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Simulation of the effects of forest harvesting under changing climate to inform long-term sustainable forest management using a biogeochemical model

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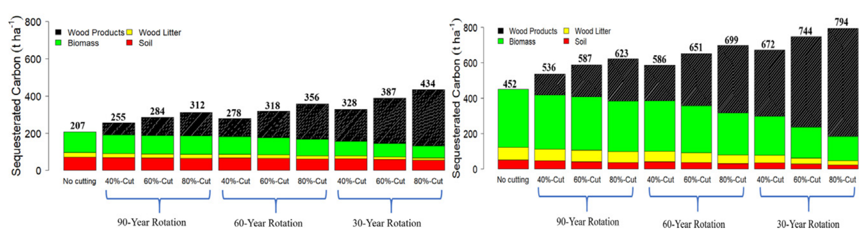
HIGHLIGHTS

- Intensive forest harvesting decreases long-term forest sustainability.
- Limited understanding of intensive harvesting in the context of climate change
- Simulation of long-term changes in forest element pools and fluxes
- Future climate change affects recovery forests following logging strategies.
- Climate change can enhance overall carbon storage but decrease soil fertility.

GRAPHICAL ABSTRACT

Comparison of simulated sequestrated/stored carbon in different ecosystem pools including soil, woody debris, aboveground biomass and cumulative removed wood products at the end of simulation period (2200) for ten scenarios of forest management under stationary (left) and changing (right) climate conditions.



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ABSTRACT

Process ecosystem models are useful tools to provide insight on complex, dynamic ecological systems, and their response to disturbances. The biogeochemical model PnET-BGC was modified and tested using field observations from an experimentally whole-tree harvested northern hardwood watershed (W5) at the Hubbard Brook Experimental Forest (HBEF), New Hampshire, USA. In this study, the confirmed model was used as a heuristic tool to investigate long-term changes in hydrology, biomass accumulation, and soil solution and stream water chemistry for three different watershed cutting intensities (40%, 60%, 80%) and three rotation lengths (30, 60, 90 years) under both constant (current climate) and changing (MIROC5-RCP4.5) future climate scenarios and atmospheric CO_2 through the year 2200. For the no future cutting scenario, total ecosystem stored carbon (i.e., sum of aboveground biomass, woody debris and soil) reached a maximum value of 207 t C ha^{-1} under constant climate but increased to 452 t C ha^{-1} under changing climate in 2200 due to a CO_2 fertilization effect. Harvesting of trees decreased total ecosystem stored carbon between 7 and 36% for constant climate and 7–60% under changing climate, respectively, with greater reductions for shorter logging rotation lengths and greater watershed cutting intensities. Harvesting under climate change resulted in noticeable losses of soil organic matter (12–56%) coinciding with loss of soil nutrients primarily due to higher rates of soil mineralization associated with increases in temperature, compared with constant climate conditions (3–22%). Cumulative stream leaching of nitrate under climate change (181–513 kg N ha^{-1}) exceeded constant climate values (139–391 kg N ha^{-1}) for the various cutting regimes. Under both climate conditions the model projected greater sensitivity to varying the length

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of cutting period than cutting intensities. Hypothetical model simulations highlight future challenges in maintaining long-term productivity of managed forests under changing climate due to a potential for a deterioration of soil fertility.

1. Introduction

Forest ecosystems provide a variety of important ecological services such as wildlife habitat, clean air and water, sequestration of atmospheric carbon dioxide, and timber production. Anthropogenic activities, such as forest harvesting, can change the structure and function of terrestrial ecosystems and the services provided. Ecosystem response to harvesting varies markedly, depending on site characteristics, forest species composition, land-use history, and the method, intensity and frequency of harvesting (Kreutzweiser et al., 2008). Climate change is an important regulator of ecosystem structure and function (Dib et al., 2014; Huang et al., 2007; Kirilenko and Sedjo, 2007; Pourmokhtarian et al., 2017). Projected changes in future climate including increases in air temperatures and changes in precipitation by atmosphere-ocean general circulation models (GCMs) and also increases in atmospheric CO_2 are expected to influence forest regeneration, growth, mortality and biogeochemical processes (Peng et al., 2002). Such changes can alter ecosystem services of forests including biofuel production (Creutzburg et al., 2016).

