Title

Wildfire exacerbates high-latitude soil carbon losses from climate warming

Journal
Environmental Research Letters, 17(9)

ISSN
1748-9318

Authors

Mekonnen, Zelalem A
Riley, William J
Randerson, James T
et al.

Publication Date
2022-09-01

DOI
10.1088/1748-9326/ac8be6

ENVIRONMENTAL RESEARCH
LETTERS

Wildfire exacerbates high-latitude soil carbon losses from climate warming

To cite this article: Zelalem A Mekonnen *et al* 2022 *Environ. Res. Lett.* **17** 094037

IOP Publishing *Environ. Res. Lett.* **17** (2022) 094037 https://doi.org/10.1088/1748-9326/ac8be6

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
23 May 2022

REVISED
9 August 2022

ACCEPTED FOR PUBLICATION
23 August 2022

PUBLISHED
9 September 2022

LETTER

Wildfire exacerbates high-latitude soil carbon losses from climate warming

Zelalem A Mekonnen[1,*], **William J Riley**[1], **James T Randerson**[2], **Ian A Shirley**[1], **Nicholas J Bouskill**[1] **and Robert F Grant**[3]

[1] Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, United States of America
[2] Department of Earth System Science, University of California, Irvine, CA, United States of America
[3] Department of Renewable Resources, University of Alberta, Edmonton, Canada
[*] Author to whom any correspondence should be addressed.

E-mail: zmekonnen@lbl.gov

Keywords: soil carbon dynamics, high-latitude carbon cycle, wildfire and climate warming, nutrient cycling, vegetation change

Supplementary material for this article is available online

Abstract

Arctic and boreal permafrost soil organic carbon (SOC) decomposition has been slower than carbon inputs from plant growth since the last glaciation. Anthropogenic climate warming has threatened this historical trend by accelerating SOC decomposition and altering wildfire regimes. We accurately modeled observed plant biomass and carbon emissions from wildfires in Alaskan ecosystems under current climate conditions. In projections to 2300 under the RCP8.5 climate scenario, we found that warming and increased atmospheric CO_2 will result in plant biomass gains and higher litterfall. However, increased carbon losses from (a) wildfire combustion and (b) rapid SOC decomposition driven by increased deciduous litter production, root exudation, and active layer depth will lead to about 4.4 PgC of soil carbon losses from Alaska by 2300 and most (88%) of these loses will be from the top 1 m of soil. These SOC losses offset plant carbon gains, causing the ecosystem to transition to a net carbon source after 2200. Simulations excluding wildfire increases yielded about a factor of four lower SOC losses by 2300. Our results show that projected wildfire and its direct and indirect effects on plant and soil carbon may accelerate high-latitude soil carbon losses, resulting in a positive feedback to climate change.

1. Introduction

The northern hemisphere high-latitude region contains large amounts of soil organic carbon (SOC) that has accumulated over thousands of years (Oechel *et al* 1992, Hobbie *et al* 2000). Cold temperatures in this region limit SOC decomposition rates, leading to slow net ecosystem carbon accumulation (Oechel *et al* 1992, Hobbie *et al* 2000), primarily in areas underlain by permafrost. However, this historical trend may be threatened by recent anthropogenic climate warming which is causing accelerated decomposition (Schuur *et al* 2015, Natali *et al* 2019) and altering wildfire regimes (Kasischke *et al* 2006, Flannigan *et al* 2009, Chen *et al* 2021). Recent and projected increases in the intensity and frequency of wildfires may exacerbate SOC losses (Balshi *et al* 2009a, Walker *et al* 2019, Chen *et al* 2021), thus contributing to a positive feedback with climate warming (Euskirchen *et al* 2009, Li *et al* 2017).

Carbon loss from wildfire is a major controller of northern ecosystem carbon balances (Bond-Lamberty *et al* 2007, Balshi *et al* 2009a, Walker *et al* 2019, Chen *et al* 2021, Mack *et al* 2021). Wildfire may affect the carbon cycle through a direct effect on combustion losses (Amiro *et al* 2001, Mack *et al* 2011), which may offset a substantial fraction of long-term net ecosystem carbon uptake (Kurz *et al* 2008, Walker *et al* 2019). With projected increases in wildfire, carbon losses from combustion may slow or reverse the historical carbon sink of northern ecosystems (Kurz *et al* 2008, Walker *et al* 2019, Wang *et al* 2021).

Wildfires also indirectly affect a complex set of soil–plant–atmosphere interactions that may alter ecosystem carbon balances (figure 1) (Liu 2005,

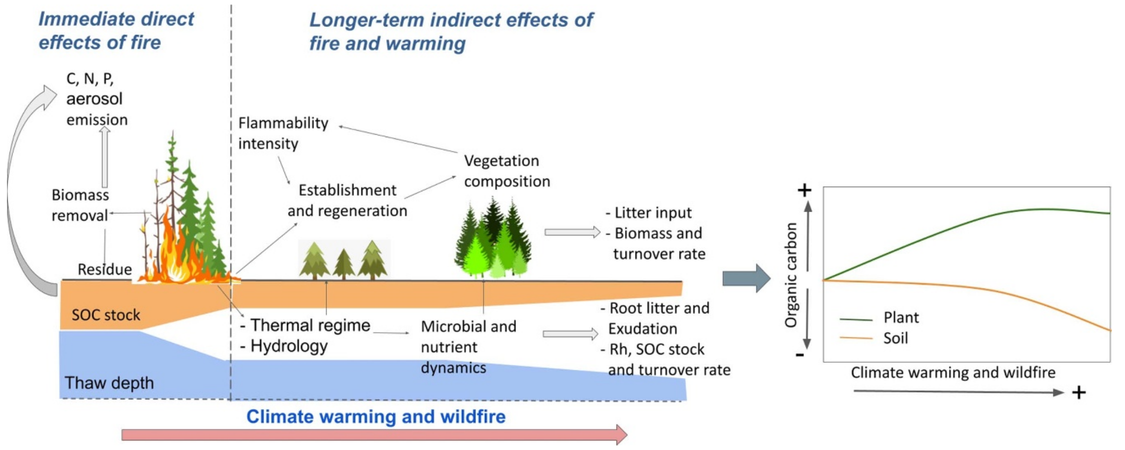

Figure 1. Immediate direct and longer-term indirect effects of wildfire interact with warming to influence high-latitude soil carbon stocks. Immediate direct effects of fire include combustion losses of plant and soil organic carbon. Longer-term indirect effects of climate warming and wildfire include a complex set of soil–plant–atmosphere interactions such as surface and subsurface thermal and hydrological processes that affect heat transfer and permafrost degradation, nutrient cycling, and vegetation composition, thereby affecting litter inputs and soil organic carbon microbial decomposition rates. Signs (±) on the arrows represent increases or decreases. The vertical dashed line separates the immediate direct effects (left) and the long-term indirect effects (right) of wildfire on soil carbon stocks. We hypothesize that these immediate and longer-term effects lead to increases in plant carbon gains and litter inputs that do not fully offset losses to SOC stocks in a warmer climate.

