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March 2016

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This article was originally published at:
<http://dx.doi.org/10.1002/2015GL067532>

Citation for this paper:

Arora, V. K., Y. Peng, W. A. Kurz, J. C. Fyfe, B. Hawkins, and A. T. Werner (2016), Potential near-future carbon uptake overcomes losses from a large insect outbreak in British Columbia, Canada, *Geophysical Research Letters*, 43(6), 2590–2598. doi: 10.1002/2015GL067532.



RESEARCH LETTER

10.1002/2015GL067532

Key Points:

- Increasing CO₂ and changing climate enhances carbon uptake by high-latitude forests
- Climate change, however, can also increase instances of future fire and insect disturbances
- Future enhanced carbon uptake by forests can potentially overcome losses from large insect outbreaks

Supporting Information:

- Figures S1–S7

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Citation:

Arora, V. K., Y. Peng, W. A. Kurz, J. C. Fyfe, B. Hawkins, and A. T. Werner (2016), Potential near-future carbon uptake overcomes losses from a large insect outbreak in British Columbia, Canada, *Geophys. Res. Lett.*, 43, 2590–2598, doi:10.1002/2015GL067532.

Received 22 DEC 2015

Accepted 19 FEB 2016

Accepted article online 22 FEB 2016

Published online 16 MAR 2016

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Potential near-future carbon uptake overcomes losses from a large insect outbreak in British Columbia, Canada

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Abstract The current capacity of northern high-latitude forests to sequester carbon has been suggested to be undermined by the potential increase in fire and insect outbreaks. Here we investigate the response of the terrestrial ecosystems in the province of British Columbia (BC), Canada, to the recent large mountain pine beetle (MPB) outbreak that started in 1999 as well as changing climate and continually increasing atmospheric CO₂ concentration up to 2050, in a combined framework, using a process-based model. Model simulations suggest that the recent MPB outbreak results in BC's forests accumulating 328 Tg less carbon over the 1999–2020 period. Over this same period changing climate and increasing atmospheric CO₂ concentration, however, yield enhanced carbon uptake equal to a cumulative sink of around 900–1060 Tg C, depending on the future climate change scenario, indicating that the reduced carbon uptake by land due to the MPB disturbance may already be surpassed by 2020.

1. Introduction

The rising concentrations of greenhouse gases in the atmosphere, and the associated climatic changes, affect various biotic and abiotic processes that regulate terrestrial ecosystems. High-latitude forests are currently known to be sinks of atmospheric carbon [Ciais *et al.*, 2013; Gourdji *et al.*, 2012]. Increasing atmospheric CO₂ concentration [CO₂], which increases photosynthesis through the CO₂ fertilization effect, and the associated changes in climate which is gradually getting warmer and wetter, on average, in high-latitude regions [Hartmann *et al.*, 2013; Mekis and Vincent, 2011] are considered to be the primary reasons for this high-latitude carbon sink. Climate change can potentially, however, also undermine the ability of northern forests to take up and store atmospheric carbon due both to increased occurrences of fire and insect outbreaks. Kurz *et al.* [2008b], for example, project the carbon balance of the managed Canadian forests to year 2022 by taking into account stochastic future disturbances and using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). They project that until 2022, the managed Canadian forests will remain a source of carbon to the atmosphere if it is assumed that all carbon in wood harvested from BC forests is instantly oxidized. The CBM-CFS3 model, however, does not explicitly take into account any effect of increased growth of [CO₂] and the associated climate change on forest growth rates, other than what is implicitly included in the empirical growth and yield data that are used to drive the model.

Here using a process-based terrestrial ecosystem model, we explicitly simulate the effects of historical and future changes in climate and [CO₂] and the recent large mountain pine beetle (MPB) outbreak that started in 1999 on the terrestrial carbon balance of the province of British Columbia (BC), Canada, in a combined framework. Our objective is to put the carbon loss associated with the recent MPB outbreak in the context of the carbon gain associated with climate change and increasing [CO₂] over historical and future periods. The inherent temporal and spatial scales associated with insect disturbances are, of course, different from those of climate change associated with increasing concentrations of greenhouse gases. Major insect disturbances are periodic, often cyclical, events that typically affect a fraction of the landscape over 2–15 year time periods. The effects of climate change and increasing [CO₂], in contrast, are more wide spread, gradual, and expected to last over decades to centuries. Nevertheless, a modeling framework that simulates the natural response of terrestrial ecosystems to an insect disturbance and increasing [CO₂] together with associated changing climate, in a combined framework, provides the means to compare the effect of both in a consistent manner.