Increasing demand for timber and other forest products as well as concern over increasing concentrations of greenhouse gases has compelled forest managers to consider the ability of forest ecosystems to sequester carbon and conserve nutrients when developing long-term management strategies (Seely et al., 2002). An important embedded concept is the term "sustainability of timber yield": keeping forests economically profitable while maintaining the structure and function of the forest ecosystems (Peng et al., 2002). Understanding both short- and long-term impacts of harvesting practices (e.g., cutting rotation length, intensity) on forest dynamics is a key factor in developing criteria and guidelines for sustainable forest management practices (Mina et al., 2017; Peng et al., 2002). Moreover, climate is changing and this will likely disrupt forest ecosystems processes (Boisvenue and Running, 2006; Ollinger et al., 2008). As the time scale of climate change is comparable to that of forest ecosystem recovery and development following harvesting and the two disturbances are interconnected, it is important to investigate forest harvesting effects in the context of climate change.

Generally, short-term studies have reported negative environmental effects on forest ecosystems associated with intensive harvesting. These effects include increases in nutrient concentrations in soil solutions and export to receiving waters (1–3 years), primarily as a result of reduced plant uptake and alteration of soil conditions and microbial activity (Fakhraei et al., 2020; Kreutzweiser et al., 2008; Nave et al., 2010a; Thiffault et al., 2011; Valipour et al., 2018). In contrast, some literature has shown evidence for little or no change in soil chemical properties during the initial years after clear-cutting (Keenan and Hamish Kimmins, 1993; Kreutzweiser et al., 2008). Only a few studies have been conducted to examine the long-term ecological impacts of alternative logging approaches and these have generally relied on simulation modeling (Blanco et al., 2005; Jiang et al., 2002; Rolff and AAgren, 1999; Vadeboncoeur et al., 2014; Wei et al., 2003). This research has generally suggested that repeated clear-cuts can diminish soil nutrient availability on nutrient poor sites, ultimately resulting in declines in forest productivity over the long term, although none of these studies considered effects of climate change.

Climate change is anticipated to have major consequences for forest ecosystems (Creutzburg et al., 2016; Dai et al., 2016; Ollinger et al., 2008). AOGCMs from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) (Flato et al., 2013) estimate potential changes in climate during the 21st century under several greenhouse gas forcing scenarios, called representative concentration pathways (RCPs) (Moss et al., 2008, 2010). For example, under the RCP8.5 scenario atmospheric CO_2 concentrations are anticipated to reach approximately 940 ppm CO_2-equivalent and approximately 540 ppm CO_2-equivalent under the RCP4.5 scenario by the end of the current century (Moss et al., 2008, 2010; Riahi et al., 2011; Thomson et al., 2011). The magnitude of corresponding changes in climate attributes are expected to be highly variable over space and time (Flato et al., 2013; Pourmokhtarian et al., 2017; Wuebbles et al., 2017). Some studies have suggested that temperate forest growth rates have been increasing since the middle of the 20th century, responding to changes in CO_2, temperature and precipitation, (Bascietto et al., 2004; Boisvenue and Running, 2006; Kirilenko and Sedjo, 2007). In contrast, other reports indicate varying trends during different periods or overall declines in forest productivity, mainly related to water stress, and increases in insects, disease and wildfire as a result of increases in temperatures (Boisvenue and Running, 2006; Creutzburg et al., 2016; Miller et al., 2004; Schimel et al., 2001).

Climate change will likely interact with timber harvesting in complex ways (Creutzburg et al., 2016; Wu et al., 2017). A few modeling studies have examined the interaction of frequent intensive harvesting of forests with changes in climate (Scheller and Mladenoff, 2005; Wu et al., 2017). For example, Aherne et al. (2012) modeled the interactive effects of forest harvesting and climate change on soil and stream chemistry using the hydrochemical model MAGIC (Model of Acidification of Groundwater In Catchments), concluding that accelerated weathering rates under future climate change might compensate for loss of nutrients due to harvesting. However, effects of CO_2 fertilization on forest growth and changes in soil mineralization due to increases in temperature and changes in soil moisture were not considered in this analysis. LANDIS-II (a spatial forest landscape model) was applied to examine long-term effects of forest management and climate change on aboveground biomass, concluding that climate change is unlikely to significantly change forest carbon storage (Creutzburg et al., 2016). Wu et al. (2017) investigated the integrated effects of harvesting and climate change, finding long-term declines in aboveground biomass as a result of cutting. However, these latter two studies but did not consider effects of CO_2 fertilization on aboveground biomass production.

