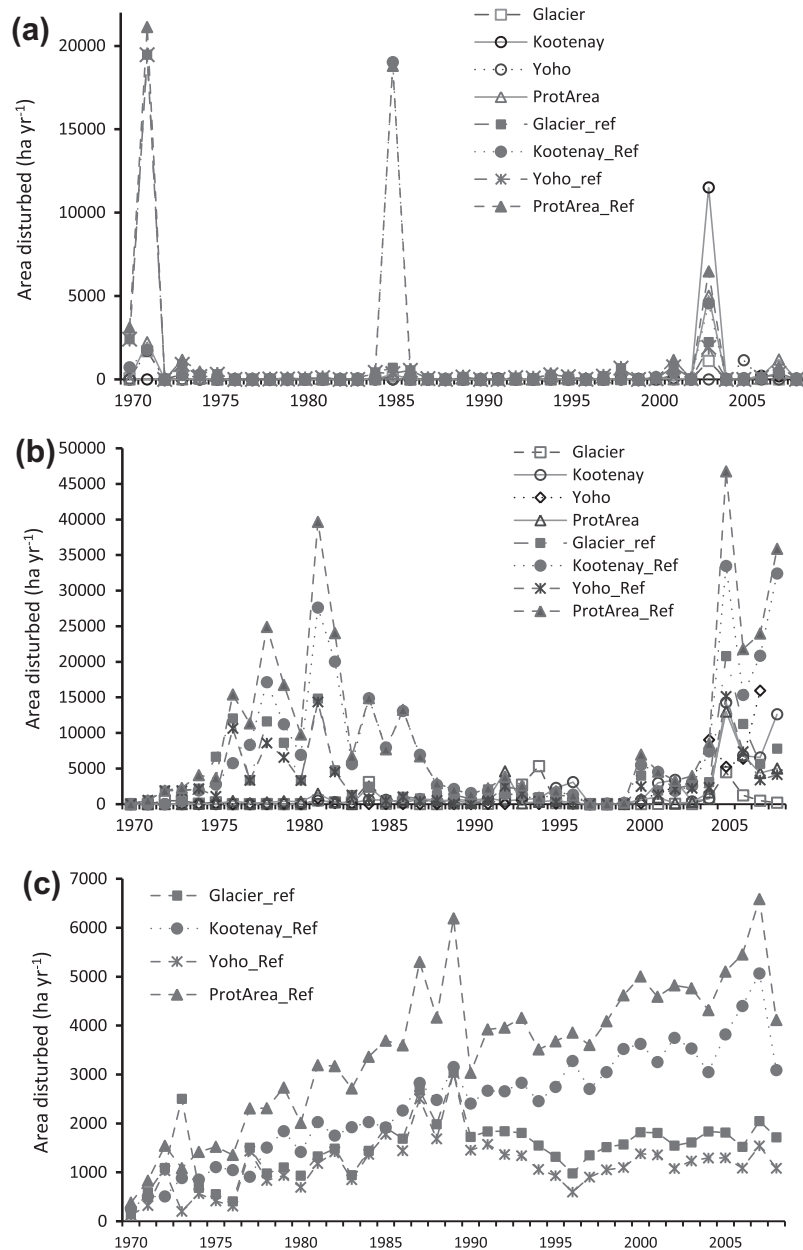


Fig. 3. Area disturbed by (a) wildfires, (b) all insects, and (c) harvest.

and federal government agency fire mapping with moderate- and medium-resolution satellite remote sensing mapping.

CFS, in cooperation with provincial agencies, conducted annual systematic province-wide aerial overview surveys of forest insect outbreaks from 1959 to 1996 (Van Sickle et al., 2001). These surveys recorded insect species, attack year, severity of attack – light, moderate, severe – the boundaries of the outbreak and the polygon size. After 1996, the BC Ministry of Forest Lands and Natural Resource Operations (MFLNRO) took over this function and has since carried out these annual surveys.

In this study, only six insect types which substantially affected trees in this area were considered: mountain pine beetle (*Dendroctonus ponderosae*), balsam bark beetle (*Dryocoetes confusus*), Douglas fir beetle (*Dendroctonus pseudotsugae*), western black-headed budworm (*Acleris gloverana*), two-year cycle budworm (*Choristoneura biennis*), and western hemlock looper (*Lambdina fuscicollis*). Disturbances by insects were simulated in the

model as partial-mortality events killing a portion of softwood biomass pools. The remaining stand continues to grow as per the defined yield of the stand. Damage by beetles was represented using four impact classes ranging from low (5%) mortality to very severe (50%) mortality while defoliators were represented by three impact classes ranging from low (4%) mortality to severe (32%) mortality.

These data on insects and wildfire occurrences were aggregated to the geographic unit level by disturbance type and year, from 1970 to 2008, using GIS to define amount of area to be disturbed each year in the simulation.

Harvest history data were obtained from British Columbia timber harvest billing system, which is a government-maintained central database containing information relevant to our model simulation, such as species, volume, harvest location and year. Harvest volume was converted into biomass based on specific density of the given species (Gonzalez, 1990). The carbon content was

estimated as 50% of the biomass values (Prichard et al., 2000; Lam- lom and Savidge, 2003).

Fig. 3a–c show the total area affected by fire, insect, and harvest disturbances each year in each geographic analysis unit. These data indicated that major fires occurred in 1971, 1985 and 2003 in the study area. Insect outbreak activity was greatest from 1975 to 1987, and then increased again after 2002. Harvest disturbances occur only outside of parks and protected areas – in reference areas – and increasingly larger areas were harvested over time.

Actual area disturbed each year was allocated to stands in the model simulation with some assumptions. We assumed that stands with highest merchantable biomass C would be considered first for harvesting with a maximum 80% of the area of any stand being affected by harvest in a single year. Minimum harvestable age of stands was assumed to be 80 years. Fire disturbances were assigned at random to stands in each spatial unit. Insect disturbances were host-specific, and these too were assigned at random to stands with suitable hosts and minimum age of 60 years for beetle attacks.

2.4.2. Forest inventory

Vegetation Resource Inventory (VRI) data (Ministry of Forests, 2012) were obtained from the BC MFLNRO for the year 2008. These data were organized as a series of records, each record representing a forest stand. It included main attributes of stands such as area, lead species, secondary species, stand age, and site classifier. Each stand was also characterized as being inside a timber harvesting land base (THLB) or in a non-harvestable land base. All forests located in parks and protected areas are clearly part of the non-harvestable land base, but there are also substantial non-harvestable forests within Timber Supply Area and Tree Farm License lands, such as riparian zones, wildlife habitats, and archaeological and/or cultural sites.

To run the model from 1970 to the date of inventory (2008), we needed to first roll the inventory back from 2008 to 1970. We reconstructed a simplified stand replacing disturbance history by applying the following set of rules:

- (1) For each stand in the inventory, we subtracted 38 years from the age of the stand in the 2008 inventory to get age in 1970.
- (2) When the resulting age in 1970 was less than or equal to zero, we assumed that a stand-replacing disturbance took place in the year corresponding to stand age zero, and also assumed that the stand present in 2008 regenerated following that disturbance without delay.

- (3) When the disturbed forest stand was in the THLB, we assumed the disturbance was clearcut harvest of a 100 year old stand of the same type present in 2008; when the forest stand was not in the THLB, we assumed the disturbance was wildfire in a 100 year old stand of the same type present in 2008.

