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- Historical and projected C balance of unmanaged Canadian boreal forest
- Projected biomass increase exceeds soil C loss
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- Supporting Information S1

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Global change induced biomass growth offsets carbon released via increased forest fire and respiration of the central Canadian boreal forest

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Abstract Northern boreal forests are sensitive to many effects of global change. This is of particular concern due to the proportionally greater climate change projected for the area in which these forests occur. One of the sensitive areas is the Far North of Ontario (FNO), consisting of one of the world's largest remaining tracts of unmanaged boreal forest, the world's third largest area of wetland, and the most southerly area of tundra. We studied past, present, and potential future carbon (C) balance of FNO forests using the Integrated Terrestrial Ecosystem Carbon Model and the Canadian Regional Climate Model with stand-replacing fire disturbance. The forced simulations of past (1901–2004) C balances indicated that vegetation C stock remained stable, while soil C stock gradually declined (-0.07 t C ha^{-1} yr^{-1}, $p < 0.001$), resulting in an overall significant decrease in total ecosystem C balance (-0.07 t C ha^{-1} yr^{-1}, $p < 0.001$). Two Representative Concentration Pathways (RCPs), RCP8.5 and RCP4.5, simulations of future (2007–2100) C balances indicated that the carbon dioxide fertilization and climate growth-enhancing effects of global change will outweigh C loss through increased ecosystem respiration, disturbance, and changes in forest age class structure resulting in an increase in total FNO ecosystem C stock by mid-21st century. However, the projected simulations also indicated that the relative sizes of forest C stocks will change, with relatively less in the soil and more in vegetation, increasing fuel loads and making the entire ecosystem susceptible to forest fire and insect disturbances.

Plain Language Summary Northern boreal forests are sensitive to many effects of changes in climate and forest disturbances. This is of particular concern due to the disproportionally greater climate change projected for the area in which these forests occur. We studied past and potential future carbon balance of the Far North of Ontario (FNO), consisting of one of the world's largest remaining tracts of unmanaged boreal forest, the world's third largest area of wetland, and the most southerly area of tundra. Our results suggest that historically, for the period of 1901–2004, the total carbon stored in 172,155 km^2 unmanaged forests of FNO decreased in average by 7.28 t carbon per hectare. This decline is linked to the increased soil carbon release and organic matter decomposition in response to the steady increase in mean air temperature. Future simulations for 2007–2100 indicate the biomass increase due to warming and fertilization from the increasing atmospheric CO_2 concentration will outweigh carbon loss through increased soil carbon release and fire disturbance. The future simulations also show decreased carbon stored in soil and increased carbon stored in vegetation compared to the historic values. This will increase fuel loads and make the entire ecosystem susceptible to potential fire and insect disturbances.

1. Introduction

To understand the influence of forests on the global carbon (C) cycle and their responses to increasing atmospheric carbon dioxide (CO_2) and climate change, the main C sinks, sources, and stocks must be quantified more accurately. During the 1980s and 1990s, global terrestrial ecosystems absorbed C at a rate between 1 and 4 Pg yr^{-1}, offsetting 10% to 60% of fossil fuel emissions [*Houghton*, 2007; *Solomon*, 2007]. Such wide-ranging estimates of the terrestrial ecosystem C sink are linked to uncertainties that are inherent in C accounting and modeling approaches [e.g., *Hayes et al.*, 2011, 2012; *Huntzinger et al.*, 2012; *Pan et al.*, 2011]. As terrestrial ecosystem C cycle models become increasingly sophisticated, this level of uncertainty has increased, as more mechanisms have been incorporated into the models. Regional patterns and sizes of terrestrial C sources and sinks therefore remain uncertain [*Schimel et al.*, 2001; *Houghton*, 2007; *Solomon*, 2007]. With increasing scientific and political interest in regional aspects of the global C cycle, there is a strong impetus to better understand the C balance of Canadian forests, which contribute significantly to the country's national income and comprise about one third of the world's circumpolar boreal forest.

Of the 3.5×10^6 km^2 of Canadian forests, 2.35×10^6 km^2 of which are managed and are growing mostly in boreal and temperate zones. The remaining 1.25×10^6 km^2 are unmanaged and located in colder and northern latitudes. C stocks and balances in Canada's managed forests are better quantified than those in unmanaged forest [e.g., *Kurz et al.*, 2013]. Improved knowledge on unmanaged forest is of particular importance, as they are located in the northern latitudes with extensive areas of deep organic soils, peatlands, and permafrost, containing large quantities of C that are vulnerable to the effects of global change. Natural disturbances and land use change affect the C balance of both unmanaged and managed forests, but the C balance of the latter is also affected by forest management practices including harvesting and protection against natural disturbances [*Kurz et al.*, 2013]. Natural disturbances, the dominant of which being fire, are the main drivers of changes in C stocks and balances on the unmanaged forest areas in Canada. The unmanaged forests are located in areas that are warming relatively faster and expected to face intensified natural disturbances. As a consequence, these forests will be subjected to disproportionally large burden from global change, compared to forests growing in managed areas. Further, if forest harvesting and land development were to expand into currently unmanaged forest areas, in response to warming, the future implications of these forests to the Canadian forest C budget will be significant, due to their extent and sensitive nature to global change.

Between 1901 and 2010, managed forests in Canada removed 7510 Tg C from the atmosphere, exceeding Canada's 7333 Tg fossil fuel-based C emissions during that time [*Chen et al.*, 2014]. This is mainly due to the young forest age structure that resulted from forest fires in the 19th century. The C balance of the unmanaged boreal forest is currently unknown. Under rapid climate change, the relatively slow-growing unmanaged forests will be exposed to substantial changes in temperature and precipitation and increasing disturbances such as pest and disease outbreaks and fire, all of which affect forest C balance. Global changes such as climate warming, CO_2 fertilization, and nitrogen (N) deposition that have varying effects on photosynthesis and respiration have the potential to alter the net C balance of Canada's forests. However, uncertainties remain in quantifying the net effect of projected global change drivers on C balance, particularly with regard to the effect of CO_2 fertilization on increased forest C uptake, which could offset or mitigate the effects of projected increases in burned area on C release.

Risk of increased forest fire in response to anticipated global warming makes future contributions of Canada's forests to the global C cycle highly uncertain [*Kurz et al.*, 2008a, 2008b]. Forest fires are influenced by climate, weather, topography, vegetation, dead trees and surface litter, and human activities and in return affect the climate through emission of gases and aerosols and changes in surface albedo, soil processes, and vegetation dynamics [e.g., *Abbott et al.*, 2016; *Balshi et al.*, 2009a, 2009b; *Bowman et al.*, 2009; *Euskirchen et al.*, 2009; *Field et al.*, 2007; *Flannigan et al.*, 2005a, 2005b; *Mack et al.*, 2011; *Randerson et al.*, 2006]. The net effects of forest fires on climate are not yet well known, but boreal forest fires are believed to have resulted in negative feedback during the 20th century and are projected to cause positive feedback by the end of 21st century [*Oris et al.*, 2014]. The estimated direct C emission by forest fires in boreal Canada is 27 ± 6 Tg C yr^{-1} for 1959–1999 [*Amiro et al.*, 2001], 32.2–32.9 Tg C yr^{-1} for 1996–2002 [*Balshi et al.*, 2007], and 23 ± 16 Tg C yr^{-1} for 1990–2008 [*Stinson et al.*, 2011]. Annual mean temperatures across the Canadian boreal zone could be 4–5°C warmer than today's by 2100 [*Price et al.*, 2013]. Therefore, over the 21st century, climate-induced increases in burned area are predicted in response to climate change in Canada [*Flannigan et al.*, 2005a, 2005b, 2009; *Balshi et al.*, 2009a; *Krawchuk et al.*, 2009; *Hély et al.*, 2010].

One region potentially sensitive to global change is the Far North of Ontario (FNO), consisting of the world's third largest area of wetland, one of the largest remaining tracts of unmanaged boreal forest, and the most southerly area of tundra. Forests in FNO are in part situated on the northern edge of the Boreal Shield and extend into the Hudson's Plain ecozone [*Wiken*, 1986]. The FNO peatland and forest ecosystems constitute globally important stores of C, mediate ecosystem hydrology, and modify local and regional climates. Yet very little is known about FNO's C stock and balance and how it responds to disturbance or may respond to global change. For 2003–2100, *Balshi et al.* [2009b] projected that FNO forests would be a C sink as a result of projected changes in atmospheric CO_2 concentration, climate, and forest fires. Emerging scientific evidence indicates that FNO ecosystems will be subjected to a magnitude and rate of climate change that exceeds historic levels [*The Far North Science Advisory Panel (TFNSAP)*, 2010], but relatively few attempts have been made to assess the effects of global change on future C dynamics.