Brown and Johnstone 2011, Mack *et al* 2021, Bouskill *et al* 2022). Loss of an insulating surface litter layer (Grosse *et al* 2011, Mack *et al* 2011) may alter surface energy balances, surface and subsurface thermal and hydrological processes that affect heat transfer, soil temperatures (Jiang *et al* 2015), and seedbed quality, thus affecting plant regeneration and establishment (Johnstone *et al* 2010, Lantz *et al* 2010). Warmer soils after fire may increase the active layer depth (Iwahana *et al* 2016, Gibson *et al* 2018, Michaelides *et al* 2019) and permafrost degradation and subsidence, particularly in ice-rich soils (Brown *et al* 2015, Zhang *et al* 2015, Holloway *et al* 2020). Surface litter losses from combustion and subsequent slow recovery to pre-combustion levels allow greater soil warming and permafrost retreat and accelerated decomposition (Harden *et al* 2006, Holloway *et al* 2020). Ecosystem carbon dynamics are also sensitive to climate-driven changes in high-latitude vegetation (Camill *et al* 2009, Bouskill *et al* 2020, Wang *et al* 2020, Mack *et al* 2021). Further, interactions between climate warming and wildfire may change vegetation composition (Johnstone *et al* 2010, Mekonnen *et al* 2019, Frost *et al* 2020, Liu *et al* 2022), and thus quality and quantity of litter inputs and carbon decomposition (Neff *et al* 2005, Christiansen *et al* 2018) and turnover rates (Hobbie *et al* 2000). Elevated atmospheric CO_2 accelerates plant nutrient demand (Hobbie *et al* 2002) and nutrient cycling (Jarvis and Linder 2000), and warming stimulates plant growth, thereby increasing the rate of plant carbon uptake (Hobbie *et al* 2002, Strömgren and Linder 2002). The resulting plant growth increases litter inputs (Leppälammi-Kujansuu *et al* 2014) to the soil and may lead to ecosystem carbon accumulation (Loisel and Yu 2013), partly offsetting combustion losses (Kurz *et al* 2008). The net effect of these contrasting and interacting processes on high-latitude soil carbon stocks is uncertain.

To disentangle the direct and indirect effects of wildfire on ecosystem and SOC stocks, we evaluated and applied a widely-tested ecosystem model, *ecosys* (Grant *et al* 2019a), across the tundra and boreal ecosystems of Alaska during historical and future time intervals. We hypothesized that climate warming and increasing atmospheric CO_2 will enhance plant carbon uptake, plant biomass, and thereby litter carbon inputs to the soil. However, accelerated soil decomposition and combustion losses from wildfire will offset the gains in litter inputs resulting in net SOC losses. We addressed this hypothesis using *ecosys*, which includes mechanistic representations of the relevant ecosystem carbon cycling processes: combustion losses of C, N, and P; prognostic post-fire successional trajectories; and fully coupled above and belowground biological, thermal, and hydrological processes (see model description in supplemental material).

2. Methods

The responses of the model to climate warming and wildfire have been rigorously tested against observations from field measurements (e.g. eddy-covariance flux towers and long-term monitoring sites (Mekonnen *et al* 2016, Riley *et al* 2021, Shirley *et al* 2022) in many high-latitude sites, and large-scale remote-sensing (Mekonnen *et al* 2017) products (Supplementary I Methods). In a recent study (Mekonnen *et al* 2019), we modeled the vegetation composition of Alaska ecosystems, and successfully tested against the land cover derived from

LANDFIRE's Fuel Characteristic Classification System maps (Prichard *et al* 2013).

2.1. Model description

2.1.1. Carbon uptake

The model, *ecosys*, includes multiple canopy and soil layers with fully coupled carbon, energy, water, and nutrient cycles at an hourly time step. Atmospheric warming increases surface heat advection, and soil heat transfers (Grant *et al* 2017, 2019a, Mekonnen *et al* 2021). Carbon uptake is controlled by plant water status, calculated from convergence solutions that equilibrate the total root water uptake with transpiration. Canopy temperatures affect CO_2 fixation rates through effects on carboxylation and oxygenation rates modeled with Arrhenius functions for light and dark reactions. Soil warming enhances carbon uptake by hastening microbial mineralization and root nitrogen uptake. Carbon uptake is affected by phenology; leafout and leafoff (deciduous plants) or dehardening and hardening (evergreen plants) are determined by accumulated exposure to temperatures above set values while day length is increasing or below set values while day length is decreasing. Senescence is driven by excess maintenance respiration and by phenology in deciduous plant functional types.

2.1.2. Soil carbon decomposition

The model represents fully coupled transformations of soil carbon, nitrogen, and phosphorus through microbially driven processes. The model represents five organic matter-microbe complexes: coarse woody litter, fine non-woody litter, manure, particulate organic matter, and humus. The decomposition rate of each organic matter-microbe complex is determined by the active biomass of heterotrophic microbial populations and the substrate concentration (Grant 2013). Surface energy and water exchanges drive soil heat and water transfers that determine soil temperatures and soil-water content across soil layers. These transfers drive soil freezing and thawing, and therefore active layer depth, through the general heat flux equation. Decomposition rate is controlled by soil temperature through an Arrhenius function and by soil water content through its effect on aqueous microbial concentrations. Soil temperature and water content are calculated from surface energy and water exchanges coupled with soil heat and water transfers through atmosphere-canopy-snow-surface residue-soil profiles (Grant *et al* 2019b). Decomposition generates dissolved organic carbon that drives microbial growth through heterotrophic respiration. The rate of heterotrophic respiration is also controlled by microbial N and P concentrations, dissolved organic carbon, soil temperature, oxygen concentration, and soil water potential. Total heterotrophic respiration drives CO_2 emission from soil through diffusion and volatilization in aqueous and gaseous phases (Grant *et al* 2017). A detailed description of inputs, parameters and algorithms used in *ecosys* is found in supplementary information II.

2.2. Simulation design

In this study, we initialized the model with equal seed carbon of five plant functional types (deciduous, evergreen, sedge, moss, lichen) across all grids. Soil attributes were obtained from large-scale gridded datasets to initialize the model. The clay and sand fraction, pH, cation exchange capacity, and bulk density in the model were initialized from the Unified North America Soil Map (Liu *et al* 2013) gridded to a 0.25° × 0.25° spatial resolution across vertical soil profiles. The SOC resolved across vertical soil profiles was initialized using data from the Northern Circumpolar Soil Carbon Database (Hugelius *et al* 2013). Temporally dynamic climate forcing and atmospheric CO_2 concentrations were used for historical and future simulations. Surface air temperature, precipitation, incoming shortwave radiation, relative humidity, and wind speed from 1980 to 1989 taken from the 3 h time-step North American Regional Reanalysis (NARR) (Wei *et al* 2014), linearly interpolated to 1 h, and cycled through 1900–1979 were used to spin-up the model. The earlier 10 years of NARR were selected to reduce the effects of amplified warming events during the later years on model spin-up. The full NARR time series was used to force the model from 1979 to 2018. Anomalies for future climate (through 2300) were derived from Representative Concentration Pathway 8.5 (RCP8.5) of the CCSM4 climate model. The CCSM4 was selected since it was shown to have a long-term (to year 2300) representation of the permafrost in the northern ecosystems and exhibited higher performance compared to current temperature and precipitation estimates (McGuire *et al* 2018).