Further experimentation and modeling are needed to improve understanding of the interactions between forest cutting approaches and future climate change. Such research should enhance predictive capabilities that could ultimately be used to develop sustainable forest management practices (Kreutzweiser et al., 2008). Process ecosystem models are effective analytical tools to depict complex interactions among ecosystem components and their response to stressors, providing insight on the transformations of key process that regulate the structure and function of forest ecosystems (Shifley et al., 2017), and eventually could be used to inform decision making. Previous modeling approaches have largely focused on the dynamics of C or N stocks in soil or vegetation to evaluate the impacts of various logging regimes (Mina et al., 2017; Shifley et al., 2017) and few have considered CO_2 fertilization effects on forest growth (Aherne et al., 2012; Creutzburg et al., 2016; Wu et al., 2017).

Moreover, few studies have rigorously compared model simulations against empirical harvesting data to test and verify simulations that would improve confidence in the extrapolation of short-term observations of nutrient dynamics to longer time scales. We used a process biogeochemical watershed model, PnET-BGC, which was modified and tested using field observations from a northern hardwood forest watershed that was subject to a whole-tree harvest (W5) at the Hubbard

Brook Experimental Forest (HBEF), New Hampshire, USA (Valipour et al., 2018). The overarching goal of this study was to apply the modified PnET-BGC model to evaluate and compare the biogeochemical response of a northern hardwood forest to different logging strategies (i.e., cutting rotation length, intensity) under stationary and changing climate, building upon observations from the HBEF. The specific objectives of this study are: (i) to project short- and long-term patterns of biomass accumulation and changes of nutrient pools and fluxes in soil and streamwater as a function of harvesting intensity and rotation length; (ii) to couple hypothetical tree-cutting scenarios with future projections of climate change to examine the interplay between these two types of disturbances and (iii) to inform forest management decisions by evaluating the trade-offs between timber production and ecosystem storage of nutrients.

2. Methods

2.1. Site description

The HBEF is located in the southern White Mountains of New Hampshire (43°56′ N, 71°45′ W). It encompasses experimental watersheds with long-term and comprehensive measurements of vegetation, soils, meteorology, hydrology and biogeochemistry, the earliest of which began in 1956 (http://www.hubbardbrook.org). The climate of the HBEF is humid-continental, with short, cool summers and long, cold winters (Bormann and Likens, 1979). Vegetation in the study area is dominated by the northern hardwood forest with a band of spruce-fir forest in the upper reaches of the watershed. This hypothetical analysis was conducted using conditions for watershed W5, with an area of 21.9 ha and elevation range of 488–762 m. An experimental whole-tree harvest of W5 was conducted during the fall of 1983 through the winter of 1984. All trees >5 cm DBH were cut with chainsaws and a track-mounted feller buncher equipped with hydraulic shears, and removed from the site with rubber tire skidders. We also present data from Watershed 6 (W6), which is adjacent to W5, with an area of 13.2 ha and an elevation range of 549–792 m, and serves a biogeochemical reference watershed without experimental manipulation. Note that soil and streams of experimental watersheds at Hubbard Brook are sensitive to acid deposition due to the low base saturation of soils (Cleavitt et al., 2018). More information about the study site can be found in Bormann and Likens (1979), Likens et al. (1970), Valipour et al. (2018) and the supplemental information provided in this paper.

2.2. Model description

PnET-BGC is a lumped-parameter simulation model of forest carbon and nutrient dynamics that has been applied and validated in a variety of eastern US forest watersheds (Fakhraei et al., 2014, 2016; Pourmokhtarian et al., 2017). The model depicts ecosystem processes of photosynthesis, canopy interactions, plant nutrient uptake, accumulation and loss of soil organic matter, soil cation exchange and anion adsorption, organic matter mineralization and nitrification, as well as hydrology, mineral weathering and solution chemical reactions to simulate the fluxes of energy and water, and the cycling and loss of nutrients in forest ecosystems (Fakhraei and Driscoll, 2015; Gbondo-Tugbawa et al., 2001). Importantly, the model simulates soil organic matter as a single pool (Aber et al., 1997) functionally equivalent to the "active" pool in the Century model (Parton et al., 1993); the implications of this simplified approach are evaluated in the Discussion. PnET-BGC is typically run on a monthly time-step with a spin-up period from year 1000 to 1850 under constant climate, pre-industrial atmospheric deposition and no land disturbance, which allows the model to come to steady-state. Hindcast simulations are then run from 1850 to present by considering historical climate, atmospheric deposition and land disturbance (i.e., forest harvest, blowdown, ice storm). The model can be used to project future conditions under given input scenarios. Sensitivity analyses of the model to input parameters have been conducted (Fakhraei et al., 2017; Valipour et al., 2018). We used a version of PnET-BGC that includes multiple soil layers (Chen and Driscoll, 2005) and added an algorithm to consider the effects of increasing atmospheric CO_2 on forest ecosystem processes: the effects of atmospheric CO_2 on vegetation, including the response of stomatal conductance, were implemented using a multilayered sub-model of photosynthesis and phenology developed by Ollinger and colleagues (Ollinger et al., 1997, 2002, 2008).