We also needed to make assumptions about stand disturbance histories prior to 1970 for C pool initialization in CBM-CFS3, which is influenced by disturbance history (Kurz et al., 2009). We assumed that all stands present in 1970 regenerated without delay following a disturbance that occurred in the year corresponding to age zero for the stand. For THLB stands 20 years old or younger in 1970, we assumed the stand initiating disturbance was clearcut harvest because industrial forestry first began in our study area in circa 1950. For all other stands, we assumed the stand-initiating disturbance was wildfire because that is the predominant stand-replacing natural disturbance in the study area's forest ecosystems (Wong et al., 2003).

The scripts we wrote to implement these rules also formatted the BC MFLNRO inventory data for input into CBM-CFS3. The study area disturbance history implied by these rules was compared with available fire and harvest disturbance history records to evaluate our assumptions and found them to be generally reasonable.

2.4.3. Growth and yield

The CBM-CFS3 uses net merchantable timber volume yield tables linked to the forest inventory to determine the C pool sizes and simulate stand-level tree growth. The net merchantable timber volumes were obtained from the standard British Columbia provincial growth and yield models, variable density yield prediction (VDYP7) and table interpolation projection for stand yield (TIPSY4.2) (Di Lucca, 1999; Ministry of Forests, 2009). VDYP used Vegetation Resource Inventory (VRI) information to produce individual stand-level growth and yield projections for unmanaged stands. TIPSY used stand regeneration assumptions adopted from recent timber supply analysis of each management unit to project stand growth and yield in managed stands. Stand site quality, leading species, second species genus types, and ecozones were used to summarize stands into an area weighted group with unique classifiers, or Analysis Unit. For illustrative purposes, a high-level summary was compiled to generate spatial unit level yield curves (Fig. 4) but model simulations were conducted using 1173 yield curves at the level of Analysis Units.

The 1970–2008 simulation period covered a time frame when there was still ongoing transition from unmanaged forest to man-

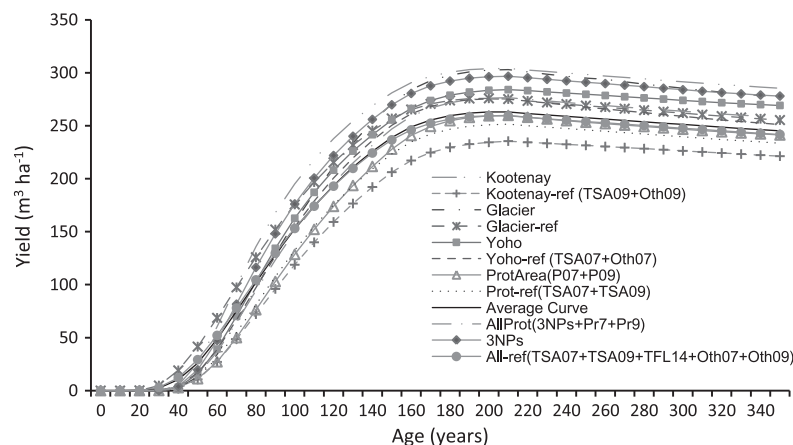


Fig. 4. Area-weighted average yield curves.

aged forest. Some of the harvesting in the study area was occurring in stands never previously harvested. All stands in parks, protected areas, and outside the THLB were assumed to be unmanaged and never previously harvested. Growth in these stands was simulated using VDYP yield tables. Growth in THLB stands greater than 20 years old in 1970 was also simulated using VDYP yield tables because it was assumed that these stands were never previously harvested. Growth in THLB stands younger than 20 years old in 1970 and growth in all stands harvested after 1970 was simulated using TIPSYP yield tables. For some stands, this involved a transition during the simulation from VDYP to TIPSYP growth curves following harvest.

3. Results

3.1. Are parks disturbed less frequently?

We found that park forests were disturbed less frequently by stand-replacing disturbances between 1970 and 2008 than the surrounding managed forest reference areas. Disturbances resulting in partial stand mortality, however, were as common in parks as in surrounding reference areas. Between 0.6% and 2.3% of forest area was disturbed annually on average in our study units during 1970–2008. Provincial protected areas (ProtArea) were disturbed least frequently and Kootenay National Park was disturbed most frequently overall (Fig. 5). Fires occurred more frequently in parks than in the surrounding forests. Kootenay National Park had the highest proportion of area (15%) affected cumulatively by fire during the study period (Table 2). However, harvesting and fire combined to result in greater stand-replacing disturbance rates in reference areas relative to park forests, where harvesting does not occur. Overall, 10% of the area was cumulatively disturbed over the 39-year study period in the 3 national parks by stand-replacing disturbances, as compared to 19% in the surrounding reference area forests. This also resulted in a higher proportion of stand-replacing disturbances versus partial-stand disturbances for reference areas than for national parks, being 0.48 and 0.14, respectively.

The proportion of forest area affected by insect disturbances during 1970–2008 was also higher for parks than for their reference areas. Kootenay National Park had the highest proportion of area affected by insects amongst all units. Mountain pine beetle, Douglas-fir beetle, and western balsam bark beetle were the main disturbance-causing agents in all the units except Glacier National

Park, which was most affected by defoliators (western black-headed budworm and western hemlock looper). Most damage in the study area occurred only at a low to moderate intensity, with less than 30% trees killed within affected forest stands (BC MoF, 2000). Less than 25% of the affected area was in the severe category, with 30% or more of trees killed within affected stands.

3.2. Do parks have older forests?

We found that parks have older forests overall, but not every park has older forests compared to its surroundings. Fig. 6 shows forest stand age distributions from the 2008 forest inventory, at the end of our study period. All parks, with the exception of Kootenay National Park, had older forests than their respective reference areas. Kootenay National Park's forests were younger than those in its reference area and were the youngest of all geographic units analyzed. Large fires burned in Kootenay National Park in 1918, 1926 (Taylor et al., 2006a) and 2003. There were also Mountain pine beetle outbreaks in the 1940s (Taylor et al., 2006b) and recently (ongoing). Glacier National Park had the oldest forests of all geographic units analyzed, with most of its forest stands more than 200 years old.

The variation in forest stand ages in parks relative to their corresponding reference areas is a result of the legacy of natural disturbances and management practices prior to 2008. These age-class distributions were somewhat impacted by conservation. The three national parks were established between 1885 and 1920, but industrial-scale forestry only began in the surrounding reference areas around circa 1950. The divergence in management history therefore only began 50–60 years ago, while natural disturbances remained important in both parks and reference areas throughout their histories.

The age dynamics of forests from 1970 to 2008 were simulated by CBM-CFS3 as forest stands grow and are subjected to harvest, natural disturbances, and succession. In the complete absence of disturbances the average forest age would increase by 39 years, but stand-replacing disturbances reduce the increase in average age, or when widespread, reduce the average age of the entire forest. The average age of Glacier and Yoho National Park forests increased by 31 and 34 years (Table 3), respectively, while in Kootenay National Park greater disturbances reduced the age increase to only 18 years. As expected, stand-replacing harvest and other disturbances in reference areas reduced the age increase to around 15 years.

3.3. Do parks have higher forest C stocks?

We found park forests to have higher forest C stocks than their surrounding reference area forests. In 2008, simulated ecosystem C stock density was 250 Mg ha⁻¹ of C to 330 Mg ha⁻¹ of C for parks and protected areas with an average of 281 Mg ha⁻¹ of C for the three national parks and 239 Mg ha⁻¹ of C for their reference areas (Fig. 7a). The highest C densities were observed in Glacier National Park – the park with the oldest forests.

Forest C stocks increased during the 1970–2008 simulation period in all three national parks and in the provincial protected areas (Fig. 7b). Glacier National Park's forest C stocks were the largest to begin with and increased only modestly, while Kootenay National Park – with its relatively young forests – exhibited the greatest gains in forest ecosystem C density despite substantial C losses during the fires of 2003.

