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Climate and atmospheric drivers of historical terrestrial carbon uptake in the province of British Columbia, Canada

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Abstract

The impacts of climate change and increasing atmospheric CO₂ concentration on the terrestrial uptake of carbon dioxide since 1900 in the Canadian province of British Columbia are estimated using the process-based Canadian Terrestrial Ecosystem Model (CTEM). Model simulations show that these two factors yield a carbon uptake of around 44 g C m⁻² yr⁻¹, during the 1980s and 1990s, and continuing into 2000s, compared to pre-industrial conditions. The increased carbon uptake translates into an increased sink of 41 Tg C yr⁻¹, when multiplied with the 944 700 km² area of the province. About three-quarters of the simulated sink enhancement in our study is attributed to changing climate, and the rest is attributed to increase in CO₂ concentration. The model response to changing climate and increasing CO₂ is corroborated by comparing simulated stem wood growth rates with ground-based measurements from inventory plots in coastal British Columbia. The simulated sink is not an estimate of the net carbon balance because the effect of harvesting and insect disturbances is not considered.

1 Introduction

Atmospheric carbon dioxide (CO₂) concentration is increasing due to emissions from anthropogenic use of fossil fuels and changes in land use. About half of the emitted anthropogenic carbon is taken up by land and ocean and this uptake has slowed the rate of increase of atmospheric CO₂ in response to anthropogenic emissions (Canadell et al., 2007; Le Quere et al., 2013). Over land, several lines of evidence indicate that carbon uptake is occurring in northern mid- to high-latitude regions (Ciais et al., 2010). This evidence includes: (1) flux towers measuring the land–atmosphere exchange of CO₂ typically over an area of a few square kilometers (e.g. Krishnan et al., 2008; Yuan et al., 2009), (2) inversion-based studies using atmospheric transport models in conjunction with observations of atmospheric CO₂ to infer the location of sinks and sources

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of carbon on the continental-scale (e.g. Deng et al., 2007; Deng and Chen, 2011; Gour-dji et al., 2012), (3) inventory based studies (Pan et al., 2011), and (4) modelling ap-proaches where terrestrial ecosystem models are driven with observed atmospheric CO₂ concentration and climate (e.g. Huntzinger et al., 2012). A combination of forest
5 inventory-based assessments and terrestrial ecosystem modelling has been used for assessing carbon uptake over land in Europe (Luyssaert et al., 2010) and Canada (Stinson et al., 2011).

The various approaches have their characteristic strengths and weaknesses. For ex-ample, the spatial coverage of flux towers is too small to infer regional or continental
10 scale land–atmosphere CO₂ exchange, although when used in conjunction with mete-orological data their measurement can be extrapolated to the global scale (e.g. Beer et al., 2010). In inversion-based studies the inferred carbon sink is a function of atmo-spheric transport of CO₂ and prior estimates of CO₂ fluxes and boundary conditions
15 (see e.g. Gourdjii et al., 2012). However, the inferred fluxes do provide useful infor-mation at continental scales. The inventory based estimates (e.g. Pan et al., 2011) are able to provide large-scale estimates of carbon sink and source distribution and are able to account for the age–class structure of forested landscapes and the strong, age-dependent impacts on net ecosystem production, but there are large differences
20 in available data, with data limitations especially for tropical regions. Finally, modelling approaches depend on assumptions made in the models and as a result these esti-mates vary from model to model even when driven with identical forcing. Huntzinger et al. (2012), for example, find that the simulated atmosphere-land CO₂ exchange over North America for the 2000–2005 period ranges from $-0.7 \text{ Pg C yr}^{-1}$ (a source) to 2.2 Pg C yr^{-1} (a sink) across nineteen terrestrial ecosystem models. Regional-scale
25 modelling studies fill in the spatial gap between the point scale flux tower measure-ments and large continental-scale inversion-based studies. Models typically provide results at higher spatial resolution than inversion-based studies. In the end, these var-ious approaches are complementary, and together provide knowledge that helps re-

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duce the overall uncertainties in regional to global scale estimates of terrestrial carbon uptake.

Here we use the process-based Canadian Terrestrial Ecosystem Model (CTEM) coupled to the Canadian Land Surface Scheme (CLASS) to simulate the terrestrial carbon budget over the province of British Columbia (BC) in Canada from 1900–2010. Our primary objective is to estimate the magnitude of the terrestrial carbon sink response to changes in climate and increasing atmospheric CO₂ concentration, which stimulates plant growth through increased photosynthesis rates (i.e. the CO₂ fertilization effect). To our knowledge this is the first such assessment for British Columbia using a process-based terrestrial ecosystem model, although such models have been employed in the past at the global (Ahlström et al., 2013), continental (e.g. Huntzinger et al., 2012; Zhang et al., 2012) and regional scales (e.g. McGuire et al., 2010).

Estimates of the carbon budget in BC forests from 1920–1989 have been previously obtained using version 2 of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) (Kurz et al., 1996), while estimates for managed forests, including those in BC, from 1990–2008 have been obtained using an updated version (CBM-CFS3, Kurz et al., 2009) of this inventory-based model (Stinson et al., 2011). Tree growth in the CBM family of models, however, only implicitly accounts for changes due to the CO₂ fertilization effect and the impacts of climate change which are inferred empirically from past tree growth (Hember et al., 2012) as reflected in empirical yield curves. The process-based model used here, on the other hand, models ecosystem response of all plant functional types (PFTs), including trees, and explicitly accounts for changes in ecosystem processes due to CO₂ fertilization and climate change.

In Sect. 2 we describe the modelling framework used in this study including the model subcomponents and the forcing data sets. Our main results are presented in Sect. 3. Finally, our results are discussed more broadly in Sect. 4 and a summary of our main conclusions is provided in Sect. 5.

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2 Model and data description

2.1 Process-based terrestrial ecosystem model

The process-based terrestrial ecosystem model used in our study is CTEM (Arora and Boer, 2005a, b), the interactive vegetation component of the Canadian Centre for Climate Modelling and Analysis (CCCma) Earth System Model (CanESM2; Arora et al., 2011), which is coupled to version 3.5 of CLASS, the physical land surface component of CanESM2 (Verseghy, 1991; Verseghy et al., 1993). The coupled system is driven with half-hourly meteorological data to simulate the physical (including soil moisture, soil temperature and snow) and biogeochemical (including vegetation biomass and soil carbon) states of the land surface. The primary terrestrial ecosystem processes that are modelled in CTEM for this study are photosynthesis, autotrophic and heterotrophic respiration, allocation, phenology, turnover of leaves, stem and root, and fire. CTEM simulates vegetation growth and calculates time-varying carbon storage in three live vegetation pools (leaves, stems and roots) and two dead carbon pools (litter and soil organic matter). When coupled with CLASS, CTEM estimates canopy conductance which is then used for energy and water balance calculations in CLASS. A single-leaf photosynthesis approach is used with coupling between photosynthesis and canopy conductance based on vapor pressure deficit (Leuning, 1995). Photosynthesis and leaf maintenance respiration calculations are performed half hourly, while other biogeochemical processes are simulated at a daily time step. While CTEM simulates fire, the effects of forest harvesting and insect disturbances are not modelled.