2. Model, Experimental Setup, and Methods

Our study is based on simulations made with the process-based Canadian Terrestrial Ecosystem Model (CTEM, version 1.1) which is coupled to the Canadian Land Surface Scheme (CLASS, version 3.5) and implemented at the 40 km resolution for the province of BC (see Figure S1 in the supporting information) [Peng *et al.*, 2014]. The model simulates carbon photosynthetic gains and respiratory losses which result in time-varying carbon storage in its three live vegetation pools (leaves, stems, and roots) and two dead carbon pools (litter and soil organic matter) for four plant functional types (PFTs) (broadleaf cold deciduous trees, coastal and interior needleleaf evergreen trees, and C₃ grasses), which are present in the province of BC. These PFTs occupy specified fractions in each 40 km grid cell, which do not change over time, and are based on a 25 m resolution land cover data set (corresponding to year 2000) that is obtained from the Canadian Forest Services' Earth Observations for Sustainable Development of Forests [Wulder *et al.*, 2003]. For this study, the physiological processes of photosynthesis, autotrophic and heterotrophic respiration, phenology, allocation, and turnover of leaves, stems, and roots are modeled in CTEM. The model also simulates area burned and CO₂ emissions associated with forest fires based on a fire parameterization of intermediate complexity [Arora and Boer, 2005].

Simulations are performed for the 1901–2050 period and summarized in Figure S2. The current characteristic return interval of MPB disturbances is around 40 years in the province [Alfaro *et al.*, 2010]. Simulations till 2050 thus last about 40 years since the end of current MPB disturbance (1999–2011) as it is implemented in the model and as discussed below. For the historical 1901–2005 period, the model is driven with climate data based on the Climate Research Unit and National Centre for Environmental Prediction (CRUNCEP) data. The CRUNCEP data are based on adjustment to the monthly means in the National Centre for Environmental Prediction (NCEP) reanalysis [Kanamitsu *et al.*, 2002] to match data from the Climate Research Unit (CRU) observations. For the period 2006–2050, the climate data are based on three future climate change scenarios, corresponding to the three representative CO₂ concentration pathways (RCP 2.6, 4.5, and 8.5) and obtained from the Max Planck Institute for Meteorology (MPI) Low Resolution Earth System Model (MPI-ESM-LR) [Giorgetta *et al.*, 2013]. Observation-based globally averaged annual atmospheric CO₂ values for the historical period, and for future RCP scenarios, used to drive the model are obtained from the International Institute for Applied Systems Analysis (<http://tntcat.iiasa.ac.at/RcpDb/>). The year 2050 [CO₂] values in the RCP 2.6, 4.5, and 8.5 scenarios are around 443, 486, and 540 ppm, respectively (see SI). The 6-hourly meteorological data from CRUNCEP and daily data from the MPI-ESM-LR model are disaggregated to half-hourly time resolution data needed to drive the CLASS-CTEM model, as explained in the SI. Both data are spatially interpolated to the 40 km grid resolution used in this study. The climate data from the MPI-ESM-LR are adjusted for biases in annual mean values as well as for their interannual variability as explained in the SI (Figure S4). The data are, however, not adjusted at the monthly scale. The amplitude of the seasonal cycle of temperature is known to reduce due to climate warming especially in northern high latitudes with greater warming in winters than in summers [Dwyer *et al.*, 2012]. Rather than bias correcting the seasonal cycle, while preserving this climate change signal, we used climate data from the MPI-ESM-LR which yields smoothest transition in simulated carbon budget quantities when switching from the historical observation-based climate data in 2005 to model-based climate data in 2006, compared to using climate data from other ESMs. Using bias corrected data for mean and interannual variability in annual values from other ESMs resulted in greater “shock” in simulated carbon budget quantities at the 2005–2006 transition. The resulting annual time series of province-wide average climate variables, together with the [CO₂], used to drive the CLASS-CTEM model are shown in Figure S3 for the historical and future periods. Finally, simulations are performed both with and without the MPB disturbance that starts in 1999 and ends in 2011, as discussed below, although the effect of the MPB disturbance on the response of the province's terrestrial ecosystems continues beyond 2011.