The purpose of this study was to (1) estimate the past and current C stock and balance of forests in the FNO and (2) study the relative impacts of CO_2 fertilization, climate change, forest age structure, and climate-induced changes in fire regime on future C dynamics of FNO forests. To parameterize and evaluate the performance of C cycle models, we used ground and satellite observations of leaf area index, field measurements of net primary productivity from tree parameters obtained from stem increment cores and forest inventory, and a database of historic burned area (see Text S1 in the supporting information). The vegetation, soil, and total ecosystem C cycle dynamics were modeled using the Integrated Terrestrial Ecosystem Carbon Cycle model (InTEC) [*Chen et al.*, 2000a] with Climate Research Unit (CRU) historic forcing data and two Representative Concentration Pathway (RCP) projections, RCP8.5 and RCP4.5, obtained from the Canadian Regional Climate Model (CanRCM4 [*Scinocca et al.*, 2016]). For future simulations, we conducted various modeling experiments to capture the likely responses of the FNO unmanaged forest C dynamics to projected climate-induced forest fire, historic level forest fire, with and without the accompanying global changes. Furthermore, factorial simulations including forest age alone, CO_2 fertilization alone, and climate change alone were also conducted to study the net effect of each global change driver on soil and vegetation C stock changes. The analysis also addressed the net impact of the combined global change (i.e., CO_2 fertilization and climate change) on soil, vegetation, and total ecosystem C balances of forests growing in cold environment. We hypothesize that the combined growth enhancing effect of global change will offset the C releases due to increased forest fire and soil respiration.

2. Material and Methods

2.1. Study Area

The FNO represents 42% (453,788 km^2) of Ontario, Canada's landmass, ranging from Manitoba in the west to James Bay and Quebec in the east (Figure 1). Portions of two ecozones make up the FNO: the Boreal Shield and the Hudson Plains [*Wiken*, 1986]. The Hudson Plains ecozone's poor drainage and flat terrain have resulted in the largest continuous wetlands in the world. Trees usually grow in drier higher altitude due to poor drainage or on lower latitudes of the study area. Forest composition in the FNO is characteristic of northern boreal forests of Canada, with black spruce (*Picea mariana* (Mill.) BSP) being the dominant species, particularly on lowland sites, along with white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* Michx.), tamarack (*Larix laricina* (Du Roi) K. Koch), and white birch (*Betula papyrifera* Marsh.) [*TFNSAP*, 2010]. Based on the land cover data used in this study (see Text S1), among the vegetated areas (413,237 km^2), conifer forests comprise 39.3% (162,575 km^2), broadleaf forests 1.7% (6,982 km^2), mixed forests 0.6% (2,598 km^2), treed-wetlands 29.9% (123,529 km^2), and other nontreed vegetated land covers including peats and bogs 28.5% (117,553 km^2). This study focused only on forested areas excluding treed-wetlands, comprising 172,155 km^2 mostly in the southern and southwestern portions of the FNO (Figure 1). The forested area is extracted from grid cells consisting conifer, broadleaf, and mixed forest land cover types at 500 m spatial resolution (see Text S1 for details of land cover data).

FNO has the lowest aboveground biomass and productivity of any forested terrestrial ecozone in Canada [*Gonsamo et al.*, 2013; *TFNSAP*, 2010], although much of the region is characterized as having the largest organic soil C storage anywhere in the world [e.g., *Hugelius et al.*, 2014]. Historic climate records (Figure 2) show that the study area is generally a forest-tundra ecotone with mean annual temperature of −2.3°C and total annual precipitation of 613.2 mm (averaged for 1901–2004). Permafrost is estimated to occur only in ~1% of the entire Hudson Bay Lowland, mostly occurring along the coasts [*Packalen et al.*, 2014], which is excluded from this study. FNO's unmanaged treed ecosystems are among the least studied vegetated ecosystems not only in Canada but also relative to other comparable regions. Compared to well-studied forests growing in comparable forest-tundra ecotone environments in Russia [*Shvidenko and Nilsson*, 2003], Alaska [*Mishra and Riley*, 2012], and Quebec [*Nelson et al.*, 2009], FNO's forests grow on the largest soil C stock that will likely be affected the most under the projected global changes.

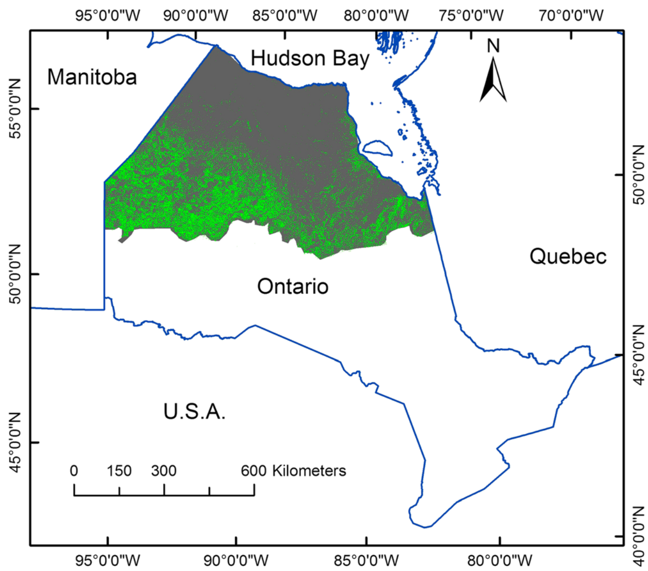

Figure 1. The shaded area reflects the study area within Ontario, Canada. The grey and green together compose the Far North of Ontario, with the green area classified as nonwetland forest.

2.2. Model Description

The forest C cycle was modeled using the Integrated Terrestrial Ecosystem Carbon Cycle model (InTEC) [*Chen et al.*, 2000a], which was developed for simulating C balance in Canada's forests by integrating effects of disturbance and nondisturbance factors such as climate, CO_2 concentration, and N deposition on C assimilation and release since the preindustrial period. After several improvements [*Chen et al.*, 2003; *Ju and Chen*, 2005; *Ju et al.*, 2007], InTEC now consists of three components: a canopy level photosynthesis module for simulating net primary productivity (NPP), a module for simulating soil C and N dynamics, and a hydrological module for simulating soil moisture and temperature [*Ju and Chen*, 2005].

The soil C and N dynamic module is based on the CENTURY model [*Parton et al.*, 1993] modified to account for multiple soil C pools; temporally and spatially varying N depositions; the effects of drainage, soil temperature, and moisture on decomposition rate; and climatic and C pool size effects on N fixation [*Ju et al.*, 2006b]. The N deposition rate is spatially and temporally interpolated based on measured N deposition rates and

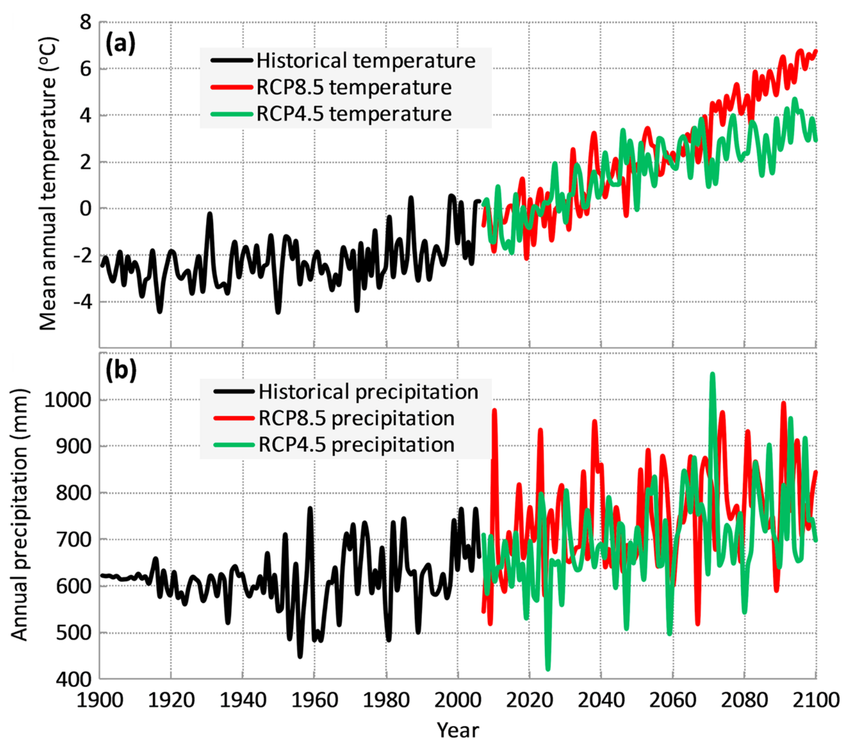

Figure 2. Mean annual temperature (a) and total annual precipitation (b) in the Far North of Ontario from historical (Climate Research Union observations) for 1901–2006 and representative concentration pathway (RCP8.5 and RCP4.5) scenarios for 2007–2100. Bias in the projected scenarios is removed using meteorology station records for 2000–2013 (see Text S1).

historical greenhouse gas concentration values [*Chen et al.*, 2003] (see Text S1). The total available N in the soils in each year is the sum of atmospheric N deposition, biotic N fixation, and net N mineralization [*Chen et al.*, 2000a]. The net N mineralization model of *Townsend et al.* [1996] is employed to simulate soil C and N cycles. N losses as a result of fire, gas emission, and leaching are accounted for when N input into and export from the forest ecosystems are calculated [*Chen et al.*, 2000a]. The complete theories, formulations, and improvements of InTEC's C:N coupling and dynamics can be found in *Chen et al.* [2000a, 2003] and *Ju et al*. [2006b].