In CTEM's standard configuration, used in CanESM2 for global application, nine plant functional types (PFTs) are considered. However, in this study, an additional needle leaf evergreen PFT is considered for simulating terrestrial ecosystem processes more realistically for the province of BC and this is briefly discussed in Sect. 3.1. The land surface scheme in CLASS employs the mosaic approach to account for sub-grid variation in vegetation types (Li and Arora, 2012) with each grid cell represented by a number of mosaic tiles depending on the PFTs present in a given grid cell. Biophys-

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ical energy, water balance and biogeochemical carbon balance calculations are performed over each mosaic tile and the results are weighted by the areal fraction of each PFT to yield a grid cell mean value. There is no representation of age-class or time since disturbance for the PFTs and all terrestrial ecosystem processes are modelled for an average aged tree in the landscape.

The net atmosphere-to-land CO₂ flux F_L (TgC yr⁻¹) in CTEM is modelled as

$$\begin{aligned}
 F_L &= \frac{dH_L}{dt} = \frac{dH_V}{dt} + \frac{dH_S}{dt} \\
 &= (G - R_A) - R_H \\
 &= N - R_H
 \end{aligned}
 \tag{1}$$

where $H_L = H_V + H_S$ is the total terrestrial carbon stock (TgC) which is made up of live vegetation biomass in leaves, stem and root carbon pools (H_V) and dead carbon in soil and litter pools (H_S). N is the terrestrial net primary productivity obtained as the difference between gross primary productivity (G) and autotrophic respiration (R_A), and R_H is the heterotrophic respiration. The time integrated version of Eq. (1) relates the change in total land carbon ΔH_L to the cumulative atmosphere-to-land CO₂ flux (\tilde{F}_L) as

$$\Delta H_L = \Delta H_V + \Delta H_S = \tilde{F}_L = \int_{t_0}^t F_L dt = \int_{t_0}^t N dt - \int_{t_0}^t R_H dt
 \tag{2}$$

Simulated F_L is thus equivalent to net ecosystem production (NEP) and does not include carbon sources from harvest (F_H) and insect disturbance (F_D). Harvesting typically includes removal of timber while any residual slash decomposes over time so harvesting also affects R_H . When estimates of F_H and F_D are available, net biome productivity F'_L (NBP) can be estimated as

$$F'_L \approx F_L - F_H - F_D
 \tag{3}$$

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2.2 Soil, vegetation and climate data

Soil depth, soil sand and clay content, and areal fraction of each PFT are based on data obtained from the Pacific Climate Impacts Consortium (PCIC), and are available at 1/16th degree resolution (Schnorbus et al., 2011). Soil types were derived from the the Global Soil Data Products (GSDT 2000), which is built from the global pedon-database produced by the International Soil Reference and Information Centre (ISRIC) (Batjes, 1995) and the FAO-UNESCO Digital Soil Map of the World (DSMW) (FAO 1995). Three soil layers are considered with the depth of the first and second layers uniform across the study area at 0.1 m and 0.25 m, respectively; the depth of the third layer depends on elevation and slope (Schnorbus et al., 2011). Fractional vegetation cover for each PFT in each grid cell was based on 25 m resolution land cover dataset from the Canadian Forest Services Earth Observation for Sustainable Development of Forests dataset (EOSD) (Wulder et al., 2003). Missing data in the EOSD dataset were filled using the University of Maryland's Advanced Very High Resolution Radiometer (AVHRR)-based Global Land Cover Classification dataset (<http://glcf.umd.edu/data/landcover/data.shtml>). Soil and vegetation data were interpolated to the spatial resolution of about 0.35° latitude \times 0.61° longitude used in this study, which is equivalent to about 40 km \times 40 km.

The primary PFTs that exist in BC are needle leaf evergreen trees, broadleaf cold deciduous trees and C_3 grasses (see Table 1). A small fraction of the province is also covered with crops but these were treated as C_3 grasses. Figure 1 shows the spatial distribution of the fractional vegetation cover of these three PFTs and the total fractional vegetation cover. At the ~ 40 km resolution used here, some grid cells at province's boundary lie partially outside its borders (see Fig. 1). As a result the area of the province used in the model is 1 005 388 km², or about 6 % higher than the actual area of 944 700 km².

Climate data to drive our model were obtained from the CRUNCEP dataset (1901–2010), which is based on the National Centre for Environmental Prediction (NCEP) re-

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analysis (Kanamitsu et al., 2002) with monthly means adjusted to match the Climate Research Unit (CRU) observations. The CRUNCEP data (surface temperature, pressure, precipitation, wind, specific humidity, shortwave and longwave radiation fluxes) are available at a resolution of 0.5° and at a six hourly time interval (http://nacp.ornl.gov/thredds/fileServer/reccapDriver/cru_ncep/analysis/readme.htm). Data were extracted for BC and spatially interpolated to the $40\text{ km} \times 40\text{ km}$ grid used in this study. The data were disaggregated to half-hourly resolution following the approach of Arora and Boer (2005a). Temperature, longwave radiation, wind speed, specific humidity, and pressure were linearly interpolated in time; short-wave radiation was assumed to change with solar zenith angle with a maximum value at the local solar noon; precipitation was disaggregated using the six-hourly precipitation amount to estimate the number of wet half hours, and total 6 hourly precipitation amount was assumed to be randomly distributed over the wet half hours.

Figure 2 shows the trends in BC province-wide averaged climate variables in the CRUNCEP data that are used to drive CLASS and CTEM. The values for pressure, wind speed and longwave radiation are unavailable from 1901 to around 1940 in the CRUNCEP data over the BC region. Over the 1901–2010 period, all province-wide averaged climate variables show positive trends, except radiation. The province-wide averaged temperature has increased by about 1.0°C . The province-wide averaged precipitation shows a weak positive trend of 4.4 % increase over the 1901–2009 period. The CRUNCEP data, however, has limitations. In particular, the weak positive trend in precipitation over BC is inconsistent with the analysis of station-based data by Mekis and Vincent (2011) who find that most of the stations in the province of BC show large positive trends in precipitation over the period 1950–2009, especially in the southern part of the province. The implications of this limitation in the CRUNCEP data are discussed later.

2.3 Simulations

We used 1901 to 1940 meteorological data repeatedly and the 1860 CO₂ concentration value of 286 ppm to spin up and bring the model's carbon pools into equilibrium. We refer to this as our pre-industrial simulation. Transient historical simulations were then performed from 1861 to 2010 driven with atmospheric CO₂ increasing from 286 ppm in 1860 to 389 ppm in 2010. For the period 1861–1900 we used 1901 to 1940 climate to drive the CLASS and CTEM models, and for the period 1901–2010 we used the actual climate data. Three transient historical simulations were performed that are driven with: (1) increasing atmospheric CO₂ but with 1901–1940 climatology (the CO₂ simulation), (2) changing climate but with fixed pre-industrial CO₂ of 286 ppm (the CLIM simulation) and (3) increasing atmospheric CO₂ and changing climate (the CLIM+CO₂ simulation). These three simulations allow estimation of the separate contributions of CO₂ fertilization and climate change to the terrestrial uptake of carbon in BC. With a constant climate and atmospheric CO₂ concentration, terrestrial C stocks would remain unchanged from their equilibrium state. Therefore that any change away from the equilibrium carbon pools is attributable to changing atmospheric CO₂ concentration, changing climate or the combination of the two. In essence, the G , R_A and R_H terms in Eq. (1) respond to changes in climate and atmospheric CO₂ concentration resulting in a positive or negative F_L (i.e., a land carbon sink or a source) with associated changes in H_V and H_S pools.