The MPB disturbance is implemented on the basis of spatially distributed data for severity index and cumulative pine volume killed available at 450 m resolution from the BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) for the period 1999 to 2011 (<http://www.for.gov.bc.ca/ftp/HRE/external/!publish/web/BCMPB/Year9/>). In the absence of spatially distributed infested fraction (*I*, fraction) in each 450 m grid cell we relate severity index to fraction of killed trees observed during aerial overview surveys using Table 2 of Westfall and Ebata [2011]. The cumulative pine volume killed data are available as fraction of trees killed in

a grid cell and used to estimate annual fraction of trees killed (K , fraction/year). The rate of change of infested area is given by $dl/dt = K - R$ and when l and K are known the annual recovery fraction (R , fraction/year) can be estimated. Finally, K and R are regridded from the 450 m resolution to the 40 km resolution at which the CLASS-CTEM model is implemented.

The effect of disturbance associated with the recent MPB outbreak is included by modifying relevant model subroutines. The fraction of interior needleleaf evergreen trees killed in a given year is gradually implemented during a year with the killed fraction increased from 1 May to 30 September. The trees of the killed fraction stop photosynthesizing and their needles, stem, and root contribute to the litter pool at a rate faster than the normal turnover rate for these components. As a result, the ecosystem loses carbon. Conversely, as recovery occurs, the recovered fraction begins to photosynthesize and slowly the ecosystem returns to being a carbon sink. The dead needles are assumed to have a half-life of 0.35 years that implies that 3 years after being attacked, trees lose all their needles which is consistent with *Wulder et al.* [2006]. The stem component in the model for MPB-affected trees has a half-life of around 8 years. The half-lives for leaf and stem components determine the rate at which these components turnover and contribute to the litter pool. The half-life of 8 years used for the stem component of the MPB-affected trees is consistent with observation-based estimates [Lewis and Hartley, 2006] which suggest in unthinned stands, 50% of trees had fallen within 9 years and 90% within 14 years after their death and the 10 year half-life used in another modeling study [Edburg et al., 2011]. In any case, Figure S5 shows that while the simulated peak impact of the MPB disturbance is sensitive to the chosen half-life of the stem component of the MPB-affected trees, the cumulative impact is not. The half-life span of needles of the healthy interior needleleaf evergreen trees is 3.5 years, and the default half-life for their stem component is 48 years [Melton and Arora, 2016]. The recovered fraction each year, which is also increased gradually from 1 May to 30 September, is assigned to a new age cohort that starts growing vegetation biomass as an interior needleleaf evergreen PFT. The simulated response to the MPB disturbance, which is the result of reduction in photosynthesis and increase in heterotrophic respiration following the disturbance, is illustrated for a single grid cell in Figure S6.

Peng et al. [2014] used the same coupled CLASS-CTEM modeling framework, as in this study, for the province of BC, Canada, over the historical 1900–2010 period driven with observation-based CRUNCEP climate data and $[\text{CO}_2]$ but without the MPB disturbance. They also evaluated CTEM's response to changing climate and increasing $[\text{CO}_2]$ against observation-based stemwood growth rate in coastal British Columbia over the historical period, which is most relevant aspect of the model for this study. For the period 1959–1998, the model simulated a rate of increase of stemwood growth of 2.7% per year and the observed inventory-based rate of increase of stemwood growth [Hember et al., 2012] was found to be 3.0% per year in response to extrinsic factors of climate change and CO_2 fertilization. Other aspects of the simulated terrestrial carbon cycle, including gross primary productivity, maximum summer leaf area index, and vegetation biomass, have also been assessed by *Peng et al.* [2014] who found that these aspects compare reasonably with observation-based estimates.

3. Results

Figure 1a shows that the time series of province-wide infested area, derived from severity index as explained in the previous section, compares reasonably well with the observation-based estimate of infested area ($R^2 = 0.95$, root-mean-square error = $0.01 \times 10^6 \text{ km}^2$). The newly infested area has been decreasing in recent years as the MPB is invading new areas but at a diminishing rate. Figures 1b–1e display the spatial distribution of cumulative fraction of trees killed (K) due to the recent MPB outbreak for years 1999, 2003, 2007, and 2011 at 40 km resolution at which the model is implemented and show how the MPB spread through the interior of the province of BC over time.

Figure 2 quantifies the effect of the recent 1999–2011 MPB disturbance using results from the historical (1900–2005) and future (2006–2050) simulations for the three climate change scenarios (Representative Concentration Pathway (RCP) 2.6, 4.5, and 8.5) that are performed with and without the MPB disturbance. The results in Figure 2a show the modeled net atmosphere-land CO_2 flux for the RCP 4.5 scenario. The simulated net atmosphere-land CO_2 flux represents the model response to changing climate and increasing $[\text{CO}_2]$ and, when included, the MPB disturbance. Positive values of net atmosphere-land CO_2 flux indicate that