2.3. Data preparation and model inputs

PnET-BGC inputs include meteorological data (photosynthetically active radiation, precipitation, maximum and minimum temperature), atmospheric CO_2 concentrations, atmospheric deposition (dry and wet), vegetation type (northern hardwoods, spruce-fir), soil characteristics, vegetation and soil element stoichiometry and land-use history. Meteorological data and atmospheric deposition (dry and wet) vary monthly over the simulation period. The model assumes constant physical properties of soil and vegetation type through the simulation period. Mineral weathering rates are assumed to be constant over time and specific element rates are obtained through model calibration (Valipour et al., 2018). Note, atmospheric deposition rates for the future years were assumed to be constant for all hypothetical scenarios. A detailed description of model inputs, data development, and model parameterization, algorithm modifications for W5 calibration and model testing is provided in Valipour et al. (2018) as well as in previous studies (Fakhraei et al., 2014, 2016, 2017). Additional details about the W5 experiment, its methodology, sampling approach and forest biomass inventory can be found in previous literature (Cleavitt et al., 2018; Dahlgren and Driscoll, 1994; Johnson et al., 1991; Valipour, 2019; Valipour et al., 2018) and Hubbard Brook Website (http://www.hubbardbrook.org).

2.4. Simulation of management scenarios

We developed multiple management scenarios, varying the rate and intensity of harvesting, combined with scenarios of stationary and hypothetical future climate change. All management scenarios were conducted for a 180-year period (e.g. 2020–2200). To evaluate forest response, we defined various cutting scenarios (CS) including three cutting rotation lengths (30, 60 and 90 years) with three watershed cutting intensities (40%, 60% and 80% of watershed area) with the assumption of 100% removal for each cutting interval, in addition to the reference no cutting scenario (NCS). We coupled these management scenarios with two climate scenarios including continuing the current climate (stationary climate and constant atmospheric CO_2) and future climate projections from a single AOGCMs model. Hence, a suite of 20 scenarios were developed for this analysis.

AOGCMs from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) (Flato et al., 2013)) estimate potential changes in climate during the 21st century under a suite of greenhouse gas forcing scenarios called representative concentration pathways (RCPs) (Moss et al., 2008). Downscaled AOGCM climate projections for the two emission scenarios in HBEF indicate the increases in average annual air temperature ranging from 3.02 to 8.22 °C and in average annual precipitation ranging from 15.4 to 29.9 cm for the period 2070–2100, relative to the reference period 1970–2000 for W5 (Pourmokhtarian et al., 2017). We selected outputs from the Model for Interdisciplinary Research on Climate version 5 (MIROC5) of Center for Climate System Research, Japan (Watanabe et al., 2010) under a lower CO_2 emissions scenario (540 ppm, RCP 4.5), which projects moderate changes in climate variables. The results of MIROC5 were statistically downscaled to obtain higher resolution for HBEF (Hayhoe et al., 2008; Pourmokhtarian et al., 2017). Downscaled MIROC5 outputs (RCP 4.5) indicate that average annual air temperature and average annual precipitation would increase by 5.1 °C and 21 cm, respectively, for the period 2070–2100, relative to the reference period 1970–2000 for W5 (Pourmokhtarian et al., 2017). We used downscaled MIROC5 outputs (RCP 4.5) for the 2018–2100 period. To extrapolate climatic variables for the period beyond MIROC5 outputs (years 2101–2200), monthly averages of last five years of 2096–2100 of the climate projections were used.