Most of BC is covered with coniferous, needle leaf, evergreen trees. However, tree species in the interior region, which experience colder winters and drier summers than those in much of the coastal region, are known to be more cold and drought tolerant compared to those in the coastal region. In its standard configuration used in CanESM2 for global application, CTEM considers nine PFTs (Table 1) which include one needle leaf evergreen PFT. However, for application over BC at a spatial resolution of 40 km we found that while CTEM's single needle leaf evergreen PFT yields reasonable LAI and gross primary productivity (GPP) in the coastal region compared to observation-based

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estimates, it yields unrealistically low LAI and vegetation biomass in the interior of the province (see Appendix). For the purposes of this modelling study, and as explained in the Appendix, we therefore make the first order distinction based on climate and split CTEM's default needle leaf evergreen PFT into coastal and interior types. The coastal type retains the default parameter values of CTEM's needle leaf evergreen PFT. For the interior needle leaf evergreen PFT, we assume lower rates of leaf loss from cold and drought in the phenology parameterization of CTEM (Arora and Boer, 2005a) and assume a longer leaf life span following Reich et al. (1995) (see Appendix).

3 Results

3.1 Comparison with observations

Simulation results obtained by including the two needle leaf evergreen PFTs are shown in Fig. 3 and Table 2 which compare simulated leaf area index (LAI) and gross primary productivity (GPP) to observation-based estimates. The observation-based estimates of LAI are based on remotely-sensed data from Deng et al. (2006) averaged over the 2000–2005 period. The observation-based estimate of GPP is from Beer et al. (2010) who analyze the ground-based carbon flux tower observations from about 250 stations and apply diagnostic models to extrapolate them to the global scale. This GPP estimate corresponds to the period 1998–2005. Being a global product, the GPP estimates from Beer et al. (2010) cannot represent the detailed spatial patterns for the province of BC but nevertheless provide an observation-based estimate. Compared to the simulation with CTEM's default single needle leaf evergreen PFT (see Fig. A1 in the Appendix), the simulation using two needle leaf evergreen PFTs (coastal and interior) increases both LAI and GPP in the interior of the province and yields better agreement with the observation-based estimates. Limitations still remain, however, and in particular simulated LAI is lower in southern British Columbia. This is either because of biases in the CRUNCEP data or the inability of CTEM to simulate vegetation realistically with

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just two needle leaf evergreen PFTs. A discussion of the challenge associated with parameterizing CTEM at the species level is presented in the Appendix. Nevertheless, the simulation with two needle leaf evergreen PFTs yields a province-wide averaged GPP of $618 \text{ gC m}^{-2} \text{ yr}^{-1}$ (1998–2005 average) and province-wide areally averaged LAI of $2.3 \text{ m}^{-2} \text{ m}^{-2}$ consistent with the observation-based estimates of $597 \text{ gC m}^{-2} \text{ yr}^{-1}$ for GPP (Beer et al., 2010) and of $2.5 \text{ m}^{-2} \text{ m}^{-2}$ for LAI (Deng et al., 2006), respectively (See Table 2).

Figure 4 shows the distribution of simulated live (vegetation) and dead (litter and soil carbon) pools from the simulation with two needle leaf evergreen PFTs. The spatial distribution of the vegetation biomass is similar to that for LAI, as expected. The spatial distribution of litter and soil carbon is somewhat different from that of vegetation biomass, with higher values towards the northern part of the province despite low vegetation density in the north. Colder climates yield lower litter and soil carbon decomposition rates and hence larger pool sizes.

Table 2 also compares the simulated total carbon pools and areally-averaged carbon fluxes averaged over 1998–2005 with available observation-based estimates. Simulated vegetation biomass is compared with three observation-based estimates in Table 2. The first observation-based vegetation biomass estimate for BC is based on a global dataset of vegetation carbon stocks in year 2000 and uses a range of spatially-explicit climate and vegetation datasets to map vegetation biomass values (Ruesch and Gibbs, 2008). This estimate yields a province-wide total vegetation biomass of 1980 TgC , while model simulation with two needle leaf evergreen PFTs yields a BC-wide vegetation biomass of 3877 TgC , almost double their estimate. The second observation-based estimate of vegetation biomass is for commercial forests in BC (Penner et al., 1997) and reports an above-ground vegetation biomass density of 15.8 kg m^{-2} for government managed forests, which we convert to carbon density (7.9 kg C m^{-2}) by multiplying by 0.5 (Lamlom and Savidge, 2003; Sarmiento et al., 2005; Fonseca et al., 2011). The third observation-based estimate is derived from Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS)

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area burned annually. Over the same duration CTEM simulates higher annual burn fraction of 0.28 %. The simulated annual burnt area and emissions ($\sim 0.8 \text{ TgCyr}^{-1}$) do not show any significant trend over the 1901–2009 period and therefore do not affect the simulated sink of 40 TgCyr^{-1} . Figure 5b shows forest-only net atmosphere-land

5 CO_2 flux for forest regions in BC from the CLIM+CO₂ simulation. The averaged forest net atmosphere-land CO_2 flux over 1990–2010 period is $63 \text{ gCm}^{-2} \text{ yr}^{-1}$ and averaged forest net primary productivity (NPP) is $355 \text{ gCm}^{-2} \text{ yr}^{-1}$ (Fig. 7b) which is lower than the NFCMARS-derived estimate of $447 \text{ gCm}^{-2} \text{ yr}^{-1}$ (updated after Stinson et al., 2011 for the period 1990 to 2011).

10 The spatial distribution of model simulated sink in response to changing climate and increasing CO_2 is shown in Fig. 6. The values peak over the centre of the province and over Vancouver Island. As expected, the sink occurs over areas with vegetation (see spatial distribution of LAI and GPP in Fig. 3). The average sink enhancement, in response to climate change and increasing CO_2 , of around $45 \text{ gCm}^{-2} \text{ yr}^{-1}$ for 1990–2005

15 may also be compared with the European carbon sink of $75 \pm 20 \text{ gCm}^{-2} \text{ yr}^{-1}$ estimated by Luysaert et al., (2010) over the same time period, given that both are located in the temperate mid- to high-latitude region. Of the cumulative realized sink of 2185 Pg C in the CLIM+CO₂ simulation, over the 1860–2000 period, about 63 % (1366 Pg C) is allocated to the vegetation pool (ΔH_V) and about 37 % (819 Pg C) to the litter and soil carbon pools (ΔH_S). Our distribution of the simulated sink into live (vegetation) and dead (litter and soil carbon) pools (63 % and 37 %, respectively) is comparable to estimates of $71 \pm 15 \%$ (woody biomass) and $29 \pm 15 \%$ (soil carbon) from Luysaert et al. (2010) for Europe.