The hydrological module, parameterized based on fractions of sand, clay, silt, and organic matter and vegetation properties, simulates soil water content (SWC) and temperatures of three soil layers at monthly time steps needed to quantify decomposition rates of soil C pools and soil water stress effects on photosynthesis [*Ju et al.*, 2010]. Temperatures of snowpack and soil are simulated using Fick's law of heat diffusion. Simulated soil temperatures are used in conjunction with SWC, texture, N availability (deposited, fixed, and mineralized N), and lignin content to determine decomposition rates by downscaling from the inherent maximum decomposition rates of various soil C pools [*Ju and Chen*, 2005]. Vegetation C is stratified into four pools (foliage, stem, fine root, and coarse root) and soil C into nine pools (surface structural litter, soil structural litter, woody litter, surface metabolic litter, soil metabolic litter, surface microbial, soil microbial, slow soil organic matter C pool, and passive soil organic matter C pool). C pool sizes are updated at the end of each annual time step.

The photosynthesis module was developed from a canopy-level Farquhar's leaf biochemical model [*Farquhar et al.*, 1980] using a temporal and spatial scaling scheme [*Chen et al.*, 2000a]. Through temporally and spatially upscaling the instantaneous leaf-level Farquhar biochemical model to the canopy level, the photosynthesis module quantifies the integrated effects of changes in stand age, climate, and CO_2 and N deposition since the preindustrial period on the interannual variability of NPP to progressively calculate annual NPP from an initial NPP value [*Chen et al.*, 2000a]. The NPP value in a reference year (we used 2004 because that was the year all spatial data sets were available), simulated at daily time steps using the Boreal Ecosystem Productivity Simulator (BEPS) [*Liu et al.*, 2002], was the benchmark used to tune the initial NPP value. For each pixel, the initial NPP value was repeatedly adjusted until the difference between NPP simulated by InTEC and the benchmark output from BEPS in the reference year (i.e., 2004) was less than 1%. This was achieved by iteratively changing the initial NPP during forward model runs simulating the integrated effects of stand age and nondisturbance factors on the forest C cycle [*Chen et al.*, 2000a]. To initialize various C pools, InTEC assumes that the C dynamics were in a steady state before 1901 for stands disturbed after 1901 or in the year before the most recent disturbance for stands undisturbed after 1901. The initialization was run until the C dynamics reached a steady state, in which the absolute value of the ecosystem net C balance became smaller than 2% of the initial NPP using the NPP and stand age in the initial year (1901) along with mean climatic conditions in 1901–1910 to initialize C pools in biomass and soil. The sizes of the various C pools were estimated by solving a set of differential equations that consider the interaction among pools under steady state C dynamics (see details in *Chen et al.* [2003]). After the initialization of biomass and soil C pools, the model is driven by historical climate, stand age, CO_2, and N deposition from 1901 to 2004.

Because stand age at the time of most recent disturbance is often unknown, a representative age at which steady state C dynamics occurred before the last disturbance is needed. This was particularly important for stands disturbed after 1901 because disturbance data for the study area were available only after 1961. Therefore, between 1901 and the year of disturbance, stand age was assumed to remain unchanged at an "equilibrium age" at which other effects of climate and atmospheric changes were considered. The equilibrium age is defined as the stand age at which C dynamics reached a steady state. Errors due to deviation from equilibrium diminish exponentially through time [*Chen et al.*, 2003]. Although we used disturbance history whenever available, errors in the initialized C pools are the major sources of uncertainties in C balance estimates. As the forced model was run (i.e., 1901–2004) for twice the mean C residence time in boreal ecosystems and disturbance data were available after 1961, which is close to the mean C residence time, final error in the C balance was assumed negligible. The InTEC model has been validated and used in several studies, for example, to analyze spatial patterns of current C sources and sinks in Canadian forests [*Chen et al.*, 2000a, 2000b, 2003]; to simulate the spatial distribution, response to climate and disturbance, and hydrological properties of soil C stocks in forests and wetlands [*Ju and Chen*, 2005; *Ju et al.*, 2006a]; and to validate unregulated streamflow measurements at watershed scales [*Ju et al.*, 2010].

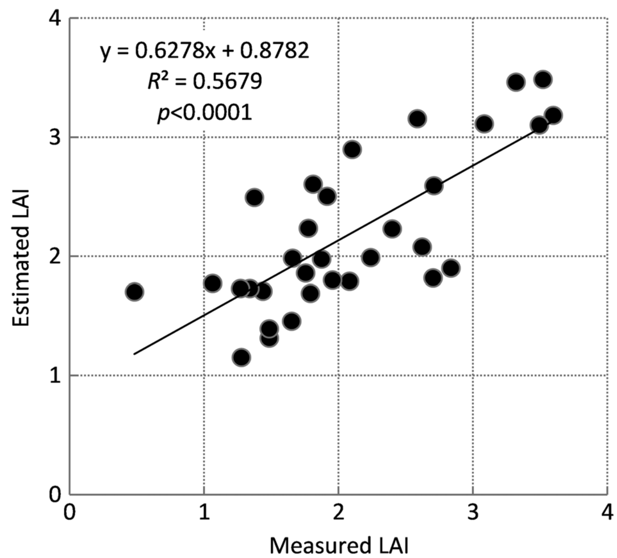

Figure 3. Comparison between measured and estimated leaf area index (LAI) for the study area in the Far North of Ontario.

2.3. Data

Inputs to the InTEC model included spatial data sets of climate, soil texture, N deposition, drainage, digital elevation model, land cover, leaf area index (LAI), forest stand age, and reference NPP for the entire FNO forest area (Figures 3, 4, and 5). Prior to model execution, all spatial data sets were interpolated to 500 m resolution, the highest spatial resolution of the remote sensing input data sets. Detailed descriptions of all input data sets are given in Text S1. Details of historical and projected forest stand ages derived from fire disturbance data are given below.

2.3.1. Historical Fire Disturbance

The historical fire disturbance data were compiled from the Canadian Large-Fire Data Base (LFDB) maintained by provincial, territorial, and federal agencies [*Amiro et al.*, 2001], which include records for 1959–1995. The data set provides polygons, which delineate the outline of the fire, and attribute information such as year of fire and final burned area. These fire polygons were coregistered with advanced very high resolution radiometer (AVHRR) data in order to develop the remote sensing algorithm for detecting and dating fire scars not included in the LFDB until 2004. The remote sensing fire scar detection algorithm is based on changes in normalized difference vegetative index in two consecutive years following methods developed by *Li et al.* [2000a, 2000b]. The LFDB data were used both to calibrate and validate the remote sensing fire scar outputs. Finally, the high-quality LFDB fire polygons starting in 1961 together with the AVHRR fire scars were used to estimate forest stand age and historical burned area. Historical records of burned area may not include all fires, especially for the earlier years and for inaccessible areas such as FNO. The amount of human-caused fires in FNO is small but cannot be ignored, especially those related to survey equipments working in remote, fire-prone areas.

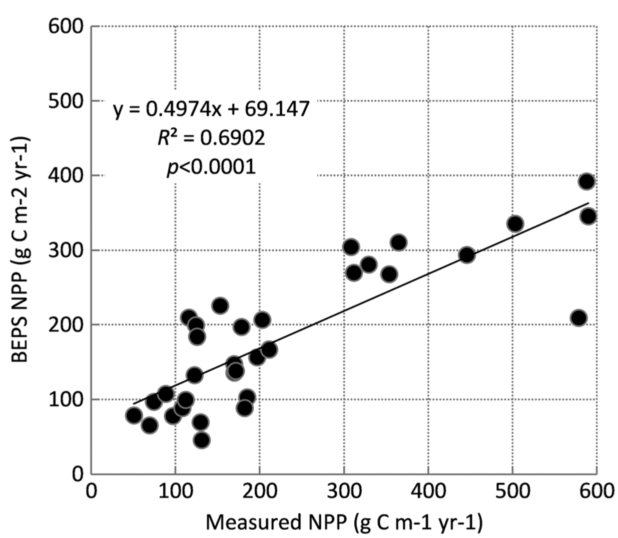

Figure 4. Comparison between net primary productivity (NPP) measured and that modeled by the Boreal Ecosystem Productivity Simulator (BEPS) for the study area in the Far North of Ontario.

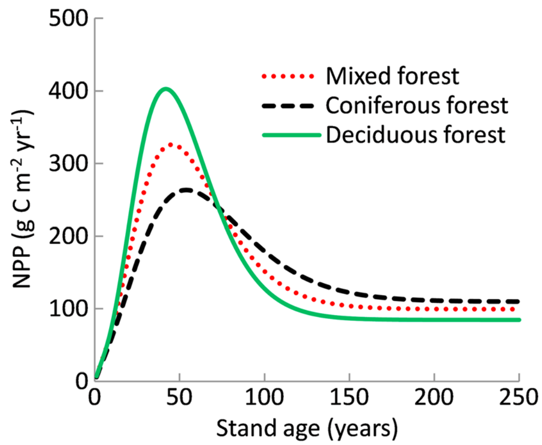

Figure 5. Net primary productivity (g C m^{-2} yr^{-1}) and age relationships for deciduous, coniferous, and mixed forests derived from yield curves developed by *Penner et al.* [2008] for several Ontario forest management units.