Changes in ecosystem C density over time were the combined result of changes in living biomass and in DOM C pools. In Kootenay National Park, biomass C increased from 1970 to 2003 by 30 Mg ha⁻¹ of C (a 37% increase), but by 2008 the net change was reduced to only 12% because of large fires in 2003 as well as

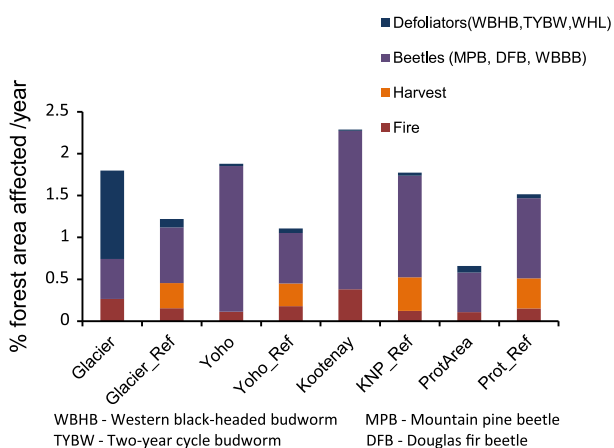


Fig. 5. Proportion of forest areas disturbed annually by different disturbance types. MPB – mountain pine beetle; DFB – Douglas-fir beetle; WBBB – western balsam bark beetle. WBHB – western black-headed budworm; TYBW – two-year budworm; WHL – western Hemlock looper.

Table 2
Cumulative area disturbed from 1970 to 2008 (as% of forested area).

	Kootenay National Park		Yoho National Park		Glacier National Park		ProtArea		Overall		
	Park	Reference	Park	Reference	Park	Reference	Park	Reference	Parks & PA	3ParksOnly	Reference
Fire	15	5	4	7	10	6	4	6	7	10	5
Harvest	0	16	0	11	0	12	0	14	0	0	14
Insects	74	49	69	26	60	30	21	39	43	70	40

Note: Fire and Harvest are stand-replacing disturbances while Insects are considered as non stand-replacing disturbances.

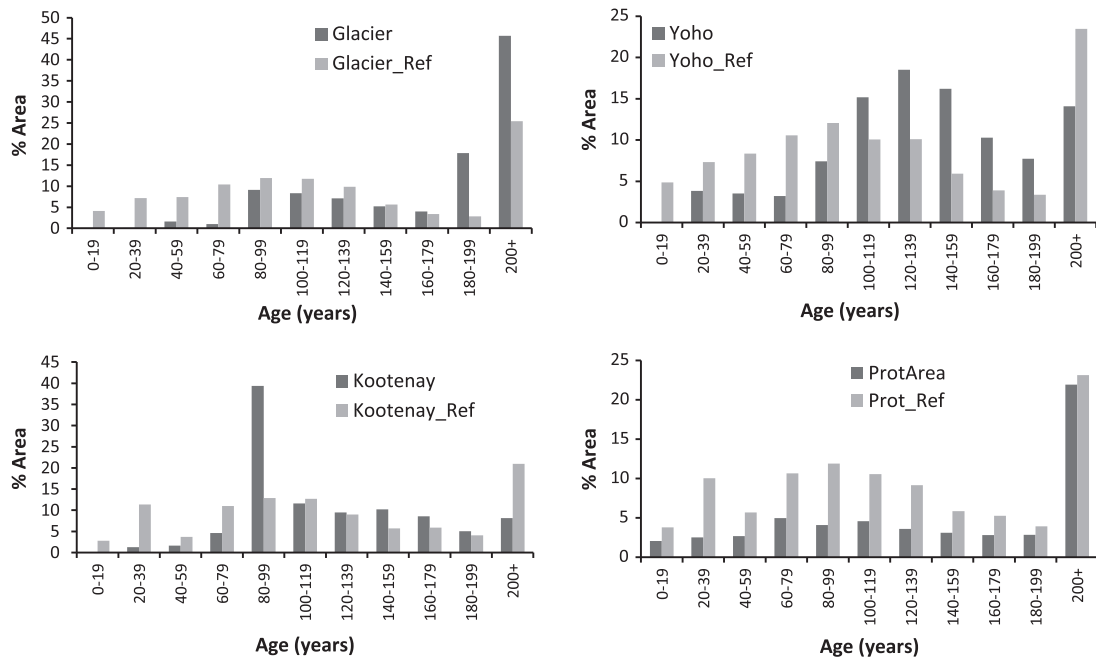


Fig. 6. Age distribution in 2008.

Table 3
Average age of stands in 1970 and 2008.

		Average age	
		Park	Reference area
1970	Glacier National Park	169	104
	Yoho National Park	105	102
	Kootenay National Park	87	104
	ProtArea	132	105
2008	Glacier National Park	200	119
	Yoho National Park	139	118
	Kootenay National Park	105	118
	ProtArea	165	119

recent insect infestations (Fig. 7c). Net biomass C changes for Yoho National Park, Glacier National Park and ProtAreas were 7, –3 and 13 Mg ha⁻¹ of C, respectively, while reference areas gained only 2 Mg ha⁻¹ of C. Over the study period, the small biomass C stock losses in Glacier National Park were more than offset by gains in DOM C stocks (Fig. 7d). These old growth forests were slowly accumulating higher C densities in dead wood, litter and soil C pools (DOM) while gradually becoming less C dense in living biomass C pools. The average amount of woody detritus in old-growth forests increases as decomposition rate-constants decrease and the mortality rate-constants increase (Harmon, 2009). Harvesting and intensive management can reduce the amounts of woody detritus at different stages of stand development. In Kootenay and Yoho na-

tional parks, much of the C lost from living biomass pools during natural disturbance events was not lost from the ecosystem, but transferred to DOM C pools from where it will be released gradually through decomposition.

Generally, C stocks in the reference areas increased at a lower rate than in the parks which were sequestering more C throughout the simulation period (Fig. 7e).

3.4. Do parks have lower net C uptake?

Net C uptake can be evaluated using several different metrics. We found that all parks had greater net primary productivity (NPP), net ecosystem productivity (NEP) and net biome productivity (NBP) than surrounding reference areas (Table 4). These measures indicate that park forests had greater net C accumulation than their respective reference area forests. This is of course consistent with our observation that parks had greater C stock increases during the simulation period. Standard errors reported here are not a measure of precision, but a measure of inter-annual variability.

NEE reports emissions to the atmosphere as a positive flux, while removals from the atmosphere have a negative sign. Over the study period, NEE (which is reported as Mg ha⁻¹ yr⁻¹ of CO₂) was negative for all geographic units (Table 4), indicating net uptake of C (sink) in all areas except in years with large fires (Fig. 8). After 2003, when there were very large fires in Kootenay National Park, its forests were a net C source because C loss from decomposition of partially burned biomass exceeded C uptake by

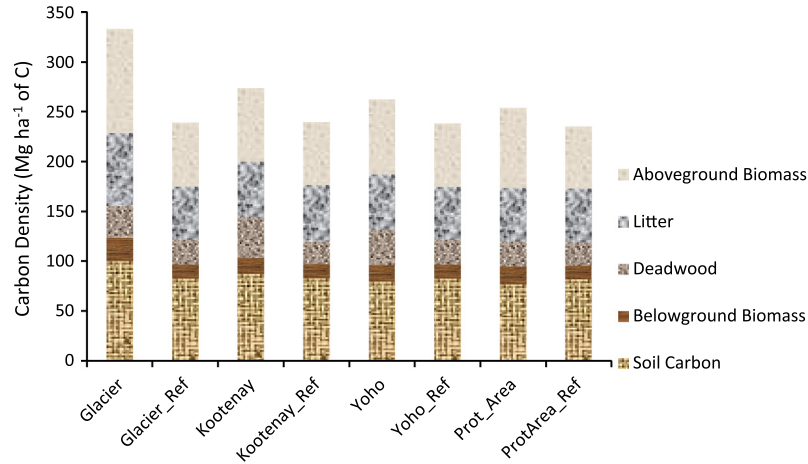


Fig. 7a. Ecosystem C stocks by pools in 2008.