4 Discussion

25 Is the simulated response to changing climate and increasing atmospheric CO_2 concentration in our study realistic? Here we attempt to answer this by comparing our simulated stemwood growth to ground-based measurements. Hember et al. (2012)

analyze data from 1267 permanent inventory plots from throughout coastal British Columbia between 1950 and 2002 that were installed by the British Columbia Ministry of Forests, Lands and Natural Resource Operations (BC MFLNRO). Measurements were made periodically over five or ten year intervals, allowing for analysis of multi-annual and decadal variability. They find overall stem wood growth rate enhancements from 1958 to 1998 with declines during drought episodes in the mid-1960s and 1980s (their Fig. 7a). The Hember et al. (2012) data supported their hypothesis that the overall positive trends in stemwood growth rate were likely driven by long-term enhancement in NPP due to climate and atmospheric CO₂ forcing. We calculate stem wood growth averaged over coastal BC (essentially the grid cells with the coastal needle leaf evergreen PFT) using NPP allocated to the stem component in CTEM. Despite the inexact match in spatial coverage between estimates, CTEM projections (black and blue lines in Fig. 7a) of multi-annual variability in stem growth are consistent with the observation-based estimate (green line in Fig. 7a). The inventory-based data reflect the aggregation of periodic (5 or 10 yr interval) measurements and therefore only represent variability on time scales exceeding the average interval length so the comparison is based on the 6 yr moving average CTEM values. The comparison of observation-based and simulated stem wood growth rate is therefore not completely consistent but nevertheless provides a valuable means of validating model simulations at this spatial and temporal scale. Observation-based data show average stem wood growth rate of 3.45 MgC ha⁻¹ yr⁻¹ over the period 1959–1998 and an average rate of increase of 1.5% per year (green line in Fig. 7a). The simulated stem wood growth averages 2.8 MgC ha⁻¹ yr⁻¹ and increases at a rate of 2.7% per year (blue line in Fig. 7a). One possible reason for higher observation-based average value is that the inventory data reflect productive forest sites while no such distinction is made in CTEM which represents average over the forested fraction in a grid cell. It is also possible that the allocation to stemwood in CTEM is low. Both observation-based and simulated data show decline in stemwood growth rate during mid-1960s. During the 1980s, while the observation-based data show a decline, the simulated values show no trend. After

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1990, both observation-based and simulated values show an increasing trend in stem wood growth rate. The simulated increase in stem wood growth in coastal and interior (not shown) regions is associated with an increasing trend in simulated NPP which is shown in Fig. 7b. Despite inconsistencies in the observation-based and simulated stem wood growth, the comparison does highlight that the model captures the broad-scale increase in stem wood growth rate and the decadal trends over the 1959–1998 period that were observed in the forest inventory plots.

There are at least two caveats associated with our results. The first is that CTEM does not take into account age–class distribution of trees and the modelled response to changes in climate and CO₂ concentration is that of a tree of an average age in the landscape. In the real world, of course, ecosystems are always recovering from disturbances and at the landscape scale there are trees of different ages. Hember et al. (2012) attempts to distinguish between the intrinsic (species composition, soil fertility and age–class) and extrinsic (CO₂ fertilization and climate change) factors on stemwood growth. They use regression models to separate out the intrinsic factors (their Fig. 7b). In the province of BC, the forest inventory is being affected by increasing average stand age and this counteracts the environmentally-driven growth enhancement. Indeed when the effect of intrinsic factors is removed the resulting rate of increase of stemwood growth attributed to extrinsic factors is 3.0% (red line in Fig. 7b), bringing it into closer agreement with CTEM simulated rate of increase of stemwood growth of 2.7%.

The second caveat is that CTEM does not model harvesting of wood and insect disturbances. Our BC-wide estimate of sink of 44 gC m⁻² yr⁻¹ over the 1980s, 1990s and 2000s (or equivalently 63 gC m⁻² yr⁻¹ over the forested area) is the response of BC's terrestrial ecosystems to changing climate and increasing CO₂ from the atmosphere's perspective. However, from a greenhouse gas accounting perspective, where the harvested wood is removed from the forests, the carbon source generated by harvesting also needs to be taken into account. The carbon source from harvesting may not be generated in the province of BC itself since most forest products are exported. In the

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absence of such an estimate in our study we use an estimate of harvest related losses from Stinson et al., (2011) who estimate the carbon budget over Canada's forests using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). If we use an estimate of harvest losses of $30 \text{ gC m}^{-2} \text{ yr}^{-1}$ averaged over the period 1990–2011 and over BC forests (updated after Stinson et al., 2011), and assuming that harvesting shows little interannual variability (see Fig. 6 of Stinson et al., 2011), the resulting sink of $33 \text{ gC m}^{-2} \text{ yr}^{-1}$ ($63 - 30 = 33 \text{ gC m}^{-2} \text{ yr}^{-1}$) is achieved over BC forests.

Insect disturbances cause foliage loss and/or tree mortality and lead to reduced carbon uptake and increased loss due to tree mortality from forest ecosystem during outbreak periods (Kurz et al., 2008). For the peak years of the mountain pine beetle outbreak in BC, the reduction in carbon uptake due to tree mortality and the increase in R_H from beetle-killed trees lowered the annual carbon sink by 20 TgC yr^{-1} (Kurz et al., 2008, their Fig. 4), which translates to a source of $30 \text{ gC m}^{-2} \text{ yr}^{-1}$ when divided by the $663\,981 \text{ km}^2$ forest area in our simulation. Adjusting our estimate further with an estimated mountain pine beetle impact of $30 \text{ gC m}^{-2} \text{ yr}^{-1}$ when averaged over the province's forests, reduces the simulated sink to $3 \text{ gC m}^{-2} \text{ yr}^{-1}$ for the peak outbreak years.

Carbon budget assessments for forests routinely take into account harvesting, insect and fire disturbance losses. These assessments are, however, based on models that simulate tree growth using empirical yield curves; for example, the CBM-CFS family of models (Kurz et al., 2009) that is used by the Canadian Forest Service (Stinson et al., 2011 and references therein). Tree growth in the CBM-CFS models does not explicitly account for changes in tree growth due to changes in climate and CO_2 fertilization. The effect of these processes is included in so far as these processes have affected past tree growth and their effect is reflected in empirical yield curves. Our results suggest that changing climate and increasing CO_2 have both contributed to an increased carbon sink for the province of BC and inclusion of these processes in forest carbon budget assessments will lead to higher estimates of carbon uptake.