Historical and projected stand-replacing fire time series were applied in *ecosys* (figure S2). The frequency of Alaska wildfire under past climate was modeled statistically using the Mean Fire Return Interval (MFRI) dataset of the LANDFIRE product (Rollins 2009), which estimates the average time between presumed past fire events (Mekonnen *et al* 2019). A temporal distribution of individual fire events was modeled in *ecosys* on the basis of stand-age-dependent fire-event-return intervals generated from a normal distribution of the base MFRI for each grid cell and the probability of fire occurrence in a grid cell was set to be dependent on the stand age as described in Mekonnen *et al* 2019. Increase in wildfire frequency under future climate was applied to the baseline to match projected changes in burned area. Projected changes in burned area over the 21st century were applied to the base MFRI using an estimated rate of increase of 350% by 2100 (Balshi *et al* 2009b). The burned area beyond the 21st century was set to increase with a rate normalized by changes in mean annual maximum temperature of CCSM4 (figure S1). All fire events were set as stand-replacing with prescribed fractions of combusted below- and above-ground biomass, SOC, nitrogen, and phosphorus. In addition to direct losses of nutrients from combustion, the model also simulates losses from leaching. We prescribed a depth of burn to 15.1 cm on the basis of observed mean depth of burn (median = 14.2 cm, and standard deviation = 6.2 cm) (Boby *et al* 2010, Turetsky *et al* 2010, Rogers *et al* 2014) from 235 burned sites across Alaska. Fire is projected to increase with warming and therefore in our simulation the depth of burn was set to linearly increase to a maximum of 26.5 cm (equivalent to the 95th percentile of data from the 235 burned sites) by 2100 and was maintained beyond 2100 through 2300. This increase in burned depth was prescribed to mimic expected increases in burn severity while maintaining a realistic range based on severe current fire conditions in the current Alaskan boreal forest. We conducted a sensitivity simulation in the absence of fire after the year 2000 while keeping all other model forcing and parameters the same, to partition the effects of fire under the future climate on SOC dynamics.

3. Results and discussion

3.1. Modeled vs. observed biomass, burned area, carbon emissions

Here, we further evaluated modeled biomass (Mekonnen 2022) using a data-derived biomass product (Xu *et al* 2021) of Alaska (figure 2). The modeled biomass agreed well across the region with the data-derived biomass (geographically weighted regression, GWR, $R^2 = 0.62$). We also tested the modeled burned area, carbon emissions, and carbon combustion losses against three remote sensing and observation-derived products (Alaskan Fire Emissions Database (AKFED)) (Veraverbeke *et al* 2015), the Wildland Fire Emissions Information System (WFEIS) (French *et al* 2011), and the Global Fire Emissions Database version 4 with small fires (GFED4s) (Randerson *et al* 2012). The modeled annual burned area (5810 ± 185 km^2), annual carbon emissions (14.4 ± 3.9 Tg C), and mean carbon combustion (2.47 ± 0.9 Kg C m^{-2}) are within the uncertainty ranges of the datasets, except for the annual carbon consumption estimates from WFEIS, which is much higher compared to the model and the AKFED and GFED4s products (figure 2). We note that our modeled burned area was in the lower range of the observations, suggesting slightly conservative model estimates (figures 2(c)–(e)). The modeled carbon combustion values are also consistent with measurements at field sites (2.88 ± 0.23 kg C m^{-2}) in interior Alaska (Rogers *et al* 2014).

3.2. Effects of fire on plant biomass and NPP

Plant biomass and SOC dynamics under changing climate and wildfire are linked. We first describe modeled plant changes and then discuss SOC changes and relevant plant-soil interactions. We found that warmer climate and higher levels of atmospheric CO_2 (figure S1) resulted in NPP increases in both Alaskan Arctic tundra and boreal forests by 2100 (figure 3). Gains in NPP and the transition from black spruce to fast-growing deciduous trees (aspen) in the boreal forest resulted in greater biomass. Plant NPP increases continued after 2100 and resulted in further biomass accumulation (figure 3(c)). The spatial mean of biomass modeled during 2100 (3691 gC m^{-2}) and 2300 (4459 gC m^{-2}) are within the ranges of currently observed biomass values from warmer areas in the boreal forest (figure 2(a)).

The modeled gains in plant carbon are attributed to warming-induced enhanced carbon fixation rates and nitrogen availability from more rapid microbial mineralization driven by warmer soils, deeper active layers, and more rapid symbiotic and non-symbiotic N_2 fixation. These carbon fixation responses drive more rapid autotrophic and heterotrophic respiration and greater root nitrogen uptake (figure S3). We showed that, although there is substantial spatial heterogeneity in NPP and biomass changes over the 21st century and beyond, sustained increases in productivity integrated over Alaska are expected (figures 3(b) and (d)), suggesting that warmer climates will likely result in plant carbon gains in cold tundra and boreal forest systems.

3.3. Post-fire carbon trajectories under current and warmer climate

Post-fire ecosystem carbon trajectories varied under different future climates (figure 4). On average across Alaska, modeled NPP recovered about 30 years after fire under recent climate vs. a more rapid recovery (about 15 years) in the warmer climate around 2100 (figure 4(b)). NPP was also shown to rapidly increase in the first few years following fires at the end of the 20th and 21st centuries and continued steadily for 50 years post-fire (figure 4(b)). Despite a rapid NPP recovery under future warming (e.g. after fire events during 2240–2250), we modeled a decline in NPP after about 20 years post-fire.

Similar to NPP, post-fire SOC stock trajectories were modeled to vary with climate (figures 4(a) and (c)). SOC dynamics following a fire are affected by factors that determine soil litter inputs, carbon removal through combustion, and surface and subsurface losses. Residue carbon (total carbon on the soil surface from litterfall and in the soil profile from root litter and exudation, and microbial carbon) increased in the first year following fire events and then rapidly declined in subsequent years as a result of accelerated decomposition from warmer post-fire soil temperatures (figure 4(a)). Post-fire residue carbon may take more than 50 years to recover to pre-fire