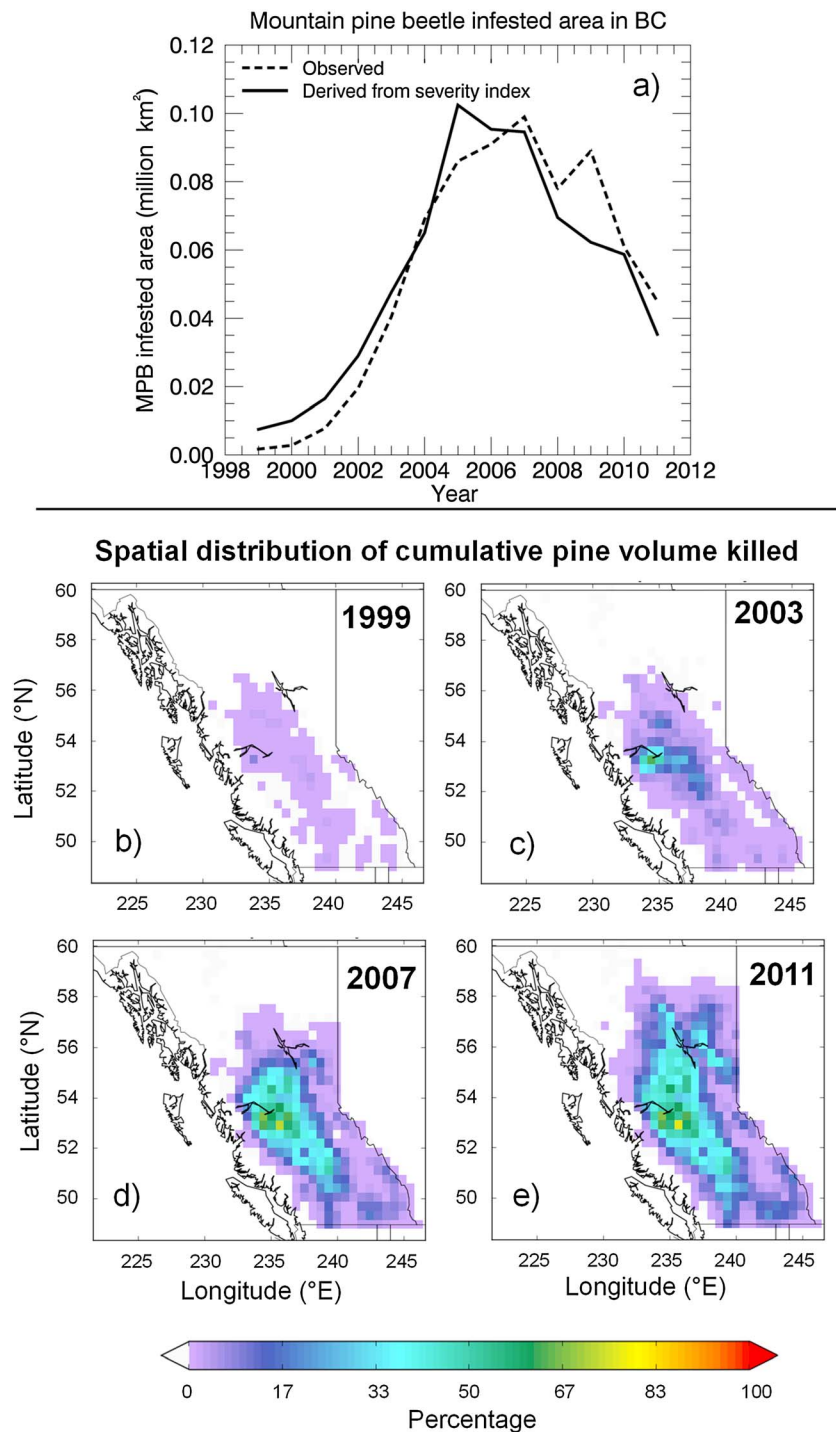


Figure 1. (a) Comparison of province-wide MPB infested area derived using severity index with the observation-based estimate [Westfall and Ebata, 2011] from British Columbia Ministry of Forests, Lands and Natural Resource Operations (BC MFLNRO). (b–e) The spatial distribution of the cumulative pine volume killed at the 40 km resolution of the CLASS-CTEM modeling framework for years 1999, 2003, 2007, and 2011, respectively.

carbon is being gained by land. The simulated net atmosphere-land CO₂ flux is lower in the simulation with the MPB disturbance after 1999 because of lower photosynthesis and higher heterotrophic respiratory losses. The strength of the sink over the 1990s and early 2000s is around 44 g C m⁻² yr⁻¹. The decrease in net atmosphere-land CO₂ flux after year 2000, even in the absence of the MPB disturbance, is due to