5 Summary and conclusions

Several lines of observation- and modelling-based studies suggest that the mid- to high-latitude ecosystems are currently a sink of carbon. Here, we have used a process-based terrestrial ecosystem model to simulate the response of terrestrial ecosystems in the province of British Columbia (BC), Canada to changing climate and increasing CO₂ over the historical 1860–2010 period. Our results suggest that these two forcings have resulted in an enhancement of BC's terrestrial ecosystems sink of carbon, relative to pre-industrial conditions, of around 44 g C m⁻² yr⁻¹ (or 63 g C m⁻² yr⁻¹ over BC's forests) during the 1980s, 1990s and 2000s. About three-quarters of the simulated sink enhancement over BC in our study is attributed to changing climate, and the rest is attributed to increase in CO₂ concentration. However, there are limitations in the driving CRUNCEP climate data and in particular it does not show a large positive precipitation trend over BC, like the station-based data. Photosynthesis at high latitudes is generally not soil moisture limited except during the peak summer months. Had the CRUNCEP data exhibited a large positive trend in precipitation, we expect the simulated sink to be somewhat stronger.

To assess if the simulated response to changing climate and increasing CO₂ in our study is realistic we have compared the simulated stemwood growth to observation-based inventory estimates from Hember et al. (2012). Our rate of increase of stemwood growth of 2.7 % over the 1959–1998 period compares well with the observation-based estimate of 3.0 % from Hember et al. (2012) when the effect of intrinsic factors (including age-class, soil fertility and species composition) is accounted for. This comparison corroborates the combined model response to changing climate and increasing CO₂. However, our average stemwood growth for all forests for coastal BC in our simulations is 2.8 Mg C ha⁻¹ yr⁻¹ is lower than Hember et al. (2012) value of 3.45 Mg C ha⁻¹ yr⁻¹. The higher values from Hember et al. (2012) are expected since they correspond to productive sites and the simulated values are for all forests since no distinction is made between productive and non-productive forests at the 40 km resolution of the model.

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Alternatively, lower simulated values may also reflect lower allocation of NPP to stem in the model. Higher values of NPP allocation to stem in the model, however, would imply even a stronger apparent increase in stem growth rates than we currently simulate.

The model validation against stemwood growth rates from inventory plots provides confidence in the simulated response of province's ecosystems to changing climate and increasing atmospheric CO₂ concentration. This validation also provides the ground work required to use our modelling framework for investigating the response of province's terrestrial ecosystems to future changes in climate and atmospheric CO₂ concentration.

The per unit area sink enhancement estimate of 44 gCm⁻²yr⁻¹ translates to an amount of 41 TgCyr⁻¹, when multiplied with the 944 700 km² area of the province. When harvest losses (30 gCm⁻²yr⁻¹ multiplied by BC forest area of about 650 000 km² equals ~ 20 TgCyr⁻¹) are taken into account then from a greenhouse gas accounting perspective the 41 TgCyr⁻¹ sink reduces to about 21 TgCyr⁻¹ if it is assumed that all of the harvested biomass, which is transferred out of the forest, oxidises instantaneously. Although, of course, only some of the emissions will occur in the province, and the remainder in countries to which forest products are exported. Losses from burning or decay of post-harvest residues and from the recent mountain pine beetle infestation will further reduce the sink estimate after 2001.

The estimated sink enhancement of 63 gCm⁻²yr⁻¹ over BC forests suggests that current estimates of the net forest carbon balance of the province, based on empirical yield curves, may be underestimated because they do not fully account for the growth enhancements due to changes in climate and increase in atmospheric CO₂ concentration.

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Dynamic global vegetation models (DGVMs) typically use vegetation classification based on the PFT concept and species-level differences are not considered. The PFT concept has emerged from the school of thought that suggests vegetation classification with a combined ecological and biophysical focus is possible in relation to a plant's form and the manner in which it interacts with its environment (Box, 1996). CTEM's use of a single needle leaf evergreen PFT works reasonably well at the global scale (e.g. Arora et al., 2009) in an Earth system model framework where grid resolutions are typically 200–300 km. However, for application over BC at a spatial resolution of ~ 40 km, we found that while this single needle leaf evergreen PFT yields reasonable LAI and gross primary productivity (GPP) in the coastal region compared to observation-based estimates, it yields unrealistically low LAI and vegetation biomass in the interior of BC (left panels in Fig. A1 compared to right panels in Fig. 3). The observation-based estimates of LAI are based on remotely-sensed data from Deng et al. (2006) averaged over the 2000–2005 period which are shown in Fig. 3. Similarly, in the lower row of Fig. A1, simulated GPP is lower than the observation-based GPP estimates (lower right panel in Fig. 3), averaged over the period 1998–2005, that is obtained from the global product of Beer et al. (2010). Model results for the single needle leaf PFT simulation are averaged over the same periods. Comparison of GPP estimates for the single needle leaf evergreen PFT case shows that representing needle leaf evergreen trees with a single PFT for the province of BC yields too low LAI and GPP in the interior (see Fig. A1 bottom left panel and Table 2). As a result, the simulated province-wide averaged GPP of $398 \text{ gC m}^{-2} \text{ yr}^{-1}$ for the period 1998–2005 is low compared to the observation-based estimate of $597 \text{ gC m}^{-2} \text{ yr}^{-1}$ based on Beer et al. (2010) shown in Fig. 3. In Table 2, province-wide areally averaged summer maximum LAI of $1.4 \text{ m}^{-2} \text{ m}^{-2}$ for the single needle leaf evergreen PFT case is also low compared to observation-based estimate of $2.5 \text{ m}^{-2} \text{ m}^{-2}$ from Deng et al. (2006).

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The BC Ministry of Forests, Lands and Natural Resource Operations (BC MFLNRO) divides the province into 16 biogeoclimatic zones characterized mainly by the climate and the species of conifers predominating. Coastal BC is occupied primarily by western hemlock, western red cedar and coastal Douglas fir while other needle leaf evergreen species (primarily pines, spruces, and subalpine fir, but also interior Douglas fir, western hemlock and western red cedar) occupy the interior of the province (BC Ministry of Forests and Range, 2008). Being a DGVM, CTEM does not represent the level of detail necessary to parameterize species-level differences, nor are there data easily available which may be used to estimate CTEM parameter values that would reflect species-level differences. For this modelling study, therefore, we make the first order distinction based on climate and split CTEM's default needle leaf evergreen PFT into coastal and interior types. The coastal type retains the default parameter values of CTEM's needle leaf evergreen PFT. For the interior needle leaf evergreen PFT, we assume lower rates of leaf loss from cold and drought in the phenology parameterization of CTEM (Arora and Boer, 2005a), consistent with colder and drier climate in the interior of the province to which the interior trees are adapted. In addition, we assume a longer leaf life span for the interior type following Reich et al. (1995) who suggest that greater conifer leaf longevity in colder environments is associated with thicker leaf cuticles and other structural modifications to minimize winter dessication. Following the BC MFLNRO's biogeoclimatic zones, we assign the coniferous forests west of the coastal mountains as CTEM's coastal needle leaf evergreen PFT and those to the east of the coastal mountains as interior needle leaf evergreen PFT.