During the period 1901 to 2004, the C emissions from forest disturbance were assumed to be only from fire, as spatially explicit, insect-induced disturbance data were unavailable. Likewise, for the projected disturbance (see below) during 2005–2100, only simulated fire disturbance was considered. InTEC assumes that fire causes complete stand mortality for both historic and projected simulations and that the disturbed forest regenerates without cover-type change in the second year after a disturbance. In InTEC, fire releases a fraction of biomass and soil C (fine fuel on forest floor, foliage, and structural detritus) into the atmosphere and transfers part of the remaining biomass C into soil pools. The amount of C directly emitted from fire is estimated as the sum of 100% of foliage C, 25% of aboveground woody material C, and 100% of surface metabolic and structural detritus pool C (fine fuel) [*Kasischke et al.*, 2000]. The coefficient of 0.25 (25%) for the aboveground woody material is used to account for the loss of secondary and primary branches during normal burning and combustion of a fraction of boles lost during severe burning [*Kasischke et al.*, 2000]. Dead biomass C remaining after fire is transferred to woody litter and surface metabolic and structural detritus [*Chen et al.*, 2003]. The effect of fire severity on C release [*Kasischke et al.*, 2000] was not considered in this study due to lack of data. The decomposition of dead organic matter is assumed to start the year after fire disturbance. Eventually, the net forest C change becomes positive and peaks as plants regenerate and soil detritus decays.

2.3.2. Future Fire Disturbance

In this study, the Canadian Fire Weather Index (CFWI) was used to predict burned area based on climate data. The CFWI, composed of fine fuel moisture, drought and duff moisture codes, and buildup, initial spread, and fire weather indices (FWIs), was developed to predict forest fire behavior in response to weather [*Van Wagner*, 1998]. A daily severity rating (DSR) designed to capture nonlinear aspects of fire spread is derived from the FWI [*Van Wagner*, 1998]. By averaging DSR over time, one can obtain a monthly severity rating, which is used as an index of fire weather from month to month.

For the purpose of this study, we used daily maximum air temperature, precipitation, relative humidity, and wind speed from CanRCM4 to calculate daily DSR values that were then aggregated to monthly resolution for model input. The CanRCM4 climate data were first spatially aggregated to 2.5° × 2.5° from original 0.22° × 0.22° grids to match the spatial resolution of the fire database as initially used by *Balshi et al.* [2009a]. To predict the annual burned area for 2006–2100 for the RCP8.5 climate scenario, we used regression coefficients from the multivariate adaptive regression spline model as presented by *Balshi et al.* [2009a] (Table S2 in the supporting information) since they only accounted for weather-related fires, which is more relevant for predicting future burned area than our observed burned area, which included both weather and human-caused fires. We used regression equations only for grids overlapping the FNO region with statistically strong fire-climate relationships ($R^2 > 0.5$) (Figure 6). Predicting burned area is challenging in eastern Canada where fire occurrence is controlled not only by fuel moisture and temperature but also by maritime influence, Atlantic moisture sources, and large water bodies (e.g., Great Lakes, Hudson Bay, and James Bay) [*Harrington et al.*, 1983; *Flannigan and Van Wagner*, 1991; *Balshi et al.*, 2009a]. Finally, to

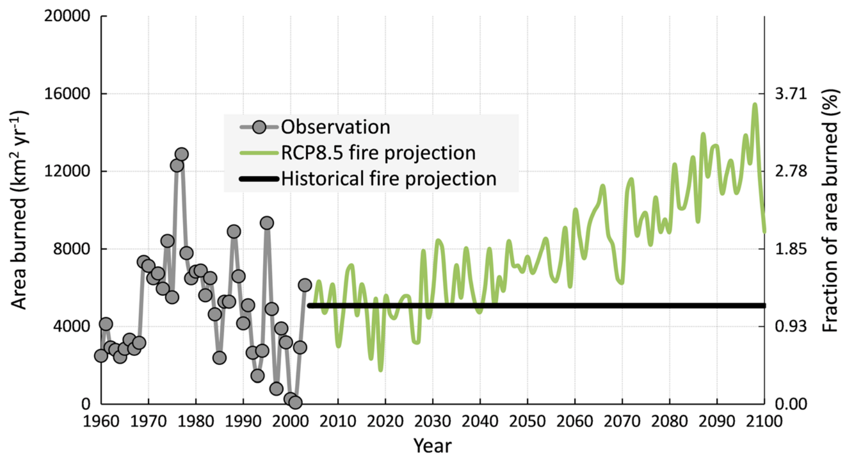

Figure 6. Projected area disturbed by fire in the Far North of Ontario for years 2005–2100 for RCP8.5 scenario and observed total area disturbed for years 1961–2004. Historical level fire projection is based on the average burned area per year between 1961 and 2004 used to simulate the future C cycle with historic fire disturbance regime. Burned area and the fractions of burned area are shown relative to the total burnable land area. The RCP8.5 fire projection is adjusted based on the ratio of historic fire to RCP8.5 fire projection for 2006–2010 to partially remove possible bias in the CanRCM4 model climate variable outputs.

adjust the effect of CanRCM4 climate data bias, the predicted burned area for 2006–2100 was further corrected by multiplying with the ratio of average historical burned area (1961–2004) to the RCP8.5 fire prediction for 2006–2010. For 2005, a year without burned area data, we used the average historical burned area for 1961–2004, meaning the "RCP8.5 fire" projected burned area in this study is for 2005–2100. The total projected burned areas were derived by averaging the predicted burned area from the fire polygons (Table S2), scaled to total burnable land pixels (i.e., all pixels excluding open water) for the entire FNO.

To account for projected C cycles with historical fire disturbance regime, we used a constant fire projection based on the average burned area per year between 1961 and 2004 (Figure 6). The annual projected burned areas for years 2005–2100 were allocated randomly to all burnable land pixels with vegetation older than 11 years. Minimum burnable age of 11 years was selected based on a previous study of long-term forest fire regime in northeastern Ontario [*Ter-Mikaelian et al.*, 2009]. Figure 6 shows the 1961–2004 observed and projected burned area between 2005 and 2100 for the RCP8.5 climate scenario and assuming future burned area occurs at the historical rate. The projected burned areas in our study rely solely on climate-induced fire occurrence and do not account for changes in land use and forest and fire management. Given that land development and forest harvest activities are likely to expand to unmanaged FNO forests in response to a warming climate [*TFNSAP*, 2010], changes in fire management, prevention, and mitigation strategies will have impact on projected burned area going forward.

2.4. Model Simulations

Historical and future forest C stocks were calculated using InTEC and considering the contributions of atmospheric CO_2, climate, forest age structure, disturbance by forest fire, and N deposition. The pixel size for all simulations was 500 × 500 m. Assumptions were that pixels were homogeneous in terms of vegetation and soil types, those remained constant throughout the simulations for each pixel, and simulated fire replaced vegetation in the entire pixel setting the age to zero. For the 172,155 km^2 study area a pixel size simulation finer than 500 × 500 m is theoretically possible, but it suffers from the need for, and inaccuracy of, spatial scaling and computational demands needed for higher spatial resolution simulation. In addition, the 500 m pixel size is currently the highest spatial resolution for satellite sensors with daily visitation frequency with all required spectral bands needed for both InTEC and BEPS inputs for this study.

Changes in C stocks (t C ha^{-1}) of soil, vegetation, and total ecosystem were projected for 10 simulation scenarios (Table 1). The "climate + CO_2" simulations indicate CO_2 fertilization, N deposition, and climate change effects considered without future fire. Several experimental [e.g., *Nowak et al.*, 2004],

Table 1. Characteristics of 10 Simulations Run to Estimate C Stock Dynamics in Forests in the Far North of Ontario

Simulation Name	Climate Scenario	CO_2 (ppmv) During 2007 to 2100	N During 2007 to 2100[a]	Fire Disturbance During 2007 to 2100
RCP8.5 climate + CO_2	CanRCM4-RCP8.5	383 to 936	Yes	No fire
RCP8.5 climate	CanRCM4-RCP8.5	383	2004 N[b]	No fire
RCP8.5 CO_2	CRU 2004 climate	383 to 936	Yes	No fire
RCP4.5 climate + CO_2	CanRCM4-RCP4.5	383 to 538	Yes	No fire
RCP4.5 climate	CanRCM4-RCP4.5	383	2004 N[b]	No fire
RCP4.5 CO_2	CRU 2004 climate	383 to 538	Yes	No fire
Age	CRU 2004 climate	383	2004 N[b]	No fire
Historical fire	CRU 2004 climate	383	2004 N[b]	Fixed burned area every year based on average historical burned area value during 1961–2004
RCP8.5 climate + CO_2 + historical fire	CanRCM4-RCP8.5	383 to 936	Yes	Fixed burned area every year based on average historical burned area value during 1961–2004
RCP8.5 climate + CO_2 + fire	CanRCM4-RCP8.5	383 to 936	Yes	Age and burned area changes based on simulated fire disturbance using RCP8.5 climate

[a]Future nitrogen (N) depositions for RCP8.5 and RCP4.5 are projected based on the relationship between N deposition measurements for Canadian forests during 1983–1994 and historical national greenhouse gas emissions. This relationship is applied to future greenhouse gas emissions under RCP8.5 and RCP4.5 scenarios.
[b]Fixed future N deposition value of year 2004. CRU is Climate Research Unit and CanRCM4 is Canadian Regional Climate Model.

observational [e.g., *Girardin et al.*, 2016], and modeling [e.g., *Friedlingstein et al.*, 2006; *Hemming et al.*, 2013] works show no general consensus on the magnitude and direction of plant productivity response to global change. In anticipation of forested ecosystems only responding to part of global change components, we conducted factorial simulations of "climate" alone and "CO_2" alone scenarios. In the "climate" simulation, only RCP8.5 or RCP4.5 climate changed with time and current (i.e., year 2004 values) CO_2, and N deposition values were used for 2007–2100 simulation. In the "CO_2" simulation, only RCP8.5 or RCP4.5 CO_2 and N deposition changed with time and current climate values were used for simulation.