3. Results

3.1. Aboveground biomass simulations

Under stationary climate conditions for the reference (no future cutting) scenario, modeled carbon stock in living aboveground biomass on W5 increased to 112 t C ha^{-1} by year 2200, 30% and 70% higher than the values in 1982 (the year before the experimental W5 clear-cutting) and 2019 (the year before the initiation of hypothetical logging regimes), respectively. Under different harvesting regimes, the carbon stock in aboveground biomass at the end of simulations (2200) were lower than the no harvesting scenario, with greater declines as the harvest rotation shortened and harvest intensity increased (Fig. 1). The most conservative scenario with a 90-year rotation length and a 40% watershed cutting level, showed only a minor decline of biomass accumulation relative to the no harvest scenario (112 t C ha^{-1}), reaching to 101 t C ha^{-1} by the end of the simulation (2200). In contrast, the most aggressive cutting scenario of a 30-year rotation period with an 80% intensity, resulted in aboveground biomass of only 64 t C ha^{-1} by 2200.

Under future climate change, an increase in biomass accumulation rate was projected for all forest management scenarios, compared with the corresponding simulations for constant climate conditions. In the reference (no harvest) scenario, modeled carbon stock in aboveground biomass was approximately three times (330 t C ha^{-1}) greater than the value simulated for stationary climate conditions in 2200. Whole-tree harvesting regimes resulted in lower projections of aboveground biomass accumulation compared to the reference (no logging) scenario, varying between 136 and 306 t ha^{-1} (Fig. 1).

3.2. Soil organic carbon simulations

The simulated soil organic carbon (SOC) pool exhibited a temporal pattern of decline and recovery after forest harvest analogous to that observed in an experimental clear-cut (1983), but the magnitude of simulated change was smaller than the empirical observations (Fig. 2); similar underpredictions were observed for W5 based on the RothC and Century models (Dib et al., 2014). Under constant climate, the soil pool slowly accumulated carbon over the long-term, reaching 72 t ha^{-1} by the end of the simulation period, 6% higher than the value in year 2019 (67 t C ha^{-1}). The soil organic carbon pool showed little response to various harvesting scenarios, with values ranging between 56 t C ha^{-1} and 69 t C ha^{-1} by the end of the simulation period. Overall, the pool of soil organic carbon remained relatively stable, with only minor declines resulting from logging regimes. In contrast, under changing climate, the modeled soil organic pool with no harvest lost carbon slowly, decreasing to 52 t C ha^{-1} by 2200 year. The interactive effects of climate change with harvesting regimes accelerated the decline in the soil organic carbon pool over the 180-year simulation period, with values between 23 t C ha^{-1} and 47 t C ha^{-1} in 2200 year, depending on the harvesting approach considered.

3.3. Woody debris and total carbon simulations

Modeled carbon storage in woody debris followed a similar pattern as aboveground biomass over the simulation period (Fig. A1). Under continuing current climate, harvesting regimes reduced the amount of woody debris, with pools ranging between 11 t C ha^{-1} and 21 t C ha^{-1} by the year 2200, compared with the no harvest scenario (24 t C ha^{-1}). Total ecosystem stored carbon (i.e., the sum of aboveground biomass, woody debris and soil) reached a maximum value of 207 t C ha^{-1} for the no cutting, constant climate scenario in 2200, while harvesting decreased this value in the range of 131–192 t C ha^{-1}, with greater reductions for shorter logging rotation lengths and greater watershed cutting intensities (Fig. 3, A2). The stored carbon was distributed among the ecosystem pools with highest fraction occurring as aboveground living biomass (44–60%), followed by soil (35–37%) and woody debris (8–13%) under all management practices (Fig. 3). Greater cumulative amounts of wood products would be extracted under the more intense removal scenarios over the 180-year simulation period of management practices, varying between 63 and 303 t C ha^{-1}. By the end of the simulation period, the amounts of total sequestered carbon (i.e., sum of total ecosystem stored carbon and total removed wood products) under all logging management scenarios