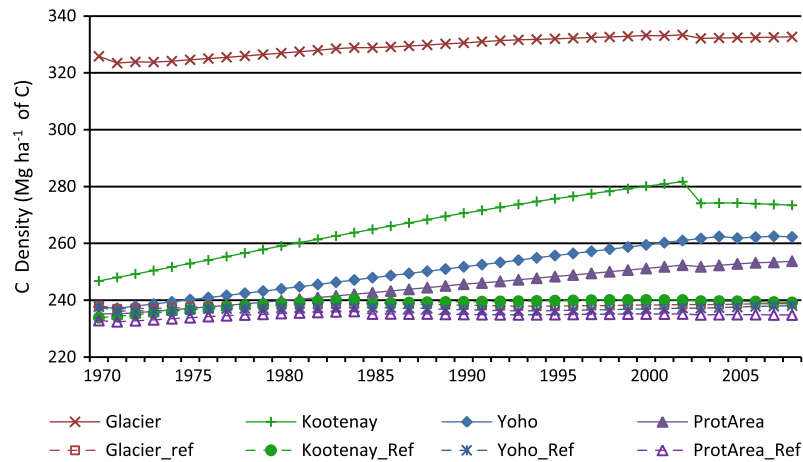


Fig. 7b. Ecosystem C stock dynamics over the study period.

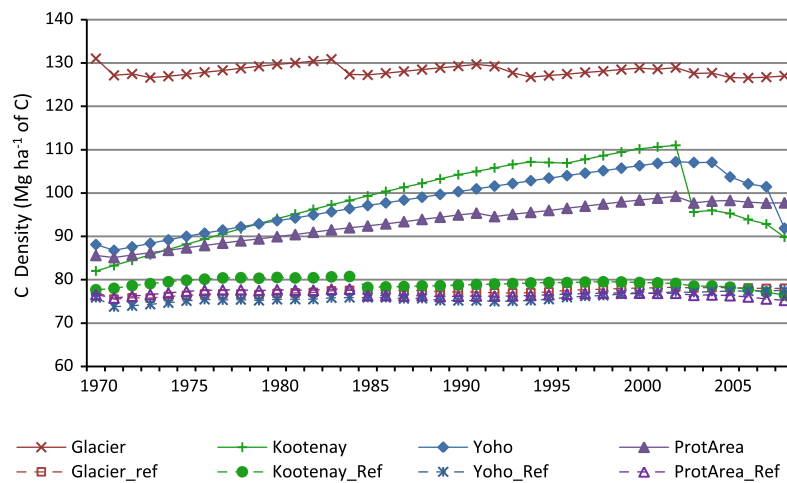


Fig. 7c. Biomass C stocks over study period.

regrowth. Over the study period overall, however, Kootenay National Park was the biggest sink, with a net uptake of 2.69 Mg ha⁻¹ yr⁻¹ of CO₂.

All parks except Glacier (the park with the oldest forests) had higher net uptake of C than their reference area forests. Glacier

National Park's forests were a smaller sink than their reference area forests although they had greater C stocks. A substantial portion of reference area forest C was transferred out of the ecosystem during harvest, while no such losses occurred in the park's forests, making it possible for the park's forests to have greater C stocks

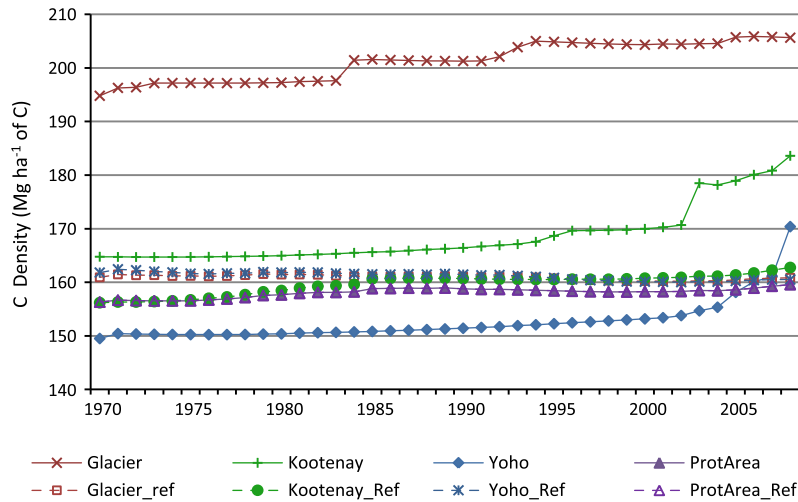


Fig. 7d. Dead organic matter (DOM) C stock dynamics over the study period.

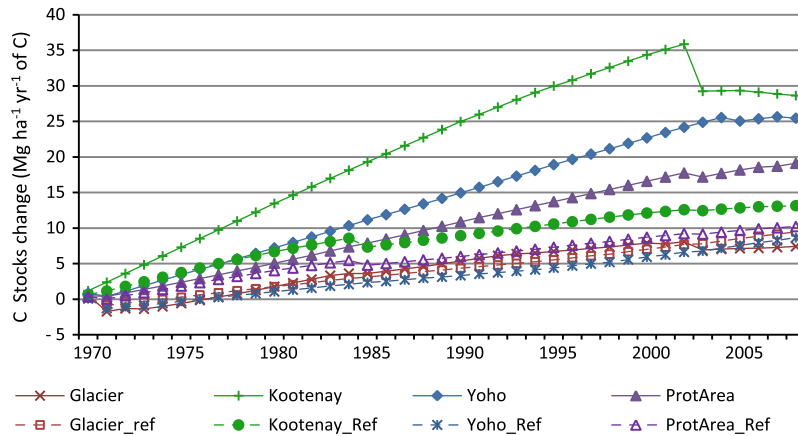


Fig. 7e. Cumulative ecosystem C stock changes.

Table 4
Indicator summary.

Indicator	Glacier	Glacier_Ref	Yoho	Yoho_Ref	Kootenay	Kootenay_Ref	ProtArea	ProtArea_Ref	3NPsOnly	Non_ParksOrPA
NPP	498(1)	384(1)	427(2)	381(1)	469(5)	406(2)	405(2)	388(1)	460(3)	396(1)
Rh	464(1)	353(0)	356(2)	351(0)	378(3)	366(1)	350(1)	354(1)	387(2)	360(1)
NEP	34(2)	31(1)	71(3)	30(1)	92(7)	40(3)	55(1)	34(2)	73(4)	36(2)
FireEmissions (Biom. +DOM)	15(8)	7(4)	6(4)	8(4)	21(20)	6(4)	6(3)	7(3)	14(10)	6(3)
Harvest transfer		22(1)		21(2)		18(1)		20(1)		20(1)
NBP	19(8)	2(4)	65(5)	01(4)	73(21)	15(6)	49(3)	6(4)	59(11)	9(4)
NEE	-0.75(0.28)	-0.92(0.12)	-2.42(0.18)	-0.85(0.15)	-2.69(0.77)	-1.27(0.18)	-1.82(0.18)	-1.00(0.12)	-2.20(0.39)	-1.11(0.11)

All values in $g\ m^{-2}\ yr^{-1}$ of C except NEE which is in $Mg\ ha^{-1}\ yr^{-1}$ of CO_2 and has the opposite sign convention - average of 1970–2008 (Numbers in parenthesis represent standard error).

while removing less C from the atmosphere. Some of the harvested C is emitted to the atmosphere elsewhere during harvested wood product processing, and some is transferred into product pools, such as paper, panels and lumber, where it may be sequestered for a few years or for several decades (Apps et al., 1999; Skog, 2008). NEE does not account for lateral transfers of C associated with harvesting. It is a representation of the forest ecosystem's impact on the atmosphere, but emissions from harvested wood products that occur elsewhere and in the years after harvest are not

included in NEE except in the case of large domain (e.g. continental) analyses such as Hayes et al. (2012).