Of the 10 scenarios, 4 were sensitivity analyses: "age," "historical fire," "RCP8.5 climate + CO_2 + historical fire," and "RCP8.5 climate + CO_2 + fire." The sensitivity analysis simulations were conducted not only to partially account for uncertainties in the disturbance impacts of future global change projections but also to study the net effect of each forest fire scenario on soil and vegetation C stock changes. In the "age" simulation, only forest stand age changed with time and current (i.e., year 2004 values) climate, CO_2, and N deposition values was used for simulation. For the "historical fire" simulation, we use fixed annual burned area for 2007–2100 based on an average historical burned area value during 1961–2004, while the current climate, CO_2, and N deposition values were used for simulation. The "RCP8.5 climate + CO_2 + historical fire" simulation considered CO_2 concentration, N deposition, RCP8.5 climate, and stand age changes through time with projected stand age based on the average historical burned area for 1961–2004 (i.e., the effects of varying climate on future burned area were excluded in this simulation and the amount of burned area set constant). The historical average burned area, i.e., 5058 km^2 yr^{-1}, is allocated randomly each year to all burnable land pixels of FNO. The complete role of fire disturbance on forest C cycle is considered in all fire simulations. Finally, in the "RCP8.5 climate + CO_2 + fire" simulation, CO_2 concentration, N deposition, RCP8.5 climate, and stand age varied through time, while the projected stand age (i.e., effects of burned area) was simulated for the RCP8.5 climate (see section 2.3 for burned area simulation), providing the most comprehensive simulation of future forest C stocks in this study.

3. Results

3.1. Effects of Climate Change and Increasing CO_2 on C Stock and Balance

Between 1901 and 2004, total FNO nonwetland forest C stock ranged between 65.9 t C ha^{-1} and 75.2 t C ha^{-1}, with 18.3–20.2 t C ha^{-1} in vegetation and 46.9–54.9 t C ha^{-1} in soil (Figure 7). Results from the forced

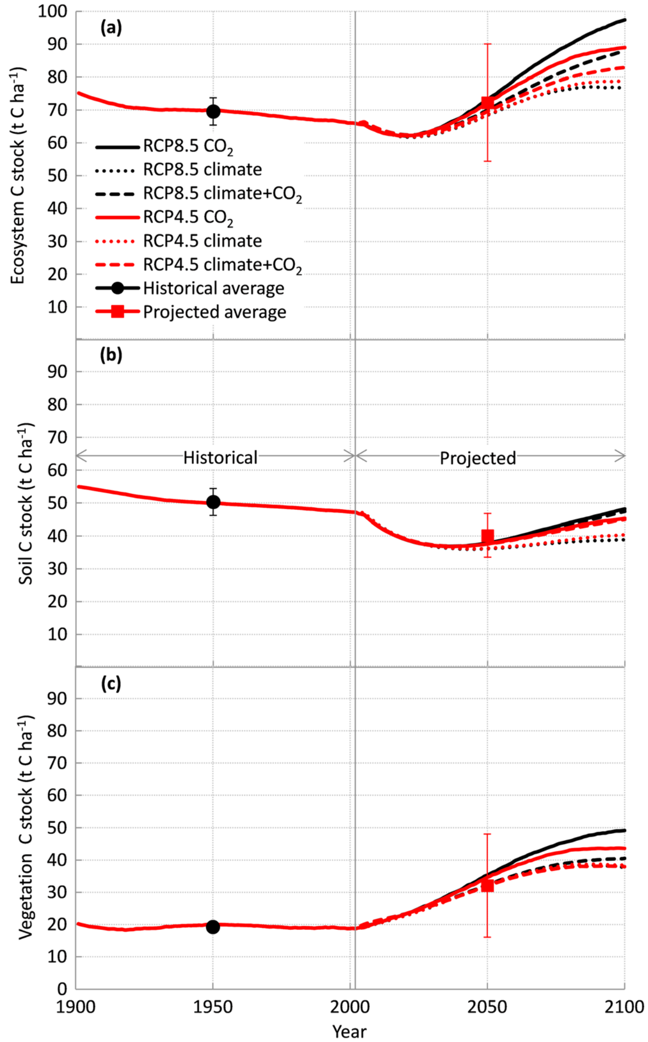

Figure 7. (a) Total ecosystem, (b) soil, and (c) vegetation carbon stocks of forest in the Far North of Ontario under RCP4.5 and RCP8.5 scenarios. Historical simulations used observations for 1901–2004, and projected simulations used the Canadian Regional Climate Model (CanRCM4) for 2005–2100. The error bars for historical and projected averages represent ±2 standard deviations around the mean, consisting of at least 75% of individual scenario yearly estimates. See Table 1 for description of each scenario.

simulations (1901–2004) indicated that vegetation C stock remained stable and soil C stock gradually declined (−0.07 t C ha^{-1} yr^{-1}, $p < 0.001$,), resulting in an overall significant decrease in total ecosystem C stock (−0.07 t C ha^{-1} yr^{-1}, $p < 0.001$). All trend statistics reported in this study were estimated from ordinary least squares regression slopes with a two-tailed Student's *t* test. After the mid-2020s, the FNO nonwetland forest switched to a C sink (Figure 7 a) mainly due to increased vegetation growth (Figure 7c), while soil C release eventually stabilized (Figure 7b). Enhanced tree growth in response to climate change and increased atmospheric CO_2 was on average projected to increase total FNO forest ecosystem C stock during 2007–2100, outweighing increased soil C release. Under both RCP8.5 and RCP4.5 scenarios, climate change alone resulted in the lowest soil and ecosystem C stocks; CO_2 fertilization alone resulted in the highest vegetation, soil, and ecosystem C stocks; while the combined effect of climate change and CO_2 fertilization resulted in intermediate C stocks. Total ecosystem C stock was greatest under the RCP8.5 scenario and least under RCP4.5 scenario. The combined effect of climate change and increasing CO_2 was projected to result in increased ecosystem C stock with mean total ecosystem C stock of 72.8 (±8.8) t C ha^{-1} for the RCP8.5 climate + CO_2 scenario, 71.5 (±6.1) t C ha^{-1} for the RCP4.5 climate + CO_2 scenario during 2007–2100, compared to 69.5 (±2.1) t C ha^{-1} for the historical simulation during 1901–2004 (Figure 7a).

The mean soil C stock for 1901–2004 in FNO forests was estimated at 50.2 (±2.1) t C ha^{-1} (Figure 7b). We projected that soil C stock would decrease until the mid-2030s for all scenarios (Figure 7b), largely a result of the increase in the mean air temperature (Figure 3a), after which soil C steadily increased through 2100. In comparison, under climate change simulations without CO_2 fertilization, soil C stocks remained much lower than historical and all other projected estimates for both RCP8.5 and RCP4.5 scenarios (Figure 7b). After the mid-2030s, soil C stock was projected to be similar in the CO_2 fertilization alone, and climate + CO_2 simulations in the RCP8.5 and RCP4.5 scenarios, at levels well below the historical soil C stock estimated during the 20th century. We project that the fraction of total ecosystem C stored in soil would decrease from the 1950s to the end of 2100 (Figure 7b), primarily linked to the increase in mean annual temperature (Figure 2a). The projected soil C stock averaged for all scenarios presented in Figure 7b for 2007–2100 is 77.7% of the estimated historical value for 1901–2004.