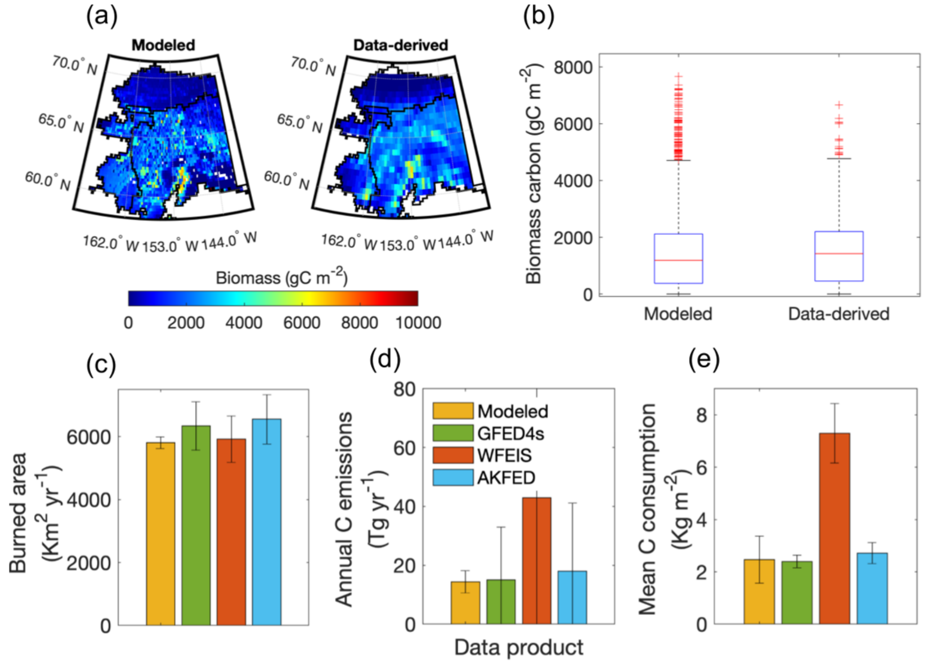

Figure 2. Modeled biomass, burned area, annual carbon emissions, and mean carbon consumption agreed well with data-derived products across Alaska. The modeled (a) biomass agreed well with a data-derived product (Xu *et al* 2021) for the 2006–2010 period. The boxes in panel (b) represent biomass mean and 25th and 75th percentile bounds. The bar graphs (c)–(e) shows modeled and data-derived (Alaskan Fire Emissions Database (AKFED)), Wildland Fire Emissions Information System (WFEIS), and Global Fire Emissions Database version 4 with small fires (GFED4s) (Veraverbeke *et al* 2015) estimates of mean (2001–2010) annual (c) burned area, (d) carbon emissions, and (e) mean carbon consumption (annual emissions per annual burned area). The error bars in panels (c)–(e) represent one standard deviation.

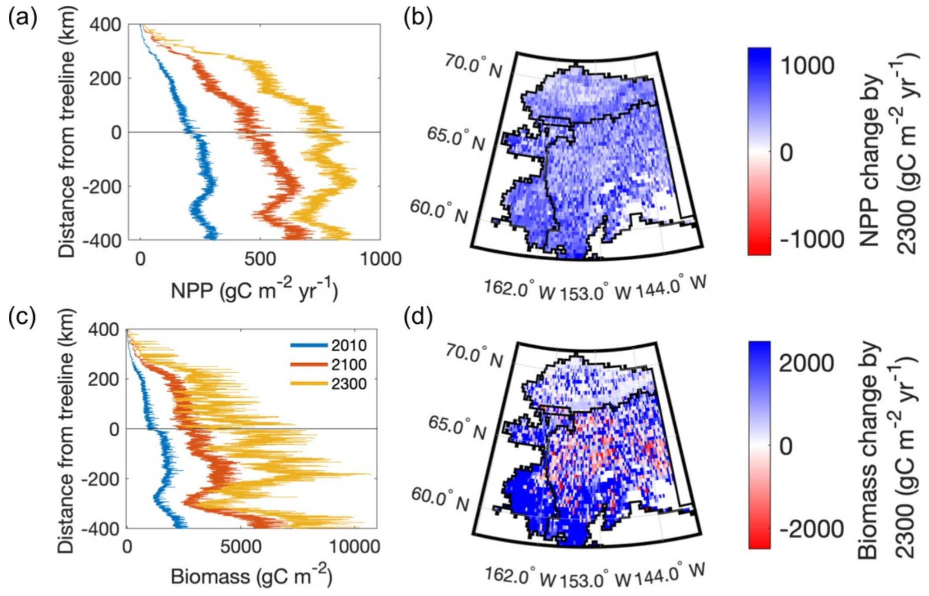

Figure 3. A warmer future climate increases NPP and plant biomass. Net primary productivity and biomass increased under climate warming and wildfire through 2300. Increases in (a), (b) NPP and (c), (d) biomass in the Arctic tundra and boreal forests of Alaska. Changes (average of 2000–2010 subtracted from the average of 2290–2300) in NPP and biomass (b), (d) show spatial heterogeneity within most regions (north and south of the treeline) experiencing increases in NPP and biomass. The zero lines in (a), (c) represent the treeline, positive values represent north, and negative values south of the treeline. The treeline is defined here as the transition zone between a climate zone that supports growth of trees (boreal) and the arctic tundra. Spatial average modeled biomass varies with time (during years 2000 (1505 gC m^{-2}), 2100 (3691 gC m^{-2}), and 2300 (4459 gC m^{-2})). NPP and biomass in northern gridcells in years 2100, 2200, and 2300 are consistent with observed values in currently productive southern Alaska gridcells (figure 2(a)).

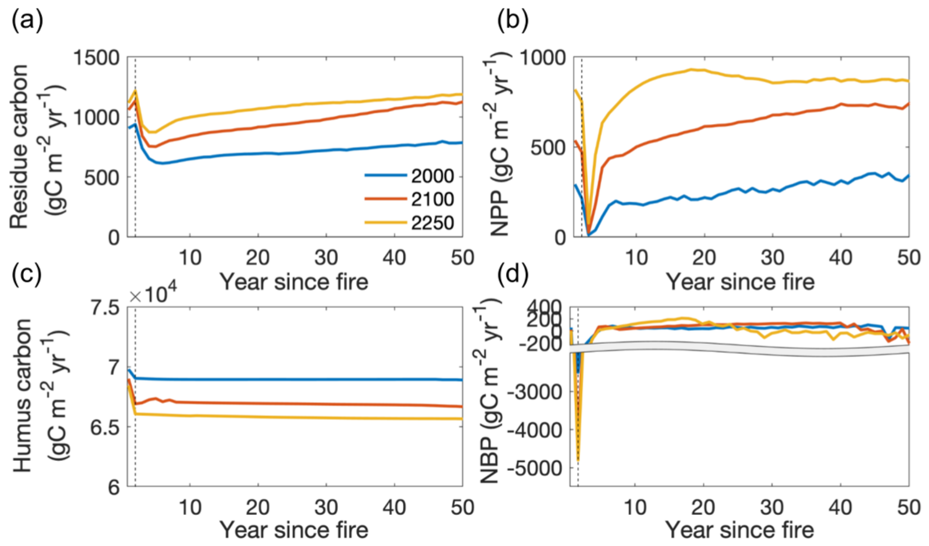

Figure 4. NPP recovery following fire accelerated under climate change. Changes in (a) residue carbon (total soil surface litterfall and soil profile litterfall + root exudation, including microbial carbon), (b) humus carbon (residue decomposition products), (c) net primary productivity, and (d) net biome productivity, spatially averaged and excluding re-burning of grid cells that burned in years 2000–2010, 2090–2100, and 2240–2250. The post-fire trajectories differed under different future climates. The vertical dotted black lines indicate the end of the year in which fire occurred. The gray line in d is a break in the *Y* axis.

levels, with slower recovery rates from lower residue carbon inputs under current vs. warmer climates (figure 4(a)). Residue carbon pool was the largest under future climate from the greater modeled net primary production that resulted in more residue carbon inputs following fire. Similarly, post-fire humus carbon substantially declined under past and future climates (figure 4(c)). The decline in post-fire humus carbon was higher during fire events under warmer climates, which we partly attribute to greater combustion intensity with climate warming (Methods). During fires in 2250, the overall decline in humus carbon stock post-fire was modeled to be high, from previous frequent fire events and rapid decomposition of the top soil layer that reduced soil carbon stocks. Under all past and future climatic conditions, post-fire humus carbon declined concurrently with rapid decomposition of residue carbon (figure 4(c)). Further, humus carbon stocks did not recover within 50 years postfire. The most rapid decline of humus carbon was modeled under warmer climate conditions that led to accelerated decomposition rates. This result suggests that climate warming beyond 2100 under the RCP8.5 climate scenario may result in severe effects on SOC stocks following wildfires. This result is consistent with other studies that show severe fire events leading to higher combustion losses of carbon and slower recovery in the tundra and boreal ecosystems (Jin *et al* 2012, Holden *et al* 2016). Under future climate, these losses may also be exacerbated by greater fuel availability (Gaboriau *et al* 2020, Walker *et al* 2020) and plant litter inputs with greater NPP driven by warmer climate and elevated atmospheric CO_2.