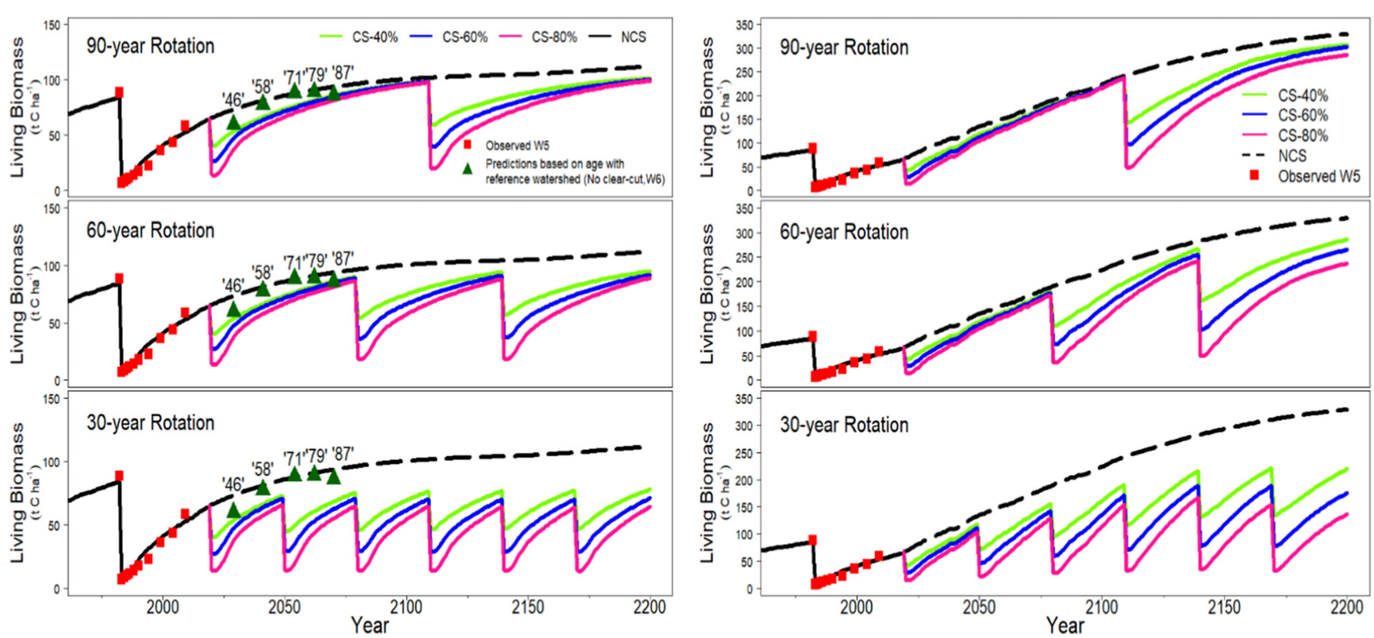

Fig. 1. Simulation of temporal dynamics of carbon storage in aboveground biomass across ten forest management scenarios under stationary climate (left) and future climate change (right) conditions. Model simulations are compared with measured values for clear-cut W5, HBEF in 1983 and W6 adjusted for years after cutting.