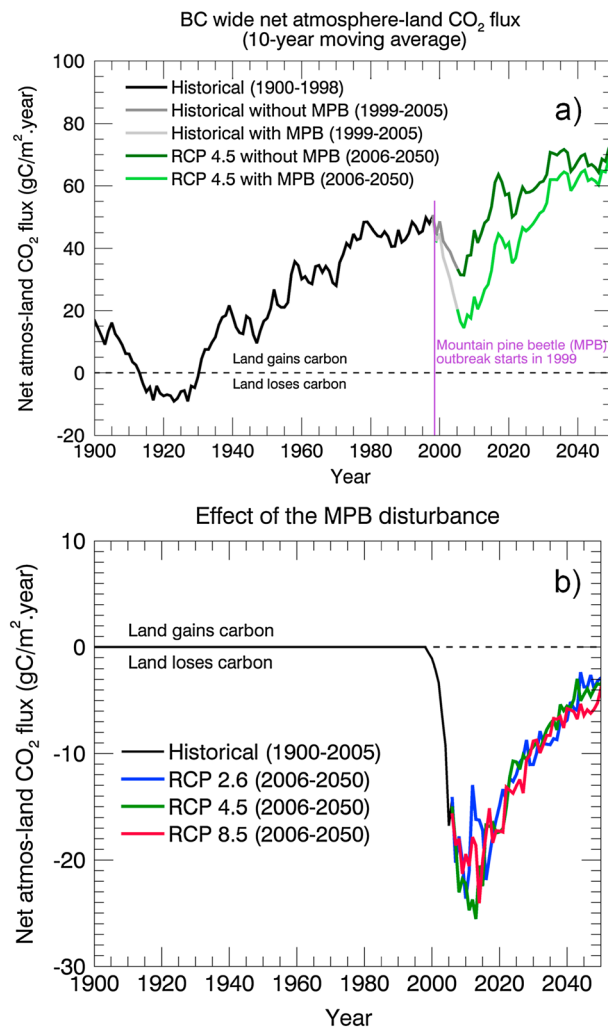


Figure 2. (a) Simulated net atmosphere-land CO₂ flux from the simulations with and without the 1999–2011 MPB disturbance for the historical (1900–2005) and future (2006–2050) periods when using the RCP 4.5 climate change scenario. (b) The calculated effect of the 1999–2011 MPB disturbance for RCP 4.5 but also RCP 2.6 and 8.5 scenarios. Negative values immediately following the start of the disturbance in 1999 indicate that the effect of the disturbance was to make land a source of carbon.

Figure S1). The period 1999–2020 is chosen for comparing the 328 Tg C estimate with *Kurz et al.* [2008a]. The cumulative reduced carbon uptake due to the MPB outbreak over the period 1999–2050 is 580 Tg C.

The effects of climate change and increasing [CO₂] are summarized in Figure 3a which shows the simulated net atmosphere-land CO₂ flux for the historical and future periods for the three climate change scenarios. These simulations include the effect of the MPB disturbance. The net province-wide averaged atmosphere-land CO₂ flux is simulated to return to its 1990s value in the 2030s, depending on the future scenario, and the province’s ecosystems are simulated to continue to take up carbon in response to increasing [CO₂] and a changing climate that gets warmer and wetter (future mean annual temperature and precipitation increase in all scenarios, see Figure S3 in the SI). In Figure 3a, differences in the scenarios emerge after 2040 and cumulative uptake is highest in the RCP 8.5 scenario and lowest in the RCP 2.6 scenario. The sink generated due to changing climate and increasing [CO₂], as reflected by positive values of the net atmosphere-land CO₂ flux in Figure 3a, is the result of a larger increase in net primary productivity than in heterotrophic respiration (see Figure S7 in the SI). The net result is an increase in total land carbon, consisting of carbon in the model’s vegetation, litter,