In Fig. A1, LAI and GPP simulated for the two needle leaf evergreen PFTs simulation yield higher LAI and GPP in the interior of the province than the simulation with CTEM's default needle leaf evergreen PFT and better comparison with observation based estimates (Fig. 3).

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Table 1. Plant functional types (PFTs) for which terrestrial ecosystem processes are modelled by CTEM in its default configuration at the global scale and for this study. CTEM PFTs that are present in the province of BC (see Fig. 1) are shown in *italic*.

CTEM PFTs when applied at the global scale	CTEM PFTs in this study
1 Needle leaf Evergreen	1 <i>Coastal Needle Leaf Evergreen</i>
2 Needle leaf Deciduous	2 <i>Interior Needle Leaf Evergreen</i>
3 Broadleaf Evergreen	3 Needle leaf Deciduous
4 Broadleaf Deciduous Cold	4 Broadleaf Evergreen
5 Broadleaf Deciduous Dry	5 <i>Broadleaf Deciduous Cold</i>
6 C ₃ Crop	6 Broadleaf Deciduous Dry
7 C ₄ Crop	7 C ₃ Crop
8 C ₃ Grass	8 C ₄ Crop
9 C ₄ Grass	9 C ₃ <i>Grass</i>
	10 C ₄ Grass

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Table 2. Comparison of British Columbia total carbon pools and averaged carbon fluxes for the period 1998–2005 derived from CLIM+CO₂ simulation with observation-based estimates. Model results are from simulations with one and two needle leaf evergreen PFTs.

	Using one needle leaf evergreen PFT	Using two needle leaf evergreen PFTs	Observation- based estimate
<i>Province-wide total carbon pools</i>			
Total carbon mass (Tg C)	8695	13 352	
Litter mass (Tg C)	685	1113	
Soil carbon mass (Tg C)	6268	8362	
Vegetation biomass (Tg C)	1742	3877	1980 Ruesch and Gibbs (2008)
Forest-only vegetation biomass (Tg C)	1670	3830	5245 Penner et al. (1997) ¹ 5181 updated from Stinson et al. (2011) ¹
Forest-only vegetation biomass density (kg C m ⁻²)	2.5	5.8	7.9 Penner et al. (1997) ¹ 7.8 updated from Stinson et al. (2011) ¹
<i>Province-wide averaged leaf area index</i>			
Summer maximum leaf area index (m ² m ⁻²)	1.4	2.3	2.5 Deng et al. (2006)
<i>Province-wide averaged carbon fluxes</i>			
Net primary productivity (g C m ⁻² yr ⁻¹)	192	289	
Gross primary productivity (g C m ⁻² yr ⁻¹)	398	618	597 Beer et al. (2010)

¹ Both Penner et al. (1997) estimate and the updated estimate from Stinson et al. (2011) are for above-ground biomass.

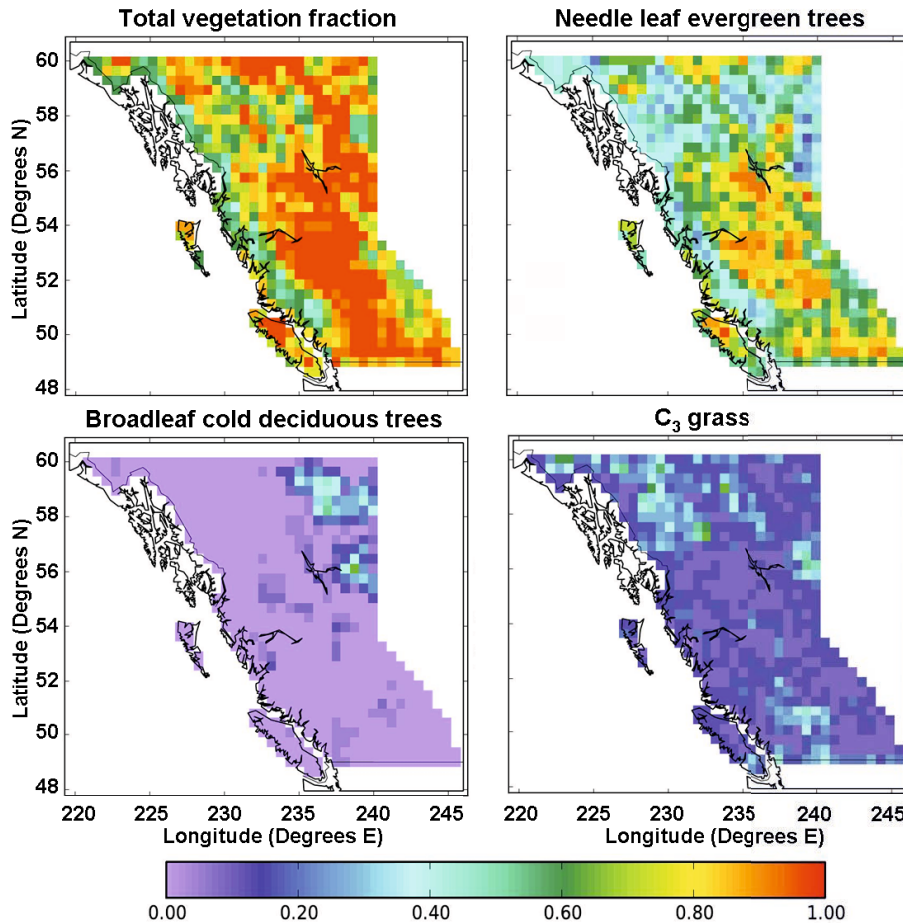


Fig. 1. Spatial distribution of fractional vegetation cover for all PFTs and for needle leaf evergreen trees, broadleaf cold deciduous trees and C_3 grass PFTs.

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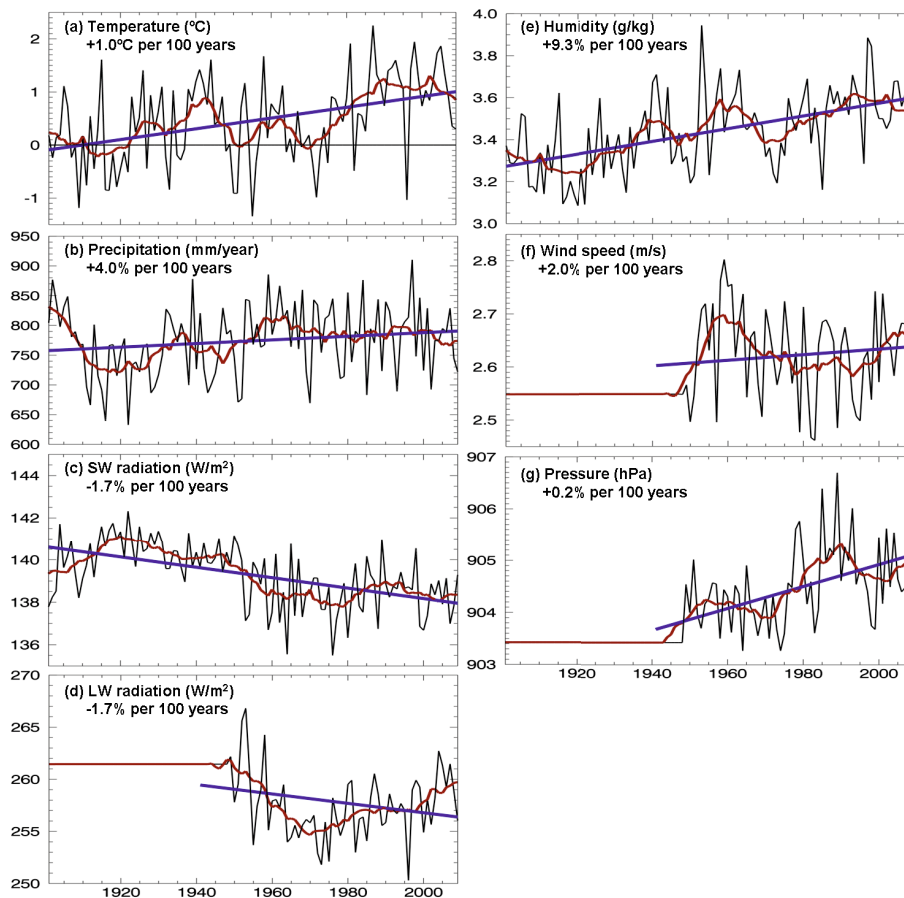