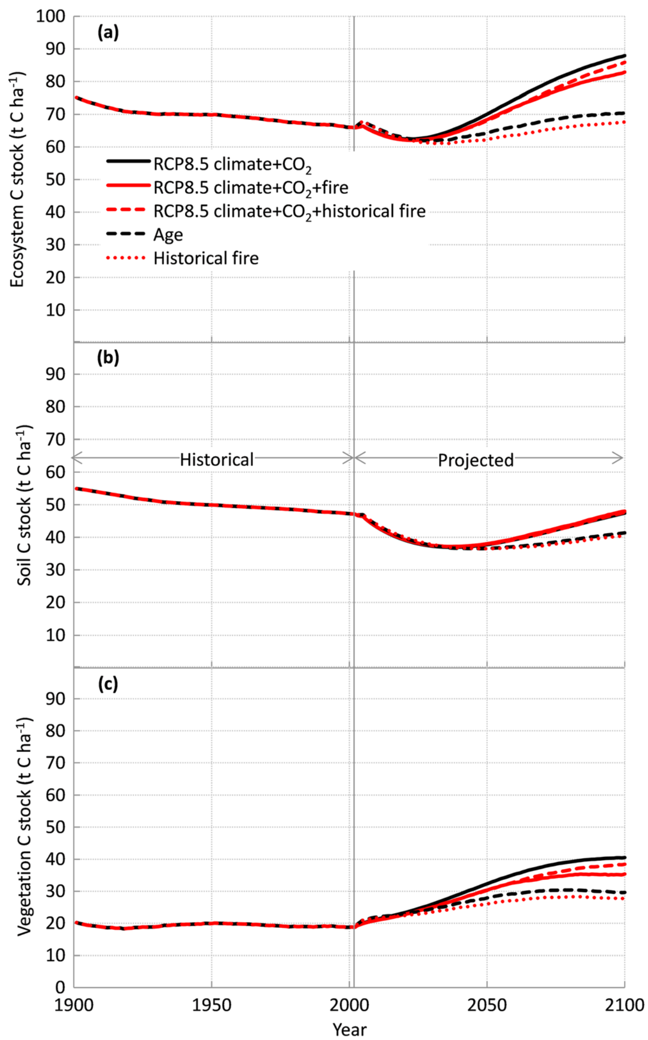

Figure 8. (a) Total ecosystem, (b) soil, and (c) vegetation carbon stocks of forest in the Far North of Ontario under combined changes in carbon dioxide (CO_2) and climate without fire (RCP8.5 climate + CO_2), combined changes in CO_2 and climate with simulated fire (RCP8.5 climate + CO_2 + fire), combined changes in CO_2 and climate with historical fire (RCP8.5 climate + CO_2 + historical fire), changes in forest age alone (age), and changes in historical fire alone (historical fire). See Table 1 for description of each scenario.

The mean vegetation C stock from 1901 to 2004 in FNO forests was estimated to be 19.3 (±0.5) t C ha^{-1} (Figure 7c). The projected vegetation C stocks under climate change alone and under combined changes of climate and CO_2 fertilization were similar for RCP8.5 and RCP4.5 scenarios. Averaged for all simulation scenarios, vegetation C was projected to increase by 66.3% during the 21st century relative to the 20th century (Figure 7c). Averaged over all scenarios, the percentage of total C stock in vegetation rose from 27.7% in the 20th century to 44.5% in the 21st century.

For much of the period from 1901 to the mid-2030s, the nonwetland forests of FNO are a C source (Figure 7), mainly due to increased soil respiration (Figure 7b) in response to the steady increase in mean air temperature (Figure 2). Averaged from 1901 to 2004, FNO forests were C sources of about −1.1 g C m^{-2} yr^{-1} from vegetation, −8.1 g C m^{-2} yr^{-1} from soil, and −9.2 g C m^{-2} yr^{-1} from the entire ecosystem. The CO_2 fertilization effect alone will make FNO C balances for 2007–2100 under RCP8.5 (RCP4.5) simulations about 31.7 (25.8) g C m^{-2} yr^{-1} for vegetation, 2.7 (−0.3) g C m^{-2} yr^{-1} for soil, and 34.4 (24.4) g C m^{-2} yr^{-1} for the entire ecosystem. The climate change effect alone will make FNO C balances for 2007–2100 under RCP8.5 (RCP4.5) simulations about 19.7 (20.3) g C m^{-2} yr^{-1} for vegetation, −7.9 (−6.3) g C m^{-2} yr^{-1} for soil, and 11.8 (14.0) g C m^{-2} yr^{-1} for the entire ecosystem. The projected C balances for 2007–2100 under climate + CO_2 RCP8.5 (RCP4.5) simulations are 21.7 (19.1) g C m^{-2} yr^{-1} for vegetation and 0.95 (−1.6) g C m^{-2} yr^{-1} for soil. The positive effect of increased atmospheric CO_2 offsets declines FNO forest productivity due to increasing stand age and increasing soil respiration, making the entire nonwetland FNO forest ecosystem a 22.6 g C m^{-2} yr^{-1} or a 17.4 g C m^{-2} yr^{-1} sink under the RCP8.5 and RCP4.5 climate + CO_2 simulations, respectively, in which both climate and atmospheric CO_2 are considered.

3.2. The Effects of Fire and Stand Age on Future C Stock and Balance

To better understand temporal changes in the relative roles of CO2, climate, and disturbance on C balance of FNO forest over the 21st century, we considered the effect of future forest fire disturbance on C balance. For most of the 21st century, FNO nonwetland forest was projected to be a C sink under the RCP8.5 climate + CO_2 simulation without fire when CO_2 fertilization and changes in climate were accounted for, with the largest C stock occurring at the end of 21st century (Figure 8). Factoring in historical fire and RCP8.5-simulated fire disturbances, the FNO forest on average remained a C sink but with lower C stocks than for simulations without fire but higher C stocks than for simulations with age alone and historic fire with contemporary climate and CO_2 concentration (Figure 8). Throughout the 21st century, fire is projected to alter the C dynamics in soil and vegetation across the FNO. Under the RCP8.5 fire simulation, burned area will increase significantly ($p < 0.0001$) between 2005 and 2100, at an average rate of 87.4 $km^2\ yr^{-1}$ (Figure 6).

The age alone simulation with contemporary (i.e., 2004) CO_2 concentration and climate resulted in overall lower C stocks in both soil and vegetation (Figure 8). Results indicated that C stocks would change by 40.9%, −22.3%, and −5.1% for vegetation, soil, and total ecosystem, respectively, between 2007 and 2100 compared to the historical values in 1901–2004 (Figure 8). With global change, the intensity and frequency of natural disturbances are likely to change. If climate change increases both factors, the future contribution of Canada's unmanaged forests to the global C cycle becomes highly uncertain. To partially account for uncertainties in future global change projections, we conducted simulations using historical fire disturbance with contemporary (i.e., 2004) CO_2 concentration and climate condition held constant through year 2100. This resulted in FNO forest C stocks changing by 33.1%, −22.8%, and −7.7% for vegetation, soil, and the total ecosystem, respectively, for 2007–2100 relative to average historical values during 1901–2005 (Figure 8). Generally, changes in forest age and forest fire disturbance alone resulted in FNO forest being a C source, while increased forest growth resulting from climate change and CO_2 fertilization overrode the effects of forest age and forest fire, making FNO forest a C sink in the 21st century. This was the case when fire disturbance remained at the historical average and when it progressively increased throughout the simulation period. This shows that C gains due to climate change and CO_2 fertilization are projected to increase the rate of forest regrowth, increasing the vegetation C sink and surpassing C losses due to the projected forest fires and young forest ecosystem respiration during the 21st century (Figure 8).

4. Discussion

In this study, the effects of climate change, climate-induced fire, and CO_2 fertilization on the C dynamics of nonwetland forests in the Far North of Ontario (FNO) were quantified. Modeling future C dynamics requires knowledge of the relationship between forest age and NPP. These relationships, presented in Figure 5, were derived from field measurements of biomass and as far as we are aware are the first such relationships derived specifically for FNO forests. Prior to modeling FNO forest C dynamics, the key input parameters, LAI and NPP, were validated through field measurements to ensure that values modeled using BEPS adequately reflected field observations. Results indicated that the BEPS model can be used to simulate NPP for FNO forests and that the model output is a suitable benchmark to support investigations of future C dynamics, using derived NPP as an input to InTEC.

4.1. The Historical C Stock and Balance of FNO Forest

The estimated vegetation C stock for the historical simulation period (1901–2004) indicated an average of 20.2 t C ha^{-1} for nonwetland FNO forest, which is comparable to treed forest-tundra ecotone in Russia (22.6 t C ha^{-1} [*Shvidenko and Nilsson*, 2003]) and Quebec (21.81–24.13 based on 0.5 conversion ratio from above ground to total vegetation C content and dry biomass to C content [*Nelson et al.*, 2009]) and is less than boreal forests growing on mineral soils in Finland (34 t C ha^{-1} [*Kauppi et al.*, 1997]). Results from the historical simulation period (1901–2004) indicated no statistically significant change in vegetation C stock, consistent with another independent study that also shows no change on overall productivity of tree species growing on FNO forests [*Girardin et al.*, 2016]. Our estimate for soil C stock for the historical simulation period indicated an average of 50.2 t C ha^{-1}, which is much lower than values documented in previous studies for comparable areas: 72 t C $ha^{-1}$for boreal forests growing on mineral soils in Finland [*Kauppi et al.*, 1997], 181.1 t C ha^{-1} for treed forest-tundra ecotone in Russia [*Shvidenko and Nilsson*, 2003], and ~190 t C ha^{-1} in the Hudson Plains ecozone in Canada [*Kurz et al.*, 2013], largely because we excluded treed wetlands from our study. The *Kurz et al.* [2013] estimate represents the total ecosystem C stock that is extrapolated from managed forest stand growth and yields information to the entire Hudson Plains ecozone and is therefore expected to be positively biased. The *Hugelius et al.* [2014] map of estimated 0–3 m soil organic C storage indicates that the Hudson Bay lowlands contain greater than 1000 t C ha^{-1}. However, this estimate is for the permafrost region, north of the study area, which is excluded from the current work and does not reflect the soil C content of the FNO treed ecosystems. To our knowledge, no other measurement-based estimates of vegetation and soil C stocks are available for nonwetland forests in the Far North of Ontario or other regions characterized by unmanaged forests growing on forest-tundra ecotone. Generally speaking, our estimates suggest that historically, during the 20th century, the nonwetland FNO forest stored 1.2 Pg C, with 0.3 Pg C in vegetation and 0.9 Pg C in soil over 172,155 km^2 area.