Examining the three national parks combined in comparison with their combined reference areas ('3NPsOnly' versus 'Non_ParksOrPA' in Table 4, respectively), we found NPP was higher in park forests than in reference area forests and more of this C uptake was sequestered in the park forests compared to reference area forests. Roughly 16% of NPP was retained as NEP in national park forests compared to 9% in reference area forests. Of the $73\ g\ m^{-2}$ -

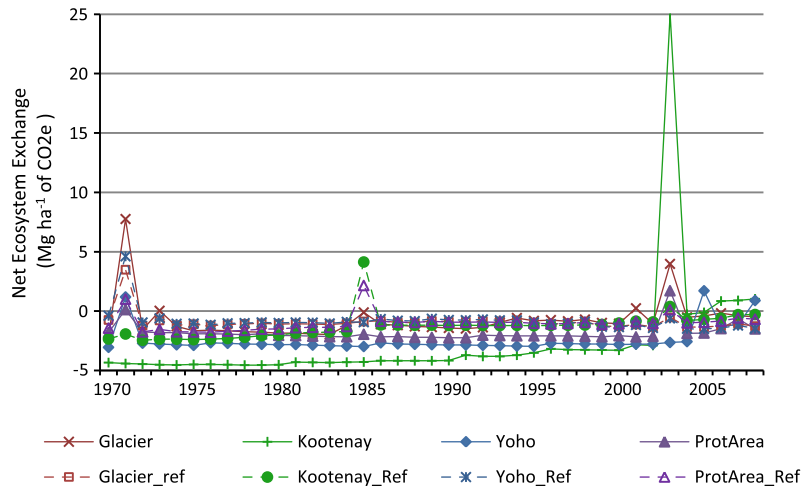


Fig. 8. Net ecosystem exchange.

yr⁻¹ NEP in national park forests, 14 g m⁻² yr⁻¹ were lost because of natural disturbances, either as direct fire emissions or indirect decay of DOM in subsequent years, leaving 13% of NPP remaining as NBP after all losses. In reference area forests, only 2% of NPP remained as NBP after accounting for all losses. While no C was harvested from park forests, 5% of the C taken up by NPP in reference area forests was harvested. Direct C emissions due to insects were found negligible in all cases. Insect disturbances resulted in large C transfers from biomass to DOM pools which eventually decay and result in C loss through heterotrophic respiration (*R_h*). On average, 35 g m⁻² yr⁻¹ of C were transferred from biomass to DOM due to insect disturbances. The three national parks together had a net uptake (NEE) of 2.20 Mg ha⁻¹ yr⁻¹ of CO₂ as compared to 1.11 Mg ha⁻¹ yr⁻¹ of CO₂ by their reference area (Fig. 9).

4. Discussion

We hypothesized that park forests, by virtue of their longstanding protection status, would be older than forests in surrounding landscapes, and that these older forests would have higher C

densities and lower CO₂ uptake. Forest C stocks and stock changes are affected by initial age-class structures (Böttcher et al., 2008), management (Hudiburg et al., 2009), and disturbances (Kurz and Apps, 1999; Bond-Lamberty et al., 2007; Kurz et al., 2008a,b). Although we found national park forests to have been disturbed less frequently overall by stand-replacing disturbances (wildfires and harvesting), as hypothesized, we also found that the cumulative area affected by insect outbreaks since 1970 (bark beetles and defoliators) was greater in the park forests. Large areas of mature pine forests throughout the study area were attacked by mountain pine beetle in the early years of our study period, and then again in recent years (Fig. 3b). The latest outbreak was part of a pandemic outbreak that affected most pine forests in British Columbia (Kurz et al., 2008b). The impact of these disturbances is, however, fundamentally different from fire or harvesting. Typically, bark beetles only cause partial stand mortality that if severe enough to allow regeneration of new tree cohorts can lead to uneven-aged stands in the pine and spruce forests of our study area (Taylor et al., 2006b; Hawkes et al., 2009). Following all but the most severe outbreaks, there are enough surviving trees from the

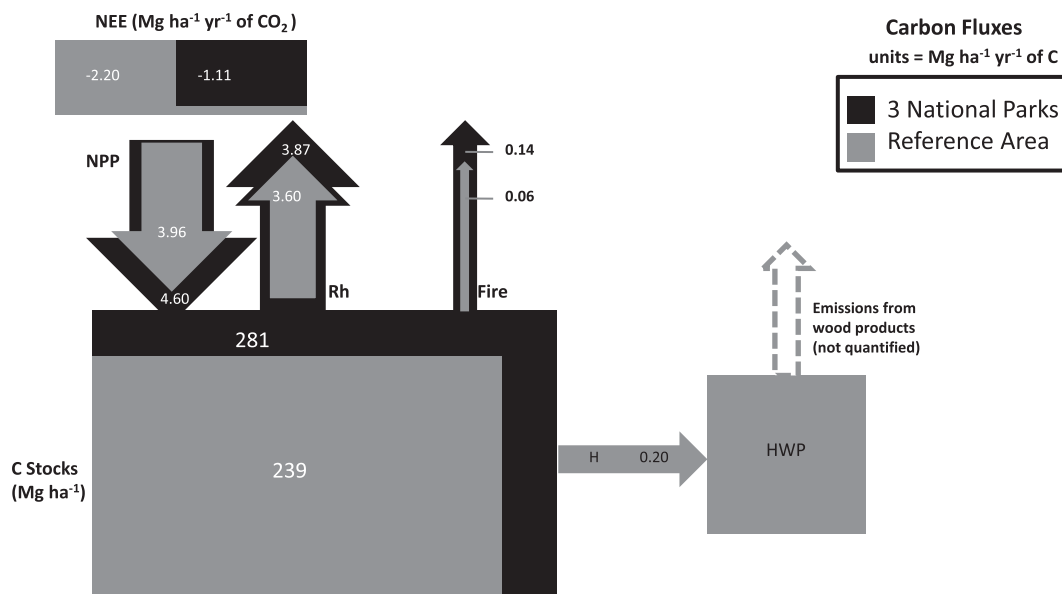


Fig. 9. Comparison of stocks and flux indicators in national parks and reference areas.

dominant cohort for affected stands to be recorded in subsequent inventory surveys as mature stands, albeit with reduced stem density, volume and living biomass and increased amounts of standing dead trees. Without salvage logging, this killed biomass is not lost from the system – it is retained on site in standing dead wood or other dead organic matter for many years before being released gradually by decomposition processes.

Fires have burned large areas of forest both inside and outside the parks since park establishment. Differences in areas burned in parks versus surrounding forests could be the result of differences in fire management, but any such effect would be extremely difficult to demonstrate quantitatively given the highly stochastic nature of wildfire ignition. It is entirely possible that more fire could have occurred inside a park (or outside a park) during the past century simply due to random chance.