climate variability. The difference in the net atmosphere-land CO₂ flux between simulations with and without the MPB disturbance yields an estimate of the effect of the MPB disturbance (Figure 2b, the green line corresponds to the RCP 4.5 scenario). Figure 2b also shows the estimated effect of the MPB disturbance when the future simulations (with and without MPB disturbance) are driven with climate and [CO₂] corresponding to the RCP 2.6 and 8.5 scenarios. The estimate of the effect of the MPB disturbance is broadly insensitive to the future scenario chosen. These results indicate that at its peak in 2006, the MPB disturbance reduced the net atmosphere-land CO₂ flux averaged over the total province area by around 24 gC m⁻² yr⁻¹ or equivalently by 36 gC m⁻² yr⁻¹ over the treed area. The effect of the MPB since then has diminished as the rate of MPB-related tree mortality is declining and forests are recovering. This recovery is simulated to continue in the future. Regardless of the changing climate and increasing [CO₂], forests recover naturally from disturbances. Increasing precipitation and temperature associated with changing climate, and increasing [CO₂], imply that the rate of this recovery is higher than the rate if the forests were to recover in the absence of changing climate and increasing [CO₂]. The cumulative loss over the period 1999–2020 is around 326 gC m⁻² which yields a cumulative reduced carbon uptake of 328 Tg C when multiplied by the provincial area of 1,005,388 km² used in the model (see

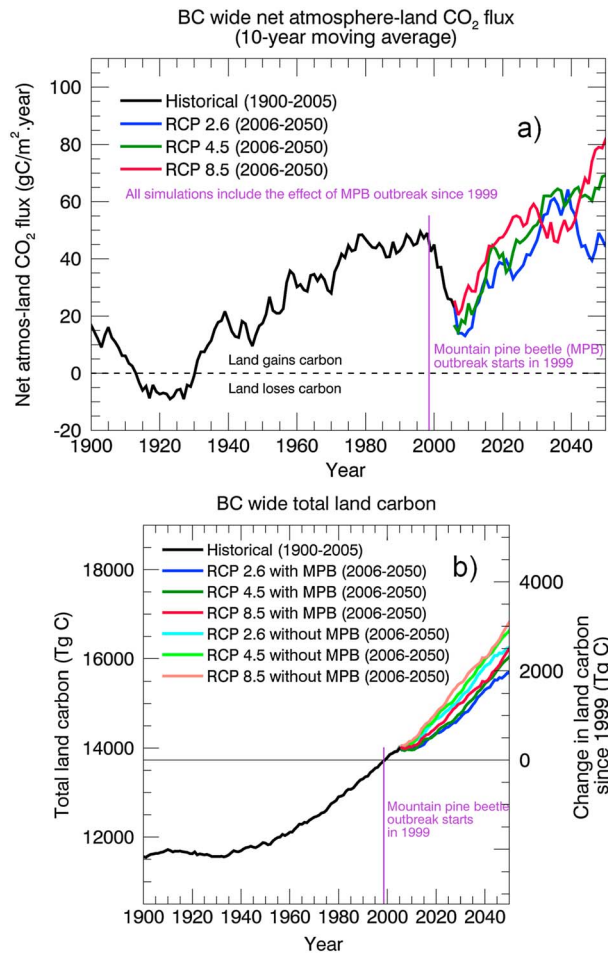


Figure 3. (a) Simulated net atmosphere-land CO₂ flux for the historical (1900–2005) and future (2006–2050) simulations for the three climate change scenarios (RCP 2.6, 4.5, and 8.5). All simulations include the effect of the 1999–2011 MPB disturbance. (b) The evolution of the total land carbon over the historical and future periods for the three climate change scenarios. Dark and light colored lines in Figure 3b correspond to simulations with and without the MPB disturbance.

by 2050 is equivalent to about 15% and 20% increase in diameter at breast height of trees in the RCP 2.6 and 8.5 scenarios, respectively, if vegetation height, stem density, and wood density do not change substantially. In Figure 3b, at 2050, the dark colored lines for each scenario that correspond to simulations with the MPB disturbance are about 580 TgC lower than the values corresponding to the simulations without the MPB disturbance (light colored lines), consistent with the 580 TgC cumulative effect of the MPB disturbance over the period 1999–2050, and due to the fact that net primary productivity is continually increasing (see Figure S7a).

Simulated area burned and fire related CO₂ emissions also increase over the 21st century. The observation-based area burned in the province of BC is small (~0.08% area burned annually over the period 1970–2010, http://nfdp.ccfm.org/data/compendium/html/comp_31e.html). The simulated area burned in the model for the same time period is higher (~0.28% burned annually) than the observation-based estimate which results in forest fire CO₂ emissions of ~0.8 TgC/yr. The simulated annual area burned and emissions, averaged across all scenarios, for the future 2030–2050 period increase to 0.47% and 1.8 TgC/yr, respectively, averaged across all scenarios. The cumulative increase in fire emissions, however, only contributes to a source of 32 TgC (over the 1999–2050 period). This is much less than the cumulative impact of the MPB disturbance and the response to climate change and increasing [CO₂].