3.4. Effects of fire on SOC and net ecosystem carbon balance

The overall effects of fire on SOC (residue + humus), net ecosystem productivity (NEP = NPP- RH), and carbon losses through combustion and surface and subsurface transport of dissolved organic and inorganic carbon resulted in a post-fire net biome productivity (NBP = NEP−disturbance losses) of −2500 gC m^{-2} yr^{-1} averaged during fire events in years 2000–2010 (figure 4(d)). During this period, NBP recovered in less than 10 years following fires. We modeled that the fire-induced carbon losses were larger under warming beyond 2100 (e.g. postfire carbon losses were >4000 gC m^{-2} during fire events in years 2090–2100 and 2240–2250), suggesting that wildfires under future climate may accelerate net ecosystem carbon losses. After a rapid initial brief recovery from net ecosystem carbon losses following fire events in years 2240–2250, we modeled that carbon losses continued for 50 years after fires, implying an adverse long-term impact of fire with further warming (figure 4(d)).

SOC dynamics across Alaska varied with soil depth (figure 5(a)). Enhanced carbon uptake under warmer climates resulted in an increase in biomass and thus litter inputs (figure 5(b)) and litter layer carbon stocks through 2300. Litter carbon stocks increased under warming until about 2200 and then remained relatively stable (figure 5(a)). Although a sustained increase in litter inputs may result in SOC accumulation in the litter layer, our modeling analysis shows that combustion losses and accelerated SOC decomposition offset increases in soil carbon (figure 5(a)). Rapid decomposition from warmer soil

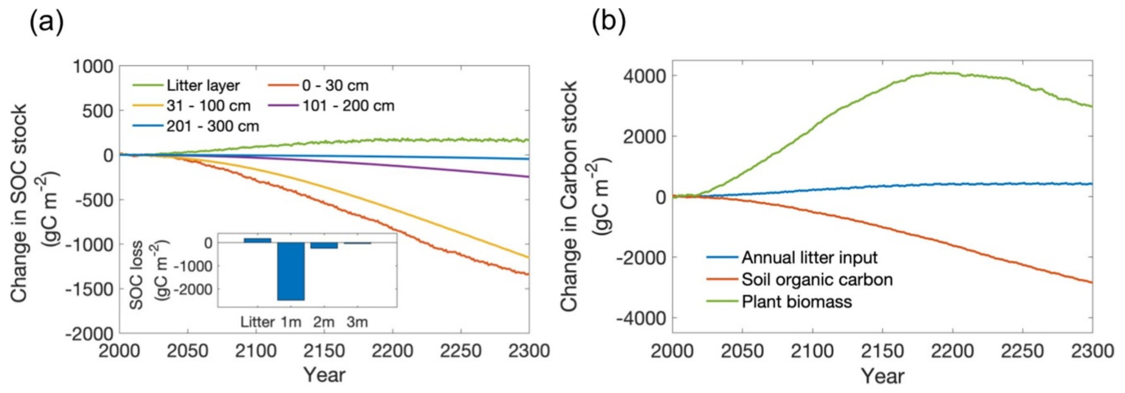

Figure 5. Most future soil organic carbon losses occur in the top 1 m of soil. Modeled changes (average of years 2000–2010 subtracted from stocks of each year) in spatially averaged (a) litter and soil carbon across Alaska were shown to change under climate warming from 2000 to 2300. The magnitude of these changes vary with depth (shown are changes aggregated to the litter layer, 0–30 cm, 31–100 cm, 101–200 cm, and 201–300 cm) and (b) annual, litter input, soil carbon stock, and biomass. We modeled divergent trends of high-latitude plant and soil carbon under future warmer climates: sustained plant carbon gains vs. soil carbon losses.

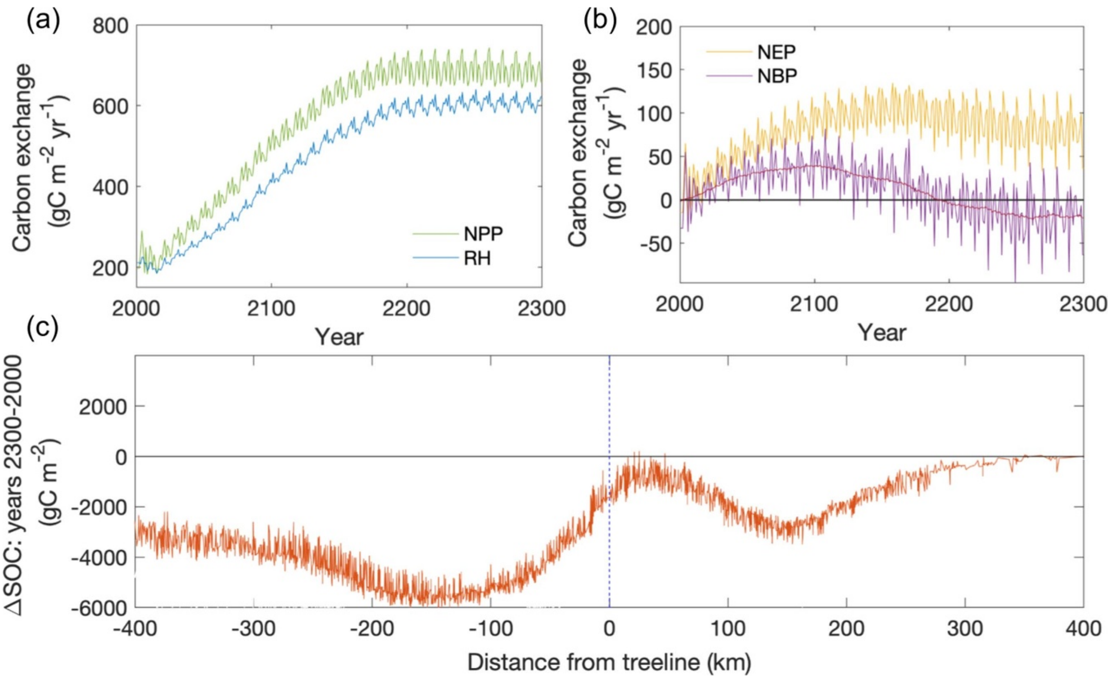

Figure 6. Substantial soil organic carbon losses and accelerated heterotrophic respiration drive Alaskan ecosystems to be a carbon source under warmer climates. Modeled spatial average (a) net primary productivity (NPP), and heterotrophic respiration (RH), (b) net ecosystem productivity (NEP = NPP − RH), and net biome productivity (NBP = NEP − losses (fire, surface, and subsurface), (c) spatial average changes (average of years 2000–2010 subtracted from the average of years 2290–2300) in SOC stock had large spatial heterogeneity; regions in interior Alaska experienced the largest declines. The magnitude and relative changes of these fluxes and their subsequent effects on the net carbon balance vary with climate. The vertical line at zero in panel (b) represents the treeline; positive values are to the north and negative values are to the south.

and permafrost thawing caused decreases in deeper SOC; the largest declines occurred between 0 and 100 cm, followed by those between 100 and 200 cm depth. The deepest soil layer (200–300 cm) had a very slight decline in organic carbon. Overall, the spatially averaged SOC losses were modeled to be the highest (about 88%) in the top 1 m of soil and lower in deeper soil layers (10% and 2% in the top 1–2 m and 2–3 m intervals, respectively). Over the entire soil column, the spatially averaged SOC losses were about 2800 gC m^{-2}, equivalent to 4.4 Pg C across Alaska by year 2300 vs. 2000.