We project that a significant decrease of ecosystem C (-0.07 t C ha^{-1} yr^{-1}, $p < 0.001$) occurred in FNO forests during the 20th century, in response to a significant warming-induced decrease in soil C balance of about the same magnitude ($p < 0.001$). During the same period, mean annual temperature increased on average by 1.5°C in the study area, while precipitation remained steady (Figure 2). Therefore, further declines in soil C stocks may follow further increases in temperature as a consequence of higher soil respiration and organic matter decomposition. Using meta-analysis of observational data, *Bond-Lamberty and Thomson* [2010] report that boreal soil respiration increased by ~7% between 1989 and 2008, which is similar to our estimate of soil C stock decline of about 6.2% for the same period, although the two are not directly equivalent measures. *Bond-Lamberty and Thomson* [2010] further suggest that soil respiration in high-latitude ecosystems had the largest relative change, consistent with the large C stocks in, and greater degree of climate change being experienced by, these areas. In FNO nonwetland forest, precipitation is not a growth-limiting factor. Therefore, a 14.3% decline in soil C stock during 1901–2004 (Figure 7b) in response to a 1.5°C increase in mean annual temperature (Figure 2) is consistent with several studies indicating an exponential increase in soil respiration with temperature when soil moisture is nonlimiting [*Singh and Gupta*, 1977; *Raich and Schlesinger*, 1992; *Lloyd and Taylor*, 1994; *Kätterer et al.*, 1998]. Furthermore, the effect of warming on soil C release is contingent on the size of the initial soil C stock, with considerable losses occurring in high-latitude areas like FNO [*Crowther et al.*, 2016]. Generally speaking, our results suggest that the respiratory release of C from soil is a major, yet poorly understood flux in the forest C cycle and therefore needs further investigation, as recent studies show a better understanding of soil respiration [*Carey et al.*, 2016; *Crowther et al.*, 2016; *Gonsamo et al.*, 2017; *Wehr et al.*, 2016].

Canada's unmanaged forests, including those in the Far North of Ontario, are among the least studied vegetated ecosystems in the country. There are no inventory-based estimates of C balance for these forests. While theoretically, it should be possible to have a leading-order estimate using atmospheric inversion models, where changes in atmospheric CO_2 concentration reflect changes in C sinks, the limited gas sampling estimates needed for inversion models do not permit the extraction of results for unmanaged areas in Canada, let alone the FNO nontreed forests. Moreover, recent comparisons suggest that not only inversion models tend to estimate substantially larger C sinks than inventory-based approaches but also several models, including some ecosystem process models, do not agree on the direction of net C flux [e.g., *Hayes et al.*, 2011, 2012; *Huntzinger et al.*, 2012; *Kurz et al.*, 2013].

4.2. The Projected C Stock and Balance of FNO Forest

Our results indicate that the projected global changes under RCP8.5 and RCP4.5 greenhouse gas scenarios, with or without climate-induced fire, will generally result in enhanced biomass growth, which, after mid-21st century, will offset C losses caused by increased soil respiration and forest fires (Figures 7 and 8). This is in good agreement with a comparable study for continental Europe, where NPP surpassed fluxes from soil respiration and biomass burning under SRES A1, A2, B1, and B2 scenarios (see Figure 4 in *Zaehle et al.* [2007]). Furthermore, global change may result in a redistribution of the relative size of forest C pools, with less in soil and more in vegetation. One consequence may be increased fuel loading, making forests more susceptible to forest fire and insect disturbances. The projected long-term decline of the fraction of total ecosystem C stored in soil is primarily attributed to the increase in soil respiration due to post-1970s warming (Figure 2) and increased fire disturbance in the 1970s (Figure 6). However, once the metabolic and fast decomposing soil C pools that were accumulated under colder climate for centuries are exhausted, soil C release eventually stabilizes after the mid-2030s. The soil C release stabilization after mid-2030s can also partly be attributed to higher litterfall and increased fine root turnover from relatively larger projected vegetation C stock. Recent findings indicate that future respiration rates are likely to follow the current temperature response function, but higher latitudes will be more responsive to warmer temperatures [*Carey et al.*, 2016]. Boreal ecosystems have been the focus of considerable research and concern because the release of vast soil C stocks as these regions warm would provide a positive feedback to global warming [*Goulden et al.*, 1998], particularly since higher latitudes are projected to warm more than most lower latitudes in

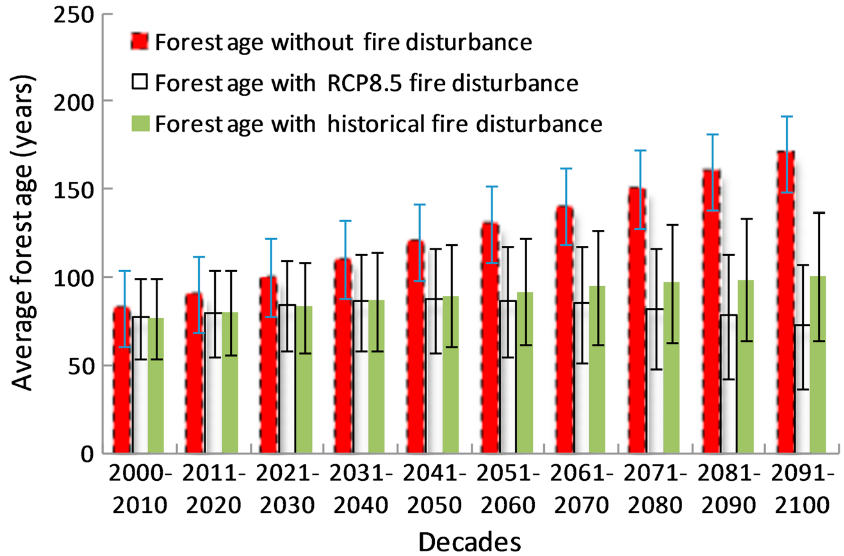

Figure 9. Average age of forest in the Far North of Ontario with simulated RCP8.5 forest fire disturbance, average historical (1960–2004) fire disturbance projected into the future (historical fire disturbance), and no fire disturbance. The error bars show the standard error of forest age (average of standard deviation of each year).

the coming century [*Hansen et al.*, 2006]. A gradual net loss of soil C in boreal forests has previously been attributed to warming-induced deepening of the layer of seasonal biological activity [*Goulden et al.*, 1998].

FNO forests are characterized mostly by slow-growing conifer species. Several studies have suggested that conifers are relatively more responsive to CO_2 than broadleaved species [*Saxe et al.*, 1998], with slower growing conifers showing greater responses [*Tjoelker et al.*, 1998]. Our results are in broad agreement with several observational and modeling studies that indicated CO_2 fertilization greatly increases both vegetation and soil C stocks, the latter through higher litterfall and increased fine root turnover [e.g., *Norby et al.*, 1999; *Friedlingstein et al.*, 2006; *Drake et al.*, 2011; *Hemming et al.*, 2013]. The evidence of CO_2 fertilization at the patch scale from the Free-Air CO_2 Enrichment (FACE) experiments is equivocal [e.g., *Ainsworth and Long*, 2005; *Leakey et al.*, 2009; *Norby and Zak*, 2011; *Nowak et al.,* 2004], although the FACE experimental setups allow interactions among C, water, and nutrients to be evaluated, as do most ecosystem process model frameworks, including InTEC. A comparison among general circulation models indicated no general consensus on the magnitude of NPP response to atmospheric CO_2 increase [*Friedlingstein et al.*, 2006]. Nevertheless, given that we use several measured benchmark data, projected N deposition, and Farquhar's leaf biochemical model, our results give a useful leading-order estimate of changes and sensitivities of forests growing in cold environment to CO_2 fertilization.

4.3. The Enhanced C Sink Mechanism From Fire-Caused Forest Regeneration Amplified by CO_2 Fertilization

The effect of fire on C balance raises an interesting question as to why, with progressively increased burned area in the RCP8.5 climate + CO_2 + fire simulation, forest C gradually increases throughout the 21st century. The C dynamics of postfire boreal forests has been investigated by several research groups [*Amiro et al.*, 2006, 2009; *Kurz et al.*, 2008b]. The effect of fire disturbance on stand age structure (Figure 9) is a key factor changing the projected C balance. The major impacts of fire on C balance are expressed through two processes. First, in InTEC simulations, part of C stock is released during fires through biomass combustion and biomass C remaining after fire is transferred to woody litter and surface metabolic and structural detritus. This may increase the soil C pool, depending on the amount of detritus C pools present before fire, while decreasing the vegetation C stock. Higher soil C pool following wildfire was also reported in a meta-analysis by *Johnson and Curtis* [2001], attributed to the sequestration of charcoal and recalcitrant, hydrophobic organic matter, and to the effects of naturally invading, postfire, N-fixing vegetation. In InTEC, the decomposition of dead organic matter is assumed to start the year after fire disturbance [*Chen et al.*, 2003] at different rates depending on the type of soil pool as standing dead trees may initially decompose at very slow rates, remaining standing for several years after fire, while fallen logs may decompose very slowly as they become part of the slowly decomposing soil organic matter C pool [*Nalder and Wein*, 1999].