and soil components, as shown in Figure 3b for simulations with and without the MPB disturbance. The change in total land carbon which is equivalent to cumulative atmosphere-land CO₂ flux, shown on the right hand side y axis of Figure 3b, ranges from an increase of about 900 TgC for the RCP 2.6 scenario to 1060 TgC for the RCP 8.5 scenario, for the period 1999–2020, in simulations without the MPB disturbance (light colored lines) indicating that the reduced carbon uptake by land due to the MPB disturbance of around 328 TgC is already surpassed by 2020. The cumulative carbon uptake in simulations with the MPB disturbance (dark colored lines) is consequently lower by 328 TgC (~570 TgC in RCP 2.6 scenario and ~730 TgC in RCP 8.5 scenario), for the period 1999–2020, because of the reduced carbon uptake associated with the MPB disturbance but still positive because of the larger effect of changing climate and increasing [CO₂].

For the period 1999–2050, the increase in total land carbon is around 2000 TgC for the RCP 2.6 scenario and about 2500 TgC for the RCP 8.5 scenario, in the simulation with MPB disturbance. Litter and soil carbon increase by about 750 TgC in all scenarios so the remaining 1250 TgC (RCP 2.6) to 1750 TgC (RCP 8.5) increase is due to increase in vegetation biomass (see Figure 4). This province-wide increase in vegetation biomass

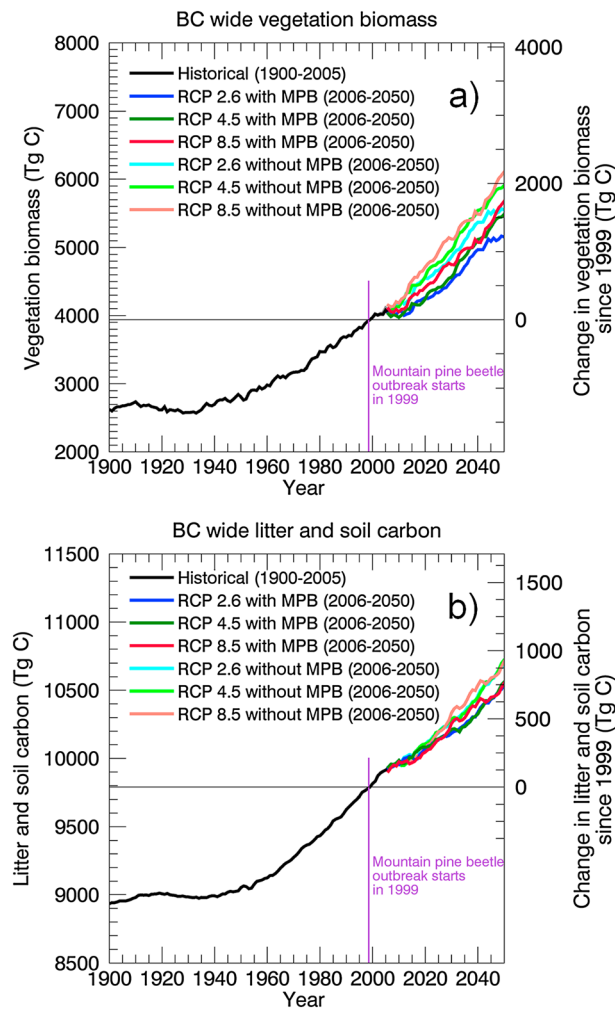


Figure 4. The evolution of the (a) vegetation carbon and (b) litter plus soil carbon over the historical and future periods for the three climate change scenarios. Dark- and light colored lines correspond to simulations with and without the MPB disturbance, respectively.

envelopes. The terrestrial ecosystem model used does not account for the age distribution of forest stands. The modeled response to climate change and increasing $[\text{CO}_2]$ is based on that of an average-aged tree in the landscape, without an explicit representation of self-thinning that would increase mortality as biomass increases. The average age of forests in BC is increasing, and so the reduction in tree growth due to increasing age counteracts the environmentally driven growth enhancement [Hember *et al.*, 2012]. Although CTEM includes a parameterization of down regulation of photosynthesis [Arora *et al.*, 2009], due to nutrient limitations, as $[\text{CO}_2]$ increases (based on results from plants grown in ambient and elevated CO_2 environments), it does not include an explicit coupling of terrestrial carbon and nitrogen cycles. Consideration of age class structure and an explicit coupling of terrestrial carbon and nitrogen cycles are both expected to reduce the simulated response to future climatic change and increasing CO_2 . Our modeling framework does not include the effect of wood harvest and other smaller insect disturbances that have occurred over the historical period, or any large future insect disturbances. Recent harvest-related transfers from the forest to harvested wood products are estimated to be around $18 \text{ g C m}^{-2} \text{ yr}^{-1}$ when averaged over the whole province (based on updated estimates from Stinson *et al.* [2011] from Natural Resources Canada, National Forest Carbon Monitoring, Accounting and Reporting System). Explicit modeling of harvest-related carbon transfers will change the absolute values of the model response to the MPB disturbance and changing climate and increasing $[\text{CO}_2]$. However, we do not expect inclusion of harvesting to substantially change the large response of the model