Accelerated decomposition from warming was modeled to increase heterotrophic respiration (figure 6(a)). Rapid decomposition is primed by increased root carbon exudation (figure S4) driven by increasing NPP. On the other hand, increased N_2 fixation and N mineralization lead to increased plant N uptake (figure S3), increased CO_2 fixation, and thereby plant growth and litter inputs to the soil. Changes in SOC stocks are spatially heterogeneous across Alaska's Arctic and boreal forest regions (figure 6(c)). Spatially aggregated as a function of the distance from the treeline, modeled changes in SOC stocks show a decline in most regions north and south of the treeline, with interior Alaska experiencing the largest decline (about 5500 gC m^{-2}) in 2300 vs. 2000.

High-latitude region carbon budgets are primarily limited by temperature and nutrients, thus climate warming deepens the active layer, relaxes temperature limitations on SOC decomposition, enhances nutrient mineralization, enhances N_2 fixation, and thereby increases CO_2 fixation rates. We projected sustained increases in ecosystem NPP that peaks around the year 2200 and then slightly decreases under further warming (figure 6(a)). Increases in RH were sustained through the year 2300, resulting in a decreasing NEP. Consistent with other models (Qian *et al* 2010), our modeled spatial average NBP shows that the Alaskan ecosystem remains a strong carbon sink during the 21st century. However, wildfire and climate warming beyond 2100 led to a sustained decline in spatial average NBP resulting in a net ecosystem carbon source after 2200 (figure 6(b)). We modeled that, over the 21st century, SOC carbon losses were offset by increases in plant biomass gains (figure 5(b)). This result is consistent with those from Mack *et al* (2021), who showed that forest stands dominated by deciduous trees offset soil carbon losses. However, we found that warming and wildfire beyond the year 2200 result in sustained declines in SOC and plant biomass accumulation (figure 5(b)).

We found from historical and future simulations that wildfire substantially decreases high-latitude SOC stocks. In a sensitivity simulation with no fire after year 2000, we modeled a decline in the spatial average SOC stock by 740 gC m^{-2} in year 2300 vs. 2000 (i.e. a 74% lower SOC loss than when considering fire (2800 gC m^{-2}); figures 5(b) and S5). This result suggests that climate warming in high-latitude regions may drive increased soil organic decomposition and thus soil carbon losses, even in the absence of fire, but that fire will exacerbate the losses and be a dominant controller of Alaskan SOC dynamics over the next several centuries. This result is consistent with other studies that have reported that high-latitude wildfires control annual and interannual carbon balances (Bond-Lamberty *et al* 2007, Balshi *et al* 2009a, Walker *et al* 2019, Chen *et al* 2021, Mack *et al* 2021).

Although climate warming may drive plant carbon gains and thus greater litter inputs to soil, increases in combustion losses from projected frequent and intense wildfire and accelerated soil carbon decomposition substantially offsets plant carbon gains leading to high-latitude ecosystems becoming a carbon source (figure 5(a)). Our results are consistent with other studies which showed that under warmer climate, projected increases in wildfire will lead to net losses of carbon to the atmosphere (Kasischke *et al* 1995, Walker *et al* 2019). We note that the relative magnitude of SOC losses depends on other factors that may affect high-latitude soil carbon dynamics which we were unable to consider in this study: e.g. uncertainties associated with our burned area estimates, mechanistic processes that lead to ignition, changes in flammability with vegetation type, topography, and other disturbances such as grazing, insects, and three-dimensional changes in landscape-scale hydrological dynamics that may lead to thermokarst development and ground collapse. Accounting for abrupt thaw and ground collapse may increase permafrost carbon losses (Turetsky *et al* 2020) offset potential carbon sinks (Turetsky *et al* 2020), and wildfire may exacerbate permafrost degradation and ground subsidence (Brown *et al* 2015, Zhang *et al* 2015, Holloway *et al* 2020). Our simulation did not account for these carbon losses from ground collapse following fire, implying that our soil carbon loss projections may be conservative.

4. Conclusions

Many observational and modeling studies have found that wildfire and climate warming may substantially affect high-latitude carbon cycling (Bond-Lamberty *et al* 2007, Balshi *et al* 2009a, Walker *et al* 2019, Chen *et al* 2021, Mack *et al* 2021). Here, using a well-tested mechanistic model of high-latitude processes, we showed that high-latitude ecosystem carbon dynamics exhibit different trends of plant and soil carbon under future warming and wildfire: sustained plant carbon gains that led to greater biomass vs. concurrent SOC losses (figure 5(b)). With large combustion losses from belowground consistent with observations (Veraverbeke *et al* 2015), we conclude that wildfire effects on soil carbon stocks will dominate the long-term carbon balance of these ecosystems. We found that wildfire increases SOC losses by a factor of about 4 across Alaska by the year 2300, compared to current conditions. We conclude that wildfire and its effects on the complex interactions between vegetation and soil carbon stocks will accelerate high-latitude soil carbon losses. Losses of these carbon stocks will have many ecological and climatic implications and affect the global carbon cycle. Combustion losses will increase carbon sources to the atmosphere and thus feedbacks to warming, further increasing wildfire. Therefore, earth system models need to account for the representation of prognostic wildfire and interacting processes to accurately model the centennial-scale carbon dynamics of northern ecosystems.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI:

https://portal-s.edirepository.org/nis/metadataviewer?packageid=edi.636.1 and https://doi.org/10.5440/1885126.

Acknowledgments

This research was supported by the Director, Office of Science, Office of Biological and Environmental Research of the US Department of Energy under Contract No. DE-AC02-05CH11231 to Lawrence Berkeley National Laboratory as part of the Next-Generation Ecosystem Experiments in the Arctic (NGEE-Arctic) project and the RUBISCO Scientific Focus Area.