The second major process affected by fire is changes in C dynamics of the postfire forest caused by changes in forest age (Figure 9). Fire replaces slower growing older forests with faster growing young forests. Young forests have smaller and often negative C balance compared to intermediate and old forests. Fire results in an immediate C loss and slow recovery of C balance as forests develop toward maturity. However, under a warmer climate and higher CO_2, the speed of C balance recovery of previously burned areas will be faster than C loss through decomposition, resulting in more productive postfire intermediate-aged forests. This mechanism is addressed in InTEC via a steep NPP-age curve until about age 50 (Figure 5) where the projected climate and CO_2 growth enhancements are superimposed on steep biomass return due to age. The new steep biomass return (i.e., NPP) is also allocated to live foliage biomass resulting in higher LAI for photosynthesis than those forest replaced by fire. In contrast, if the forest simply ages with historical fire disturbance rates or without fire with contemporary CO_2 concentration and climate (see "age" and "historic fire" simulations in Figure 8), C stocks will be much lower than those for the other scenarios we modeled. *Yue et al.* [2013] also reported increased postfire C sinks due to a combination of CO_2 fertilization and forest succession. We believe this shows that increase in growth from CO_2 fertilization has a proportionally larger effect on intermediate-aged than older forest. Greater CO_2 fertilization effect in younger and intermediate-aged compared to older forests was also reported in experimental studies [e.g., *Hättenschwiler et al.*, 1997]. In the long term, fire disturbance losses are negated by regrowth of more productive vegetation.

Atmospheric CO_2 is projected to increase the C sink the most, without which forest age alone is projected to result in net C loss throughout the 21st century (Figure 8). Projected CO_2 fertilization more than offsets increased C emissions due to fire. Our results are in good agreement with a previous study by *Balshi et al.* [2009b], who also found that the projected combination of CO_2, climate, and fire makes the FNO a C sink for the period 2003–2100. However, our results do not agree with those of *Metsaranta et al.* [2010], whose simulations project that Canada's managed forest may be a cumulative C source from 2010 to 2100, even if annual burned area does not increase, which may reflect the fact that they do not account for the C sink enhancing mechanisms of N deposition and CO_2 fertilization. Finally, the strength of this study is based on the use of large sets of measured data both to parameterize the InTEC model and to validate key input surface variables such as LAI and NPP. However, several challenges and limitations remain, which are discussed below.

5. Challenges and Limitations

The simulations conducted in this study that include the effects of fire should be interpreted as a conservative estimate of possible fire effects on C stock and balance in FNO forest for two reasons: (1) we allocated fire to all burnable pixels with vegetation older than 11 years, and (2) the fire prediction model using CFWI is known to perform poorly in eastern Canada, greatly underestimating burned area compared to the other parts of Canada and northwest U.S. [*Balshi et al.*, 2009a]. If we had allocated the burned area preferentially to older stands, the C stock during the 21st century would have been significantly lower because older stands contain larger C stock, which would be emitted through biomass combustion and decomposition of fire-killed trees, and the new forest would emit more C until sequestration surpassed C released by decomposing organic matter.

Projecting future C dynamics based on potential climate and atmospheric CO_2 inherently has potential for significant error. Both forest C cycle and climate model projections are uncertain due to the highly unpredictable nature of climate change and its effects. Furthermore, the dynamics of forest age as influenced by disturbance may affect C cycling more than climate change. Future disturbance regimes are difficult to predict. We only considered forest fire effects, and other disturbances such as insects and disease were overlooked. This may result in overestimated C sink estimates. Nonetheless, changes in climate will alter ecosystem composition and much more study and attention must be paid to the potential consequences of these changes.

Our factorial simulations did not consider changes in leaf- and tree-level ecophysiology in responses to changes in vapor pressure deficit and atmospheric humidity. Although we believe these are of second-order importance in terms of FNO C cycle, where changes in disturbance and temperature are the dominant driving factors, they are critical to understand how leaf-level physiological dynamics manifest under global change. Nevertheless, InTEC model follows the strategy of the TEM model [*Pan et al.*, 1998] to calculate the intercellular CO_2 concentration as a function of the ratio of actual evapotranspiration to potential evapotranspiration to account for the changes in stomatal conductance related to soil moisture availability (see details in *Ju et al.* [2007]).

FNO forest is one of the least studied forest ecosystems in Canada. Although we have excluded treed-wetlands in our current analysis, we believe that the soil C pool may still be underestimated in our study, given that the FNO nonforested bogs and fens store approximately 36 Pg C [*McLaughlin and Webster*, 2013], with Hudson Bay Lowlands alone storing 30 Pg C [*Packalen et al.*, 2014, 2016; *Packalen and Finkelstein*, 2014]. Soil and vegetation C stocks in the FNO are poorly documented due to the remoteness of the region, and we expect that many of the forests are on peat deposits and not on mineral soil as was assumed in this study.

Several other challenges were also encountered when coupling future burned area to the current framework of InTEC. The first challenge was extrapolating the climate-fire relationship observed for six fire grids to the entire FNO, which required several assumptions. For the sake of simplicity, we evenly distributed the burned area estimates for each year to all FNO burnable land pixels with stands older than 11 years. This assumption may result in underestimating the projected burned area and its effect on C storage and balance. Although the accuracy of future stand age distributions and their spatial pattern depends on the accuracy with which stand ages in year 2004 were assigned, making the entire FNO burnable can be considered a robust approach. Changes in climate are likely to be accompanied by increases in fuel loading in areas that have not historically burned and therefore are more likely to burn if warmer, drier conditions prevail. Accounting for future fire in grid cells that are historically assumed not to burn would be a possible effect of changes in climate on FNO.

One of the main limitations of the current study is that our C balance estimates are based on a fixed vegetation distribution (in space and time). This can be problematic since C dynamics can be influenced for several decades following fire due to differences in postfire responses of different vegetation types (e.g., deciduous versus coniferous) [*Amiro et al.*, 2006]. Nonetheless, if fire were to migrate into areas currently dominated by wetlands, the reductions in C storage and effects on overall C balance could be significant. If fire seasons become longer, burn depth may increase (i.e., greater severity) due to the potential for drier conditions in the duff layer in addition to deeper soil thaw. Increases in fire severity have the potential to decrease the amount of insulating moss and soil organic layers, which can also feedback to soil thermal and permafrost regimes by increasing the active layer depth and thawing of permafrost [*Hinzman et al.*, 2003].

6. Conclusions and Recommendations

The main objectives of this work were to quantify the past, current, and future C stocks and to study the relative impacts of CO_2 fertilization, climate change, and climate-induced changes in fire regime on future C balances of Far North of Ontario (FNO) forests, one of the least studied forest ecosystems in Canada. Although we encountered many challenges and limitations (see section 5), we can conclude the following based on our findings. For the historical period (1901–2004), the FNO treed ecosystem vegetation C stock remained stable, while the soil C stock gradually declined due to increased soil respiration in response to the steady increase in mean air temperature. This resulted in an overall significant decrease in total ecosystem C stock, indicating that the FNO treed ecosystems had likely been a small C source for much of the studied historic period. The same trends in the soil and ecosystem C balances continued until the mid 21st century, after which the higher litterfall and increased fine root turnover from a relatively larger projected vegetation C stock exceeded the soil C loss. On average, the simulations of future (2007–2100) C balances indicated that the CO_2 fertilization and climate growth enhancing effects of global change will outweigh C loss through increased ecosystem respiration, disturbance, and changes in forest age class structure. The opposing impacts of projected global change on soil and vegetation C stocks resulted in changes in the relative sizes of forest C stocks—less in soil and more in vegetation. This increases the fuel loads and makes the entire ecosystem more susceptible to forest fire and insect disturbances.

Our simulations did not dynamically include postfire vegetation changes in response to changes in climate (i.e., vegetation types were static). Incorporating the role of dynamic vegetation and temporal changes in fire severity and other disturbances in future modeling studies is important. This is particularly indispensable with respect to capturing a better representation of C storage and balance at the time of disturbance as well as the C dynamics associated with the secondary successional processes following disturbance. Interactions between fire severity, soil temperature, and slow soil C pools should be considered in future work. Finally, it is important to consider the role of other disturbances (e.g., insects and disease [*Arora et al.*, 2016]) and how they interact with fire regime across the FNO [e.g., *Fleming et al.*, 2002]. As insect outbreaks and disease result in more available fuel for disturbance by wildfire, larger and more frequent fires may have greater impacts on FNO C stocks than historically observed. Incorporating the response of disease and insect disturbances to climate change and the interactions between these disturbances and the fire regime may improve projections of forest C balance.

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