Total forest ecosystem C stock densities that we estimated for Glacier, Yoho, and Kootenay national park forests in 2008 were 333, 262, 273 Mg ha⁻¹ of C, respectively. These estimates are higher than those reported in a study for Canadian Parks Council by Kulshreshtha et al. (2000), who estimated 117, 125, and 165 Mg ha⁻¹ of C for Glacier, Yoho, and Kootenay national parks, respectively. However, their study was based on secondary sources of data and, in cases where there were no data available, C stock densities for the park were based on the value for an ecozone or for that of the neighbouring park. These assumptions due to data limitations in their study may be a reason for the difference in the observed C stock densities. Our estimated C stocks compare favourably with those from other studies carried out for Canadian forests. Morton et al. (2007) estimated forest C stock densities between 234 and 340 Mg ha⁻¹ of C in four protected wilderness areas in Nova Scotia. Colombo et al. (2007) estimated a density of 200 Mg ha⁻¹ of C for managed forests in the southern region of Ontario.

We found that park and protected area forests had higher C densities than reference area forests. Even Kootenay National Park had higher C densities throughout the study period despite having younger forests than its reference area. Kootenay National Park supports higher C densities because its forests have the highest average yield of all units, while Kootenay reference area forests have the lowest average yield (Fig. 4). The average yield in Yoho National Park is also slightly higher than that of the Yoho reference area. Yield differences arise because of natural site quality differences and may also be influenced by silviculture and tree breeding efforts in the managed forests outside the parks. In our study area, any yield enhancements that may have been brought about by silviculture or tree breeding are clearly secondary to natural site quality differences because the highest yields are found in park forests. Our findings about the impacts of conservation are therefore confounded by natural site quality differences between the parks and their surroundings.

In order to explore the effects of conservation in isolation from site and productivity differences, we ran an additional hypothetical simulation where all forests in the study area were assigned a single, normalized yield curve calculated as an area-weighted average all the yield curves used in our main model simulations. After normalization, Kootenay National Park forests behaved as expected relative to reference area forests, with lower initial C densities and higher rates of CO₂ uptake. Yoho National Park, which in 1970 had forests of similar average forest stand age to its reference area, exhibited substantially greater C uptake (more negative NEE) even after normalization. While similar with respect to average forest stand age, the age-class distribution differs substantially. The Yoho reference area has more forest in the oldest age class (Fig. 6) than does Yoho National Park. Yields at these ages are declining according to the yield data (Fig. 4), and these areas thus contribute negative biomass growth. This also means that there are

substantial areas of forest within the reference areas that have never been harvested. These old forests in reference areas display C dynamics that are similar to what we would expect to see in a park or protected area.

Glacier National Park's forests are typical of what we imagined national park forests to be: predominantly old with high C stocks and low net CO₂ uptake. Glacier National Park's forest C density was substantially higher than its reference area forests (Fig. 7), and its CO₂ uptake was lower (Table 4). Unlike Glacier, Kootenay National Park forests were younger than those in its reference area (because of large wildfires prior to the start of our simulations) and had higher rates of CO₂ uptake because of their younger age and higher productivity. Kootenay National Park's forests did not conform to our expectations about how C dynamics would be affected by almost a century of conservation which excluded human but not natural disturbances. Yoho National Park conformed to our expectations with respect to C density, but not C uptake.

There are several types of uncertainty to consider in our results: (i) model input uncertainties (forest inventory, growth, and disturbance datasets), (ii) model parameter uncertainties (litterfall, decay, transfer, biomass expansion, disturbance impacts), (iii) model structure uncertainties (incorrectly specified or excluded processes, model algorithms), and (iv) uncertainties arising from human error (mistakes during processing of data – which are minimized through rigorous quality control, but cannot be eliminated entirely). We used the same model and the same quality control procedures for the data processing and simulation of park and reference forests. Uncertainty types (ii), (iii) and (iv) were therefore controlled for. The input datasets (forest inventory and disturbance monitoring data, in particular) may have been collected differently in park and reference area forests because of the different operational requirements for these datasets in forests managed primarily for conservation versus sustainable timber harvest. Whether these differences would be systematically sufficient to cause a bias in our results for park forests relative to reference area forests is not known, but it is unlikely that such a bias is strong enough to render our conclusions false.

4.1. Management implications

Climate change mitigation objectives are achieved when CO₂ sources to the atmosphere are decreased or CO₂ sinks are increased or both. Forests and the forest sector can contribute to climate change mitigation by (i) maintaining or increasing forest area, (ii) increasing stand- and landscape-level C density, and (iii) providing timber, fiber or energy from sustainable forest management to store C in long-lived products and displace the production of more emissions-intensive products such as steel, concrete or plastics (Werner et al., 2006; Nabuurs et al., 2007). When assessing the mitigation contribution of specific management actions, including conservation decisions, the impacts on C can be evaluated taking a systems perspective that includes assessment of changes in C storage in forest ecosystems, changes in C storage in harvested wood products in use and in landfills, and changes in emissions associated with the use of wood products to displace other products and fossil fuels (Sathre and O'Connor, 2010). Mitigation benefits also need to be assessed relative to a “business-as-usual” baseline. Forest conservation through the designation of national parks can generally be expected to result in increased forest ecosystem C stocks, but depending on the amount of harvesting that would have occurred without conservation, it will result in a reduction in C storage in harvested wood products and increased emissions from reduced substitution benefits. While it is possible to estimate the product displacement benefits from wood use (e.g. Sathre and O'Connor, 2010) it is difficult to quantify the specific changes in product displacement benefits resulting from forest conservation.

When exploring candidate forest areas for conservation aimed at achieving climate change mitigation objectives, criteria for selection could include forested landscapes that (a) are substantially younger than the average age expected from the prevailing regional natural disturbance regime or have unnaturally reduced tree cover, (b) have a low probability of natural disturbance, and (c) support tree species that can be expected to maintain high growth rates for many years into the future. Such forested landscapes will be well below their potential C storage capacity and conservation can be reasonably expected to provide sustained mitigation benefits into the future. Depending on tree species, risks of natural disturbances and other factors such as climate change impacts, the landscape-level C stocks will eventually saturate, resulting in high C stocks and decreased C uptake rates, as observed in Glacier National Park.

Where old forests that already support high C stocks are threatened by human disturbance or deforestation, conservation can provide substantial C benefits up front, but this strategy must be accompanied by documentation of what the “business as usual” management actions would have been in the absence of conservation so that the true incremental climate change mitigation benefit of conservation can be estimated.

Our results reveal that the climate change mitigation benefits of forest conservation can be heavily influenced by natural disturbances. Whereas Glacier National Park’s forests are typical of what we imagined national park forests to be: predominantly old with high C stocks and low net CO₂ uptake, Kootenay and Yoho national parks forests are not. Natural disturbances play important ecological roles in many forest ecosystems and their exclusion for C management purposes could undermine ecological integrity. Moreover, where disturbance risk increases with forest age, as in the case of mountain pine beetle (Taylor et al., 2006b), exclusion of one disturbance type (harvest) may result in increased risks of other disturbances (insects). Similarly, exclusion of natural disturbances can result in greater risk of future disturbance (Kurz et al., 2008b).

Although we found that two of the three national parks examined had substantially higher CO₂ sequestration rates than their reference areas, we caution that this result cannot be extrapolated to other areas. In Kootenay National Park, the higher C sequestration rates we found were the result of high average yield (relative to the reference area) and the ongoing C stock recovery from major natural disturbance losses that occurred prior to the analysis period. In Yoho National Park, the higher C uptake rates we found were also the result of higher average yields, plus the unusual age-class structure of the reference area that contained a much larger proportion of very old stands than the park.