References

Amiro B D, Todd J B, Wotton B M, Logan K A, Flannigan M D, Stocks B J, Mason J A, Martell D L and Hirsch K G 2001 Direct carbon emissions from Canadian forest fires, 1959–1999 *Can. J. For. Res.* **31** 512–25

Balshi M S, Mcguire A D, Duffy P, Flannigan M, Kicklighter D W and Melillo J 2009a Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century *Glob. Change Biol.* **15** 1491–510

Balshi M S, McGUIRE A D, Duffy P, Flannigan M, Walsh J and Melillo J 2009b Assessing the response of area burned to changing climate in western boreal North America using a multivariate adaptive regression splines (MARS) approach *Glob. Change Biol.* **15** 578–600

Boby L A, Schuur E A G, Mack M C, Verbyla D and Johnstone J F 2010 Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest *Ecol. Appl.* **20** 1633–47

Bond-Lamberty B, Peckham S D, Ahl D E and Gower S T 2007 Fire as the dominant driver of central Canadian boreal forest carbon balance *Nature* **450** 89–92

Bouskill N J, Mekonnen Z, Zhu Q, Grant R and Riley W J 2022 Microbial contribution to post-fire tundra ecosystem recovery over the 21st century *Commun. Earth Environ.* **3** 1–15

Bouskill N J, Riley W J, Zhu Q, Mekonnen Z A and Grant R F 2020 Alaskan carbon-climate feedbacks will be weaker than inferred from short-term experiments *Nat. Commun.* **11** 5798

Brown C D and Johnstone J F 2011 How does increased fire frequency affect carbon loss from fire? A case study in the northern boreal forest *Int. J. Wildland Fire* **20** 829

Brown D R N, Torre Jorgenson M, Douglas T A, Romanovsky V E, Kielland K, Hiemstra C, Euskirchen E S and Ruess R W 2015 Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests *J. Geophys. Res.* **120** 1619–37

Camill P, Barry A, Williams E, Andreassi C, Limmer J and Solick D 2009 Climate-vegetation-fire interactions and their impact on long-term carbon dynamics in a boreal peatland landscape in northern Manitoba *Can. J. Geophys. Res.* **114** G04017

Chen Y, Romps D M, Seeley J T, Veraverbeke S, Riley W J, Mekonnen Z A and Randerson J T 2021 Future increases in Arctic lightning and fire risk for permafrost carbon *Nat. Clim. Change* **11** 404–10

Christiansen C T, Mack M C, DeMarco J and Grogan P 2018 Decomposition of senesced leaf litter is faster in tall compared to low birch shrub tundra *Ecosystems* **21** 1564–79

Euskirchen E S, McGuire A D, Rupp T S, Chapin F S III and Walsh J E 2009 Projected changes in atmospheric heating due to changes in fire disturbance and the snow season in the western Arctic, 2003–2100 *J. Geophys. Res.* **114** G04022

Flannigan M, Stocks B, Turetsky M and Wotton M 2009 Impacts of climate change on fire activity and fire management in the circumboreal forest *Glob. Change Biol.* **15** 549–60

French N H F *et al* 2011 Model comparisons for estimating carbon emissions from North American wildland fire *J. Geophys. Res.* **116** G00K05

Frost G V, Loehman R A, Saperstein L B, Macander M J, Nelson P R, Paradis D P and Natali S M 2020 Multi-decadal patterns of vegetation succession after tundra fire on the Yukon-Kuskokwim Delta, Alaska *Environ. Res. Lett.* **15** 025003

Gaboriau D M, Remy C C, Girardin M P, Asselin H, Hély C, Bergeron Y and Ali A A 2020 Temperature and fuel availability control fire size/severity in the boreal forest of central Northwest Territories, Canada *Quat. Sci. Rev.* **250** 106697

Gibson C M, Chasmer L E, Thompson D K, Quinton W L, Flannigan M D and Olefeldt D 2018 Wildfire as a major driver of recent permafrost thaw in boreal peatlands *Nat. Commun.* **9** 3041

Grant R F 2013 Modelling changes in nitrogen cycling to sustain increases in forest productivity under elevated atmospheric CO_2 and contrasting site conditions *Biogeosciences* **10** 7703–21

Grant R F, Mekonnen Z A and Riley W J 2019a Modeling climate change impacts on an arctic polygonal tundra: 1. Rates of permafrost thaw depend on changes in vegetation and drainage *J. Geophys. Res.* **124** 1308–22

Grant R F, Mekonnen Z A, Riley W J, Arora B and Torn M S 2017 2. Microtopography determines how CO_2 and CH_4 exchange responds to changes in temperature and precipitation at an Arctic polygonal tundra site: mathematical modelling with ecosys *J. Geophys. Res.* **122** 3174–87

Grant R F, Mekonnen Z A, Riley W J, Arora B and Torn M S 2019b Modeling climate change impacts on an arctic polygonal tundra: 2. Changes in CO_2 and CH_4 exchange depend on rates of permafrost thaw as affected by changes in vegetation and drainage *J. Geophys. Res.* **124** 1323–41

Grosse G *et al* 2011 Vulnerability of high-latitude soil organic carbon in North America to disturbance *J. Geophys. Res.* **116** G00K06

Harden J W, Manies K L, Turetsky M R and Neff J C 2006 Effects of wildfire and permafrost on soil organic matter and soil climate in interior Alaska *Glob. Change Biol.* **12** 2391–403

Hobbie S E, Nadelhoffer K J and Högberg P 2002 A synthesis: the role of nutrients as constraints on carbon balances in boreal and arctic regions *Plant Soil* **242** 163–70

Hobbie S E, Schimel J P, Trumbore S E and Randerson J R 2000 Controls over carbon storage and turnover in high-latitude soils *Glob. Change Biol.* **6** 196–210

Holden S R, Rogers B M, Treseder K K and Randerson J T 2016 Fire severity influences the response of soil microbes to a boreal forest fire *Environ. Res. Lett.* **11** 035004

Holloway J E, Lewkowicz A G, Douglas T A, Li X, Turetsky M R, Baltzer J L and Jin H 2020 Impact of wildfire on permafrost landscapes: a review of recent advances and future prospects *Permafr. Periglac. Process.* **31** 371–82

Hugelius G *et al* 2013 A new data set for estimating organic carbon storage to 3 m depth in soils of the northern circumpolar permafrost region *Earth Syst. Sci. Data* **5** 393–402

Iwahana G, Harada K, Uchida M, Tsuyuzaki S, Saito K, Narita K, Kushida K and Hinzman L D 2016 Geomorphological and geochemistry changes in permafrost after the 2002 tundra wildfire in Kougarok, Seward Peninsula, Alaska *J. Geophys. Res.* **121** 1697–715

Jarvis P and Linder S 2000 Constraints to growth of boreal forests *Nature* **405** 904–5

Jiang Y, Rocha A V, O'Donnell J A, Drysdale J A, Rastetter E B, Shaver G R and Zhuang Q 2015 Contrasting soil thermal responses to fire in Alaskan tundra and boreal forest *J. Geophys. Res.* **120** 363–78

Jin Y, Randerson J T, Goetz S J, Beck P S A, Loranty M M and Goulden M L 2012 The influence of burn severity on postfire vegetation recovery and albedo change during early succession in North American boreal forests *J. Geophys. Res.* **117** G01036

Johnstone J F, Hollingsworth T N, Stuart Chapin F and Mack M C 2010 Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest *Glob. Change Biol.* **16** 1281–95

Kasischke E S, Christensen N L Jr and Stocks B J 1995 Fire, global warming, and the carbon balance of boreal forests *Ecol. Appl.* **5** 437–51

Kasischke ES and Turetsky MR 2006 Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska *Geophys. Res. Lett.* **33** L09703

Kurz W A, Stinson G and Rampley G 2008 Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? *Phil. Trans. R. Soc.* B **363** 2259–68

Lantz T C, Gergel S E and Henry G H R 2010 Response of green alder (*Alnus viridis* subsp. *fruticosa*) patch dynamics and plant community composition to fire and regional temperature in north western Canada *J. Biogeogr.* **37** 1597–610