Fig. 2. BC province-wide averaged climate variables from the CRUNCEP data that are used to drive CLASS and CTEM models for the period 1901–2010. Red curves are 10 yr moving averages and the blue lines are linear trends whose values are also noted. The trend values are normalized to change per 100 yr.

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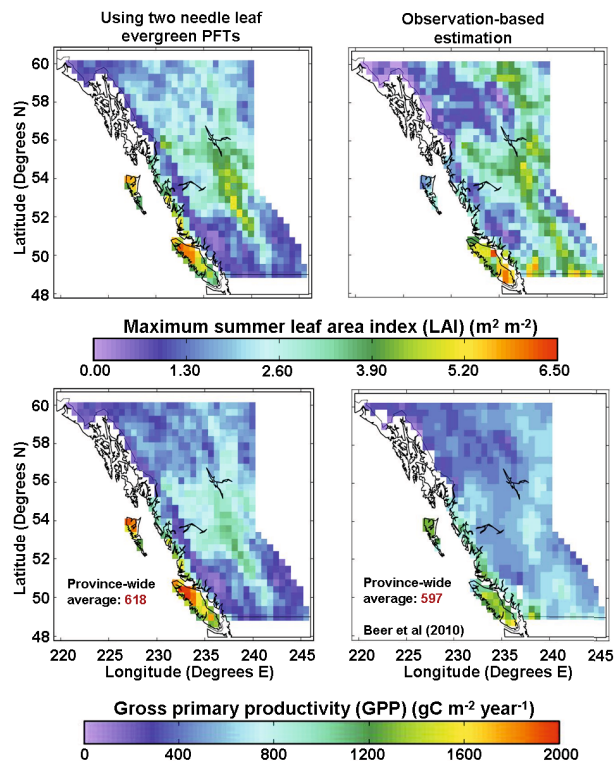


Fig. 3. Geographic distribution of simulated maximum leaf area index (LAI) and gross primary productivity (GPP) for BC compared to observation-based estimates. The left column shows results from the simulation that considers coastal and interior needle leaf evergreen PFTs separately. LAI observations are from Deng et al. (2006) averaged over the 2000–2005 period and GPP observations are from the global product of Beer et al. (2010). The model results are averaged over the same respective periods as well.

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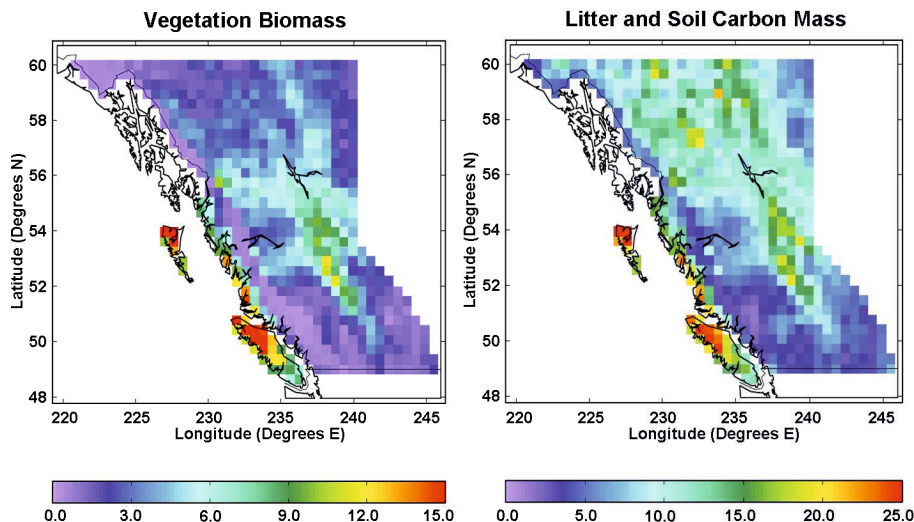


Fig. 4. Spatial distribution of simulated vegetation biomass (left panel) and litter and soil carbon mass (right panel) (kg C m^{-2}). Data are derived from the CLIM+CO₂ simulation and averaged over the period 1990–2005.

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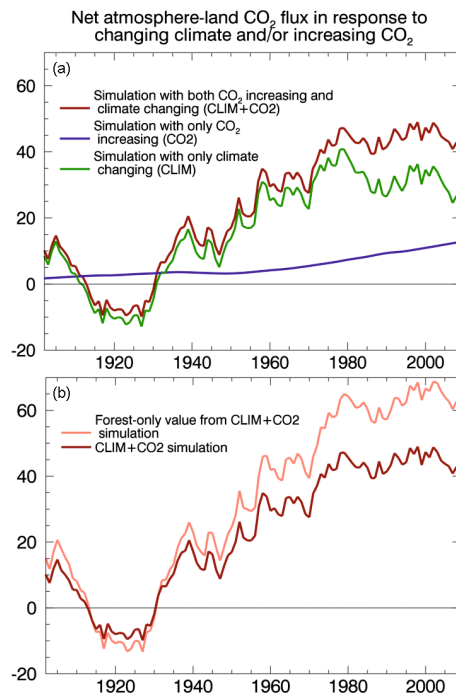


Fig. 5. (a) BC-wide simulated net atmosphere-land CO₂ flux, in response to changing climate and/or CO₂ concentration, during the 1900–2010 period for three historical simulations CO₂, CLIM and CLIM+CO₂ as explained in Sect. 2.3. The lines are 10 yr moving average. Positive values indicate a carbon sink over land and negative imply a source of carbon to the atmosphere. **(b)** Forest-only net atmosphere-land CO₂ flux compared to province-wide averaged net atmosphere-land CO₂ flux from the CLIM+CO₂ simulation, excluding the impacts of forest insect disturbances and harvesting. Units are g C m⁻² yr⁻¹.