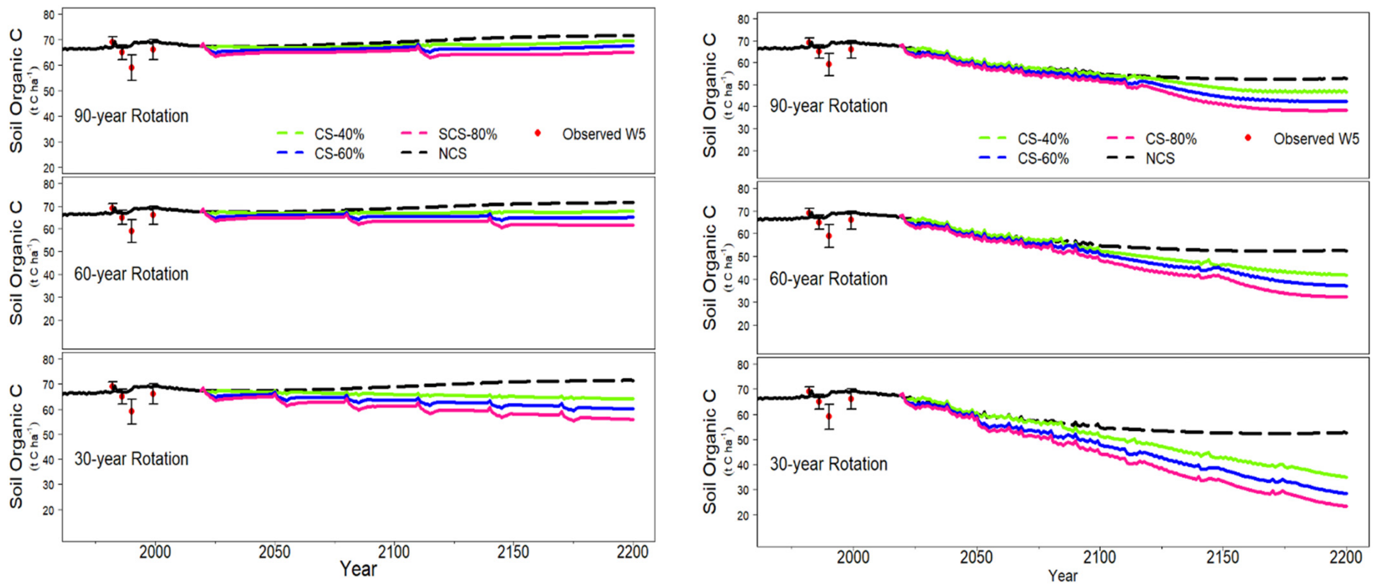

Fig. 2. Simulation of temporal dynamics of carbon storage in soil organic matter across ten forest management scenarios under stationary climate (left) and future climate change (right) conditions. Model simulations are compared with measured values for clear-cut W5, HBEF in 1983.

exceeded the value for the reference scenario without harvesting (207 t C ha^{-1}), ranging between 255 and 434 t C ha^{-1}. Note wood products would sequester C only to the extent that the products are permanent. Overall, under constant climate, woody debris and living aboveground biomass experienced the largest decline in carbon sequestration with harvesting regimes, ranging between 10 and 52% and 9–42%, respectively by 2200.

Climate change increased carbon accumulation in the woody debris pool (71 t C ha^{-1}) by 2200 for the no harvest scenario. Most of the ecosystem carbon accumulated in the aboveground biomass (57–85%) followed by woody debris (13–18%) for all scenarios of management practices by the end of simulation period (Fig. 3). Total ecosystem carbon (aboveground biomass, woody debris and soil) peaked at 452 t C ha^{-1} in 2200 for the no cutting scenario, while harvesting trees decreased in the range of 184–418 t C ha^{-1} under changing climate (Fig. 3, A2). Cutting trees resulted in greater total carbon sequestration (i.e. including wood products) by the end of the simulations, ranging between 536 t ha^{-1} and 794 t C ha^{-1} relative to the no cut scenario (452 t C ha^{-1}) (Fig. 3).

3.4. Simulations of nitrogen dynamics in plant, woody debris and soil

For the harvesting simulations, the relative temporal variations of N in plant, woody debris and soil pools were similar to those of carbon pools as the C:N ratios of these pools did not change substantially. Under constant climate, levels of stored N in plant, woody debris and soil were reduced by 10–37%, 11–52% and 3–22% by the end of the simulation period compared to corresponding values for the no harvest scenario (655 kg N ha^{-1}, 131 N kg ha^{-1} and 4491 kg N ha^{-1} respectively). Under changing climate, the response of N stocks in vegetation, woody debris and soil were predicted to be greater than under stationary climate, declining by 7–58%, 8–67% and 11–54%, respectively, at the end of the simulation period relative to the corresponding values for the no harvest scenario (Figs. A7, A8, A9). Under all management scenarios with stationary climate, the simulated distribution of N stocks among ecosystem pools varied between 85 and 88% for soil, 10–12% for total plant biomass and 1–2% for woody debris. Under the climate change scenario, a much higher proportion of ecosystem N was projected for the living biomass pool reflecting the higher forest growth.