Leppälammi-Kujansuu J, Salemaa M, Kleja D B, Linder S and Helmisaari H-S 2014 Fine root turnover and litter production of Norway spruce in a long-term temperature and nutrient manipulation experiment *Plant Soil* **374** 73–88

Li F, Lawrence D M and Bond-Lamberty B 2017 Impact of fire on global land surface air temperature and energy budget for the 20th century due to changes within ecosystems *Environ. Res. Lett.* **12** 044014

Liu H 2005 Changes in the surface energy budget after fire in boreal ecosystems of interior Alaska: an annual perspective *J. Geophys. Res.* **110** D13101

Liu S, Wei Y, Post W M, Cook R B, Schaefer K and Thornton M M 2013 The Unified North American soil map and its implication on the soil organic carbon stock in North America *Biogeosciences* **10** 2915–30

Liu Y, Riley W J, Keenan T F, Mekonnen Z A, Holm J A, Zhu Q and Torn M S 2022 Dispersal and fire limit Arctic shrub expansion *Nat. Commun.* **13** 3843

Loisel J and Yu Z 2013 Recent acceleration of carbon accumulation in a boreal peatland, south central Alaska *J. Geophys. Res.* **118** 41–53

Mack M C, Bret-Harte M S, Hollingsworth T N, Jandt R R, Schuur E A G, Shaver G R and Verbyla D L 2011 Carbon loss from an unprecedented Arctic tundra wildfire *Nature* **475** 489–92

Mack M C, Walker X J, Johnstone J F, Alexander H D, Melvin A M, Jean M and Miller S N 2021 Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees *Science* **372** 280–3

McGuire A D *et al* 2018 Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change *Proc. Natl Acad. Sci.* **115** 3882–7

Mekonnen Z A, Grant R F and Schwalm C 2016 Sensitivity of modeled NEP to climate forcing and soil at site and regional scales: implications for upscaling ecosystem models *Ecol. Model.* **320** 241–57

Mekonnen Z A, Grant R F and Schwalm C 2017 Carbon sources and sinks of North America as affected by major drought events during the past 30 years *Agric. For. Meteorol.* **244–245** 42–56

Mekonnen Z A, Riley W J, Grant R F and Romanovsky V E 2021 Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate *Environ. Res. Lett.* **16** 024008

Mekonnen Z A, Riley W J, Randerson J T, Grant R F and Rogers B M 2019 Expansion of high-latitude deciduous forests driven by interactions between climate warming and fire *Nat. Plants* **5** 952–8

Mekonnen Z A 2022 Wildfire exacerbates high-latitude soil carbon losses from climate warming: modeling archive *Next Generation Ecosystem Experiments Arctic Data Collection* (Oak Ridge, TN: Oak Ridge National Laboratory, U.S. Department of Energy) (https://doi.org/10.5440/1885126)

Michaelides R J, Schaefer K, Zebker H A, Parsekian A, Liu L, Chen J, Natali S, Ludwig S and Schaefer S R 2019 Inference of the impact of wildfire on permafrost and active layer thickness in a discontinuous permafrost region using the remotely sensed active layer thickness (ReSALT) algorithm *Environ. Res. Lett.* **14** 035007

Natali S M *et al* 2019 Large loss of CO_2 in winter observed across the northern permafrost region *Nat. Clim. Change* **9** 852–7

Neff J C, Harden J W and Gleixner G 2005 Fire effects on soil organic matter content, composition, and nutrients in boreal interior Alaska *Can. J. For. Res.* **35** 2178–87

Oechel W C *et al* 1992 Effects of global change on the carbon balance of arctic plants and ecosystems *Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective* (San Diego, CA: Academic Press) pp 139–68

Prichard S J, Sandberg D V, Ottmar R D, Eberhardt E, Andreu A, Eagle P and Swedin K 2013 Fuel characteristic classification system version 3.0: technical documentation *General Technical Report* PNW-GTR-887 (Portland) (https://doi.org/10.2737/pnw-gtr-887)

Qian H, Joseph R and Zeng N 2010 Enhanced terrestrial carbon uptake in the Northern High latitudes in the 21st century from the coupled carbon cycle climate model intercomparison project model projections *Glob. Change Biol.* **16** 641–56

Randerson J T, Chen Y, van der Werf G R, Rogers B M and Morton D C 2012 Global burned area and biomass burning emissions from small fires *J. Geophys. Res.* **117** G04012

Riley W J, Mekonnen Z A, Tang J, Zhu Q, Bouskill N J and Grant R F 2021 Non-growing season plant nutrient uptake controls Arctic tundra vegetation composition under future climate *Environ. Res. Lett.* **16** 074047

Rogers B M, Veraverbeke S, Azzari G, Czimczik C I, Holden S R, Mouteva G O, Sedano F, Treseder K K and Randerson J T 2014 Quantifying fire-wide carbon emissions in interior Alaska using field measurements and Landsat imagery *J. Geophys. Res.* **119** 1608–29

Rollins M G 2009 LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment *Int. J. Wildland Fire* **18** 235

Schuur E A G *et al* 2015 Climate change and the permafrost carbon feedback *Nature* **520** 171–9

Shirley I A, Mekonnen Z A, Grant R F, Dafflon B, Hubbard S S and Riley W J 2022 Rapidly changing high-latitude seasonality: implications for the 21st century carbon cycle in Alaska *Environ. Res. Lett.* **17** 014032

Strömgren M and Linder S 2002 Effects of nutrition and soil warming on stemwood production in a boreal Norway spruce stand *Glob. Change Biol.* **8** 1194–204

Turetsky M R *et al* 2020 Carbon release through abrupt permafrost thaw *Nat. Geosci.* **13** 138–43

Turetsky M R, Kane E S, Harden J W, Ottmar R D, Manies K L, Hoy E and Kasischke E S 2010 Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands *Nat. Geosci.* **4** 27–31

Veraverbeke S, Rogers B M and Randerson J T 2015 Daily burned area and carbon emissions from boreal fires in Alaska *Biogeosciences* **12** 3579–601

Walker X J *et al* 2019 Increasing wildfires threaten historic carbon sink of boreal forest soils *Nature* **572** 520–3

Walker X J *et al* 2020 Fuel availability not fire weather controls boreal wildfire severity and carbon emissions *Nat. Clim. Change* **10** 1130–6

Wang J A, Baccini A, Farina M, Randerson J T and Friedl M A 2021 Disturbance suppresses the aboveground carbon sink in North American boreal forests *Nat. Clim. Change* **11** 435–41

Wang J A, Sulla-Menashe D, Woodcock C E, Sonnentag O, Keeling R F and Friedl M A 2020 Extensive land cover change across Arctic-Boreal Northwestern North America from disturbance and climate forcing *Glob. Change Biol.* **26** 807–22

Wei Y *et al* 2014 The North American carbon program multi-scale synthesis and terrestrial model intercomparison project—part 2: environmental driver data *Geosci. Model Dev.* **7** 2875–93

Xu L *et al* 2021 Changes in global terrestrial live biomass over the 21st century *Sci. Adv.* **7** eabe9829

Zhang Y, Wolfe S A, Morse P D, Olthof I and Fraser R H 2015 Spatiotemporal impacts of wildfire and climate warming on permafrost across a subarctic region *Can. J. Geophys. Res.* **120** 2338–56