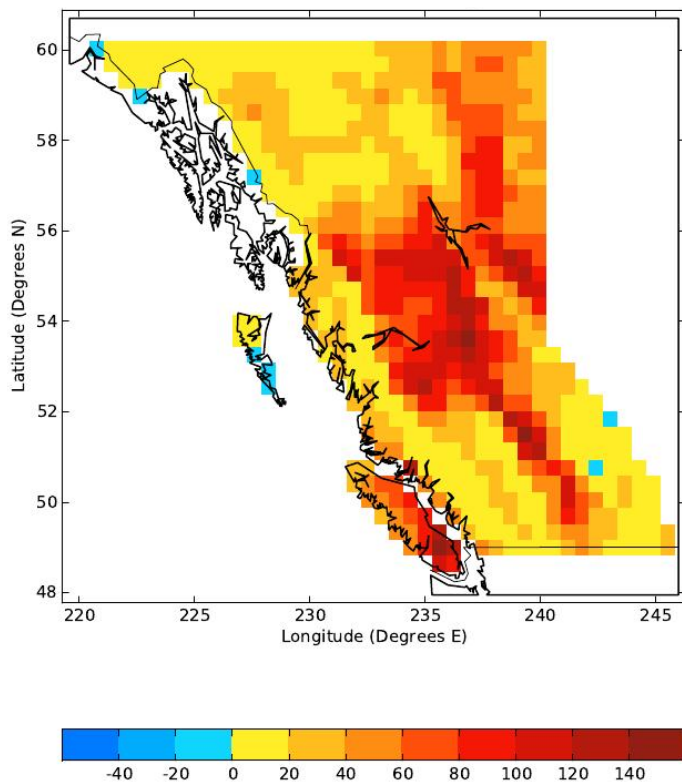


Fig. 6. Annual mean simulated net atmosphere-land CO₂ flux, in response to changing climate and CO₂ concentration for the period 1990–2005. Results are from the CLIM+CO₂ simulation and units are gC⁻² yr⁻¹. Positive values indicate a carbon sink over land and negative imply a source of carbon to the atmosphere.

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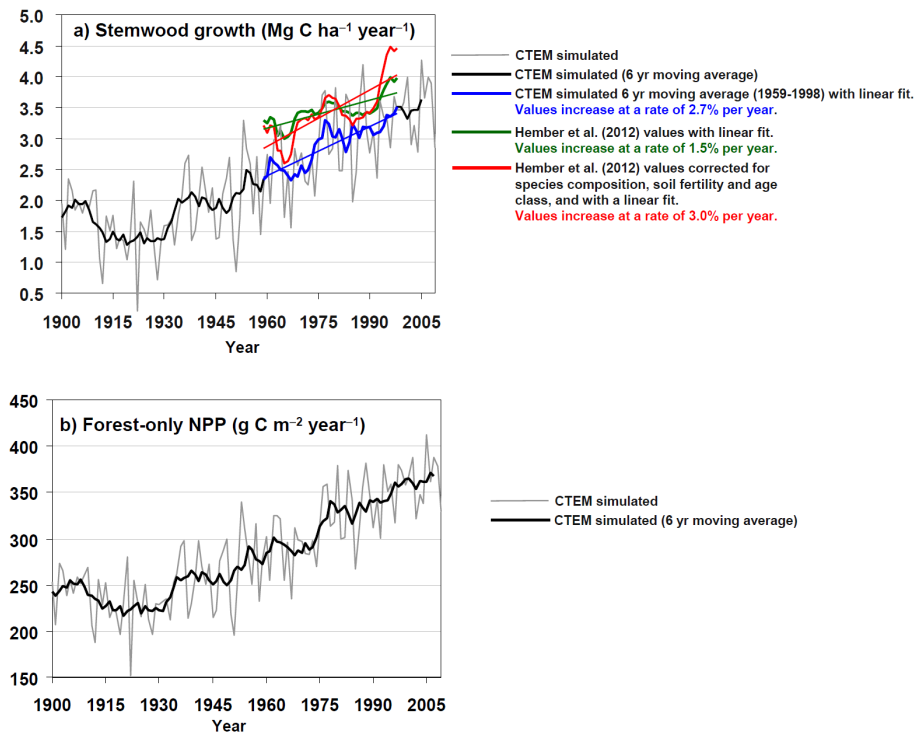


Fig. 7. Comparison of simulated and ground-based observed stem wood growth rate of conifer trees in coastal BC **(a)**. Observations are based on data collected over the period 1959–1998 as explained in Hember et al. (2012). Model estimates are for all needle leaf evergreen trees exclusively in coastal region of BC. Black and blue lines for simulation results are 6 yr moving averages. Linear regression lines are on top of the model estimates and observations during the 40 yr period for which observations are available. **(b)** shows forest-only net primary productivity (NPP) in all forest covered region in BC, as well as 6 yr moving average of forest NPP.

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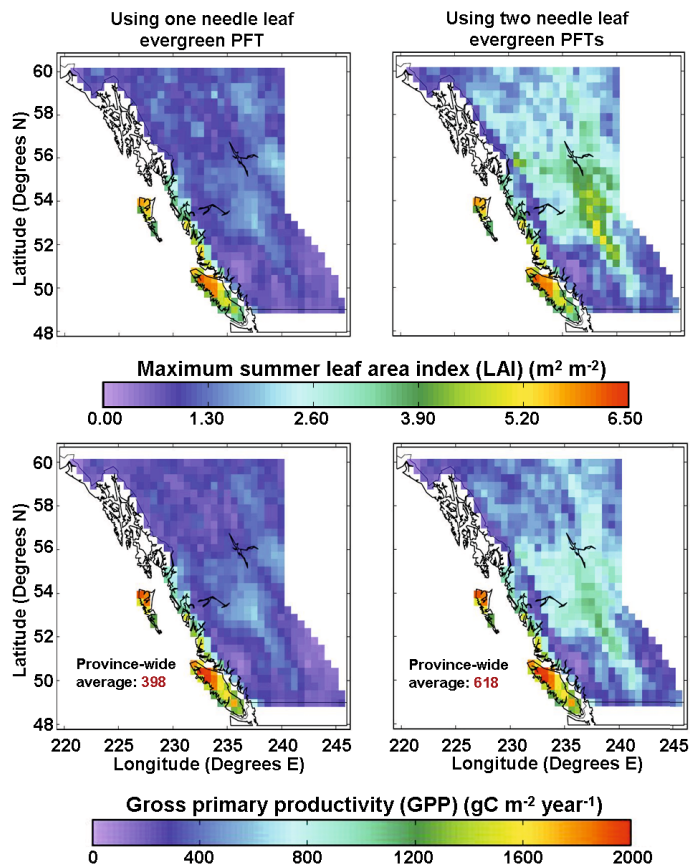


Fig. A1. Geographic distribution of simulated maximum leaf area index (LAI) and gross primary productivity (GPP) for BC. The left column shows results from the simulation with CTEM's default needle leaf evergreen PFT and the right column from the simulation that considers coastal and interior needle leaf evergreen PFTs separately. The model results are averaged over the periods same as in Fig. 3.