Implementing a conservation strategy in a young, recently disturbed forest landscape can be expected to provide C sinks for many years to decades, provided that natural disturbances do not recur. Predictions of changes in fire regimes in the region of the Mountain Parks consistently indicate increased risks of fire disturbances with associated reductions in C stocks and increases in CO₂ emissions (Flannigan et al., 2005; Balshi et al., 2009; Metsaranta et al., 2010; Haughian et al., 2012). Therefore, the risks associated with anticipated changes in fire regimes need to be assessed prior to implementation of a conservation strategy aimed at climate change mitigation.

The results of this study present compelling evidence that conservation of natural forest ecosystems for the purposes of maintaining ecological integrity can also contribute to climate change mitigation. This study reveals, however, that achieving climate change mitigation objectives through conservation is more likely under some ecological circumstances than others. Where natural disturbances are an important part of the forest ecology, conservation may or may not contribute to climate change mitigation because of the risk of C loss in the event of wildfire or insect-

caused tree mortality. Anticipated increases in natural disturbance resulting from global warming may further reduce the climate change mitigation potential of forest conservation in disturbance-prone ecosystems. On the other hand, global warming may cause an increase in forest productivity as was observed by Hember et al. (2012) for Coastal Douglas fir and Western Hemlock on coastal BC, which would result in an increased uptake of CO₂ sequestration rates by these forests. A sound understanding of ecosystem forest C dynamics and prognosis for future CO₂ sequestration or natural release is required in order to understand which protected areas are most likely to provide sustained climate change mitigation. Balancing these relatively new management concerns with the traditional concerns about biodiversity and ecological integrity, which are legislated responsibilities for Parks Canada, will be a new and challenging task for protected area managers just as it is for land resource managers in many other jurisdictions.

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References

- Apps, M.J., Beukema, S.J., Kurz, W.A., 1999. Carbon budget of the Canadian forest product sector. *Environ. Sci. Policy* 2, 25–41.
- Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., Melillo, J., 2009. Assessing the response of area burning to changing climate in western boreal North America using a multivariate adaptive regression splines (MARS) approach. *Glob. Change Biol.* 15, 578–600.
- BCMFLNRO, 2012. Provincial map of tree farm licenses, timber supply areas, regions and districts. [WWW Document]. B.C. Ministry of Forests, Lands, and Natural Resource Operations. <<http://www.for.gov.bc.ca/hth/timber-tenures/provincial-map.htm>> (accessed on 10.10.11).
- BC MoF, 2000. Forest health aerial overview survey standards for British Columbia, Version 2.0, June 2000. Prepared by B.C. Ministry of Forests, Forest Practices Branch and Canadian Forest Service [WWW Document]. <<http://ilmb.gov.bc.ca/risc/pubs/teveg/foresthealth/index.htm>> (accessed on 18.07.12).
- Bond-Lamberty, B., Peckham, S.D., Ahl, D.E., Gower, S.T., 2007. Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature* 450, 89–92.
- Böttcher, H., Kurz, W.A., Freibauer, A., 2008. Accounting of forest carbon sinks and sources under a future climate protocol – factoring out past disturbance and management effects on age-class structure. *Environ. Sci. Policy* 11, 669–686.
- Boudewyn, P., Song, X., Magnussen, S., Gillis, M.D., 2007. Model-Based Volume-to-Biomass Conversion for Forested and Vegetated Land in Canada (Inf. Rep. No. BC-X-411). Canadian Forest Service, Victoria, BC.
- Chapin, F.S., Woodwell, G.M., Randerson, J.T., Rastetter, E.B., Lovett, G.M., Baldocchi, D.D., Clark, D.A., Harmon, M.E., Schimel, D.S., Valentini, R., Wirth, C., Aber, J.D., Cole, J.J., Goulden, M.L., Harden, J.W., Heimann, M., Howarth, R.W., Matson, P.A., McGuire, A.D., Melillo, J.M., Mooney, H.A., Neff, J.C., Houghton, R.A., Pace, M.L., Ryan, M.G., Running, S.W., Sala, O.E., Schlesinger, W.H., Schulze, E.-D., 2006. Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems* 9, 1041–1050.
- Colombo, S.J., Chen, J., Ter-Mikaelian, M.T., 2007. Carbon storage in Ontario’s forests 2000–2100. (Research Information Note 6). Ontario Ministry of Natural Resources, Applied Research and Development Branch, [Toronto]. 8p.
- Coursolle, C., Margolis, H.A., Giasson, M.-A., Bernier, P.-Y., Amiro, B.D., Arain, M.A., Barr, A.G., Black, T.A., Goulden, M.L., McCaughey, J.H., Chen, J.M., Dunn, A.L., Grant, R.F., Lafleur, P.M., 2012. Influence of stand age on the magnitude and seasonality of carbon fluxes in Canadian forests. *Agric. For. Meteorol.* 165, 136–148.
- Di Lucca, C.M., 1999. TASS/SYLVER/TIPSY: systems for predicting the impact of silvicultural practices on yield, lumber value, economic return and other benefits. In: Stand Density Management Conference: Using the Planning Tools. November 23–24, 1998, Bamsey Colin R. (Ed.) Clear Lake Ltd., Edmonton, AB, pp. 7–16.
- Dudley, N., Stolton, S., Belokurov, A., Krueger, L., Lpoukhine, N., MacKinnon, K., Sandwith, T., Sekhran, N., 2010. Natural solutions: protected areas helping