4. Discussion and Conclusions

Limitations remain in our study. First, we do not comprehensively assess the effect of uncertainty in model parameter values. Figure S5 characterizes how the uncertainty in the half-life of the stem component of the dead trees changes the diagnosed effect of the MPB disturbance. Similar sensitivity analyses for other model parameters, planned for future, will yield further insight into the associated uncertainty in so far as the objective is to determine the model response to the MPB disturbance versus the response to changing climate and increasing $[\text{CO}_2]$. Second, the model also suffers from structural uncertainty due to lack of representation of certain processes whose effect can only be assessed qualitatively. The model version used in our study does not dynamically simulate the fractional coverage of its PFTs. Studies that have used bioclimatic envelopes for projecting future distribution of tree species in BC [Hamann and Wang, 2006; Wang *et al.*, 2012] suggest that climate envelopes for relatively productive species that currently exist in coastal and mild-climate interior regions will expand over rest of BC at the expense of less productive subboreal, subalpine, and alpine ecosystems. The implications for the resulting carbon balance of these projected changes, however, are unclear since tree species do not migrate as quickly as the projected shifts in climate

to climate change and increasing atmospheric CO₂ relative to the MPB disturbance. Finally, had the model been driven with climate data from different ESMs, the results would have provided an estimate of uncertainty related to uncertainty in future climate projections. However, we do not expect the near-term results for the 1999–2020 period to be substantially different, when using climate data from different ESMs, because climate projections from ESMs remain fairly consistent across models as well as scenarios for the near-term period up until 2020 [e.g., see Collins *et al.*, 2013, Figure 12.5].

The response of the CLASS-CTEM modeling framework to changing climate and increasing CO₂, expressed in terms of stem wood growth rate, compares well with observation-based estimates in coastal BC [Peng *et al.*, 2014]. The magnitude of the simulated sink of around 44 g C m⁻² yr⁻¹ during the 1990s and early 2000s in Figure 3a is also comparable to an estimate based on atmospheric CO₂ inversion [Deng *et al.*, 2007] (38 ± 66 g C m⁻² yr⁻¹ for 2003). Our estimate of the cumulative effect of the MPB disturbance for the period 1999–2020 of 328 Tg C (based on Figure 2b) is also in broad agreement with an existing estimate of 270 Tg C from Kurz *et al.* [2008a]. The response of the CLASS-CTEM model to climate change and increasing [CO₂] and the recent MPB insect disturbance is thus consistent with observation-based and other estimates over the historical period. The extended simulations to 2050 then suggest that the enhanced carbon uptake by the forests of BC in response to increasingly warmer and wetter climate and gradually increasing [CO₂] more than compensates for the reduced carbon uptake associated with the recent MPB outbreak by 2020. The future carbon balance of the province's forests is, however, expected to be adversely affected by the likely increase in frequency of large insect disturbances associated with future warm winters which are known to increase winter survival of the bark beetles larvae [Bentz *et al.*, 2010]. The extent to which this and other factors not included in our simulations will modify future carbon balance of province's forests is subject of ongoing research, and therefore, the results obtained from application of the CLASS-CTEM model for future climatic and atmospheric CO₂ conditions must be interpreted in that context.

Acknowledgments

This research was made possible by funding from the Pacific Institute for Climate Solutions (PICS), which is hosted and led by the University of Victoria in collaboration with BC's three other research-intensive universities. We would like to thank the BC MFLNRO, Tim Ebata, and Adrian Walton for the MPB disturbance data and their help in interpreting these data. We would also like to thank the National Center for Environmental Prediction (NCEP), the Climate Research Unit, University of East Anglia, and Nicolas Viovy, whose work led to the CRUNCEP data set. We would also like to thank Juha Metsaranta and Bill Merryfield for their comments on an earlier version of this manuscript. We also acknowledge salary support from Environment Canada and Natural Resources Canada. Comments from two anonymous reviewers are also acknowledged which greatly helped to improve this manuscript. The data used to generate figures in the manuscript and supporting information can be obtained from the first author.

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