- people cope with climate change, PACT 2020: protected areas and climate turnaround. IUCN-WCPA, TNC, UNDP, WCS, The World Bank and WWF, Gland, Switzerland.
- Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., Stocks, B.J., 2005. Future area burned in Canada. *Clim. Change* 72, 1–16.
- Gonzalez, J.S., 1990. Wood density of Canadian tree species (Inf. Rep. NOR-X-315 No. NOR-X-315). Northern Forest Centre, Canadian Forest Service, Edmonton.
- Harmon, M.E., 2009. Woody detritus mass and its contribution to carbon dynamics of old-growth forests: The temporal context, in *Old-Growth Forests: Function, Fate and Value*, Ecol. Stud., vol. 207. In: Wirth, C., Gleixner, G., Heimann, M. (Eds.) pp. 159–189, Springer, New York.
- Haughian, S.R., Burton, P.J., Taylor, S.W., Curry, C.L., 2012. Expected effects of climate change on forest disturbance regimes in British Columbia. *BC J. Ecosyst. Manage.* 13, 1–24.
- Hawkes, B., Stockdale, C., Shore, T., Dalrymple, G., Unger, L., Taylor, S., 2009. Impact of mountain pine beetle on stand and fuel dynamics in Kootenay National Park. Executive Summary [WWW Document]. Parks Canada. <<http://www.pc.gc.ca/docs/v-g/dpp-mpb/sec4/dpp-mpb4a/dpp-mpb4a1.aspx>> (accessed on 20.03.13).
- Hayes, D., Turner, D., 2012. The need for “apples-to-apples” comparisons of carbon dioxide source and sink estimates. *EOS* 93, 404–405.
- Hayes, D.J., Turner, D.P., Stinson, G., West, T.O., Wei, Y., Heath, L.S., Birdsey, R.A., deJong, B., McGuire, A.D., Kurz, W.A., Jacobson, A.R., McConkey, B.G., Huntzinger, D.N., Pan, Y., Post, W.M., Cook, R.B., 2012. Reconciling estimates of the contemporary North American carbon balance among an inventory-based approach, terrestrial biosphere models, and atmospheric inversions. *Glob. Change Biol.* 18, 1282–1299.
- Hember, R.A., Kurz, W.A., Metsaranta, J.M., Black, T.A., Guy, R.D., Coops, N.C., 2012. Accelerating regrowth of temperate-maritime forests due to environmental change. *Glob. Change Biol.* 18, 2026–2040.
- Hudiburg, T., Law, B., Turner, D., Campbell, J., Donato, D., Duane, M., 2009. Carbon dynamics of Oregon and Northern California forests and potential land-based carbon storage. *Ecol. Appl.* 19, 163–180.
- Keith, H., Mackey, B.G., Lindenmayer, D.B., 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world’s most carbon-dense forests. *Proc. Natl. Acad. Sci. USA* 106, 11635–11640.
- Kull, S.J., Rampley, G.J., Morken, S., Metsaranta, J., Neilson, E.T., Kurz, W.A., 2011. Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2: User’s Guide. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB, Edmonton.
- Kulshreshtha, S.N., Lac, S., Johnston, M., Kinar, C., 2000. Carbon Sequestration in Protected Areas of Canada: An Economic Valuation (Economic Framework project 549). Canadian Parks Council.
- Kurz, W.A., Apps, M.J., 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecol. Appl.* 9, 526–547.
- Kurz, W.A., Beukema, S.J., Apps, M.J., 1998. Carbon budget implications of the transition from natural to managed disturbance regimes in forest landscapes. *Mitig. Adapt. Strat. Glob. Change* 2, 405–421.
- Kurz, W.A., Stinson, G., Rampley, G.J., Dymond, C.C., Neilson, E.T., 2008a. Risk of natural disturbances makes future contribution of Canada’s forests to the global carbon cycle highly uncertain. *Proc. Natl. Acad. Sci. USA* 105, 1551–1555.
- Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., Safranyik, L., 2008b. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452, 987–990.
- Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecol. Modell.* 220, 480–504.
- Lamlop, S.H., Savidge, R.A., 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. *Biomass Bioenergy* 25, 381–388.
- Li, Z., Kurz, W.A., Apps, M.J., Beukema, S.J., 2003. Belowground biomass dynamics in the carbon budget model of the Canadian forest sector: recent improvements and implications for the estimation of NPP and NEP. *Can. J. For. Res.* 33, 126–136.
- Masek, G.J., Goward, N.S., Kennedy, E.R., Cohen, B.W., Moisen, G.G., Schleeuwis, K., Huang, C., 2013. United States Forest Disturbance Trends Observed Using Landsat Time Series. *Ecosystems*. Published online May 17, 2013. doi: 10.1007/s10021-013-9669-9.
- Meidinger, D.V., Pojar, J., 1991. *Ecosystems of British Columbia (Special Report Series 6)*. Ministry of Forests, B.C.
- Metsaranta, J.M., Kurz, W.A., Neilson, E.T., Stinson, G., 2010. Implications of future disturbance regimes on the carbon balance of Canada’s managed forest (2010–2100). *Tellus B* 62, 719–728.
- Ministry of Forests, 2009. Variable density yield projection, Volume 1 – VDYP7 Overview, version 2.0. Forest Analysis and Inventory Branch, BC [WWW Document]. British Columbia Ministry of Forests. <http://www.for.gov.bc.ca/hts/vdyp/user_guides/volume1_vdyp_overview_revised_april2010.pdf> (accessed 17.06.13).
- Ministry of Forests, 2012. Vegetation resource inventory data dictionary, version 4.0. Forest Analysis and Inventory Branch, BC [WWW Document]. British Columbia Ministry of Forests. <http://www.for.gov.bc.ca/hts/vridata/standards/datadictionary/vegcomp_poly_rank1_data_dictionary_draft4.0.pdf> (accessed 17.06.13).
- Morton, C., Cameron, R., Duinker, P., 2007. Beyond boundaries. Proceedings of the Sixth International Conference of Science and the Management of Protected Areas, in: *Beyond Boundaries*. Presented at the Sixth International Conference of Science and the Management of Protected Areas, 21–26 May 2007, Acadia University, Wolfville, Nova Scotia.
- Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsidig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhancabal, W., Ravindranath, N.H., Sanz Sanchez, M.J., Zhang, X., 2007. Forestry, in: *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 543–578.
- Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world’s forests. *Science* 333, 988–993.
- Prichard, S.J., Peterson, D.L., Hammer, R.D., 2000. Carbon distribution in subalpine forests and meadows of the olympic mountains, Washington. *Soil Sci. Soc. A. J.* 64, 1834–1845.
- Safranyik, L., Shore, T.L., Carroll, A.L., Linton, D.A., 2004. Bark beetle (Coleoptera: Scolytidae) diversity in spaced and unmanaged mature lodgepole pine (Pinaceae) in south-eastern British Columbia. *For. Ecol. Manage.* 200, 23–38.
- Sathre, R., O’Connor, J., 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environ. Sci. Policy* 13, 104–114.
- Scott, D., Lemieux, C., Pentelov, L., 2008. A Review of the Role of Protected Ecosystems in Climate Change Mitigation (University of Waterloo Report Submitted to the Parks Canada Agency). Parks Canada Agency, Gatineau, Quebec.
- Skog, K.E., 2008. Carbon storage in forest products for the United States. *For. Prod. J.* 58, 56–72.
- Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., Dietzsch, L., Merry, F., Bowman, M., Hissa, L., Silvestrini, R., Maretti, C., 2010. Role of Brazilian Amazon protected areas in climate change mitigation. *Proc. Natl. Acad. Sci. USA* 107, 10821–10826.
- Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., Boisvenue, C., Rampley, G.J., Li, Q., White, T.M., Blain, D., 2011. An inventory-based analysis of Canada’s managed forest carbon dynamics, 1990–2008. *Glob. Change Biol.* 17, 2227–2244.
- Taylor, S., Thandi, G., Carroll, A.L., Hawkes, B., Nealis, V., Parminter, J., Ebata, T., Lindgren, S., 2006a. Development and analysis of a British Columbia natural disturbance database (Y06-2233 Final Report). Natural Resources Canada, Pacific Forestry Centre, Victoria, BC.
- Taylor, S.W., Carroll, A.L., Alfero, R.I., Safranyik, L., 2006b. Forest, Climate and Mountain Pine Beetle Outbreak Dynamics in Western Canada, in: *The Mountain Pine Beetle: A Synthesis of Biology, Management and Impacts in Lodgepole Pine*. Natural Resources Canada, Canadian Forest Service, Victoria.
- Ter-Mikaelian, M.T., Colombo, S.J., Chen, J., 2008. Fact and fantasy about forest carbon. *For. Chron.* 84, 166–171.
- Trofymow, J.A., Stinson, G., Kurz, W.A., 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. *For. Ecol. Manage.* 256, 1677–1691.
- Van Sickle, A., Fiddick, R.L., Wood, C.S., 2001. The forest insect and disease survey in the Pacific Region. *J. Entomol. Soc. BC* 98, 169–176.
- Werner, F., Taverna, R., Hofer, P., Richter, K., 2006. Greenhouse gas dynamics of an increased use of wood in buildings in Switzerland. *Clim. Change* 74, 319–347.
- White, J., Wulder, M.A., Gomez, C., Stenhouse, G., 2011. A history of habitat dynamics: characterizing 35 years of stand replacing disturbance. *Can. J. Remote Sens.* 37, 234–251.
- Wong, C., Dorner, B., Sandman, H., 2003. Estimating historical variability of natural disturbances in British Columbia (Land Management Handbook No. 53). B.C. Ministry of Forests, Research Branch, B.C. Ministry of Sustainable Resource Management, Resource Planning Branch, Victoria, BC.
- Woodley, S., 2009. Planning and managing for ecological integrity in Canada’s national parks. In: Dearden, P., Rollins, R. (Eds.), *Parks and Protected Areas in Canada*. Oxford University Press, Oxford, p. 117.