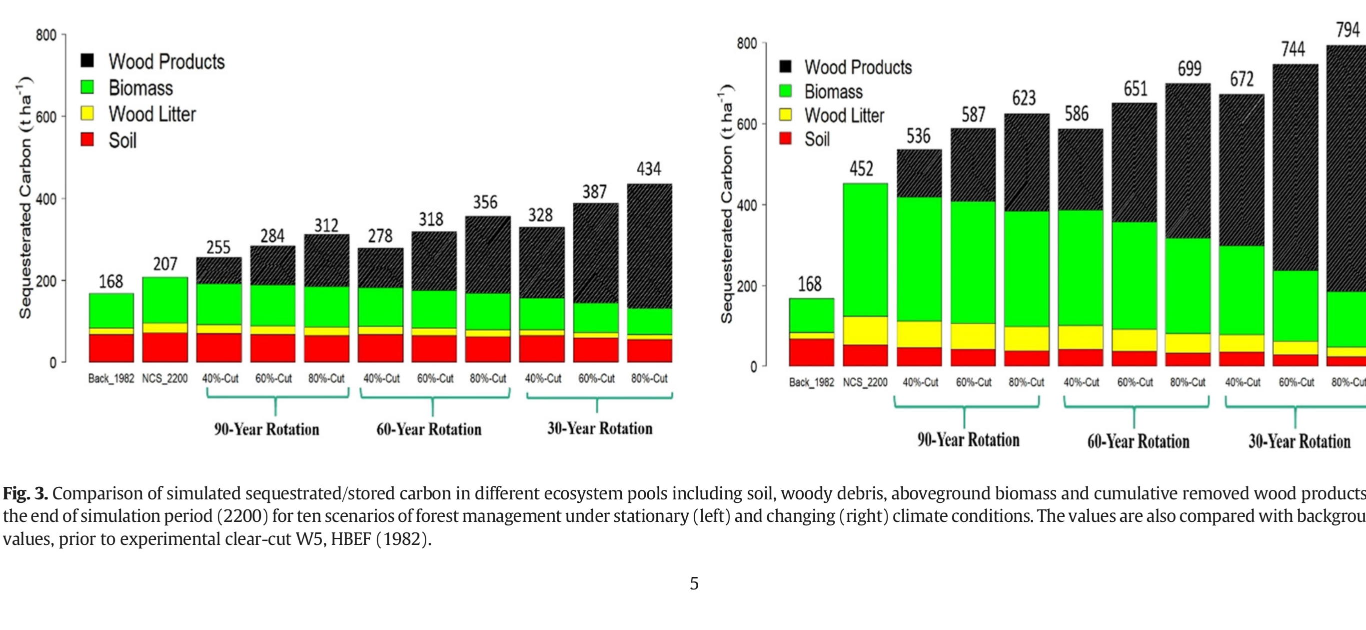

Fig. 3. Comparison of simulated sequestrated/stored carbon in different ecosystem pools including soil, woody debris, aboveground biomass and cumulative removed wood products at the end of simulation period (2200) for ten scenarios of forest management under stationary (left) and changing (right) climate conditions. The values are also compared with background values, prior to experimental clear-cut W5, HBEF (1982).

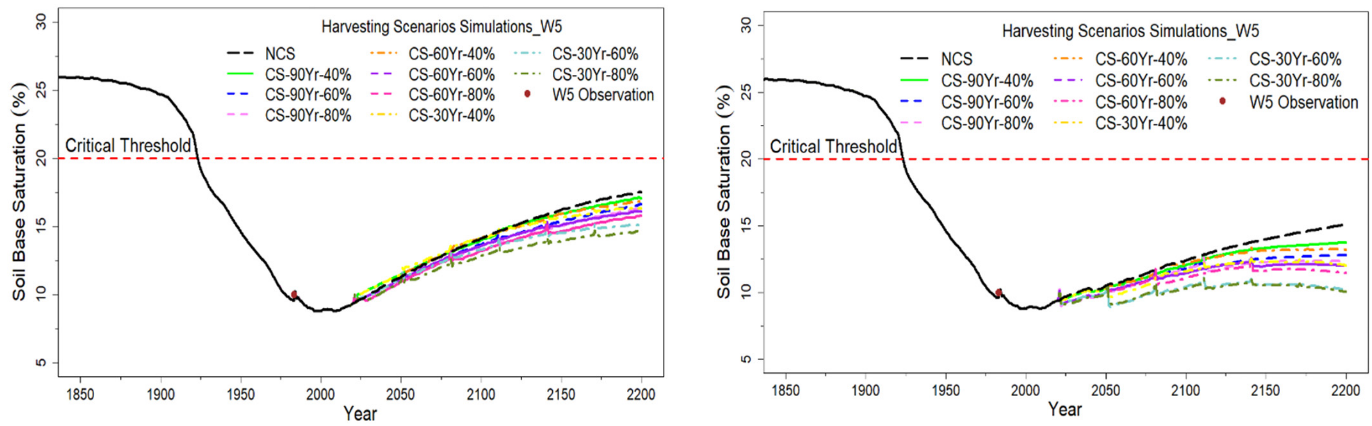

Fig. 4. Simulation of temporal changes of soil percent base saturation across ten forest management scenarios under stationary climate (left) and future climate change (right) conditions. Model simulations are compared with measured value prior to experimental clear-cut W5, HBEF (1982).

3.5. Soil base saturation simulations

Previous research at the HBEF indicated that acid deposition severely depleted soil base saturation (Likens et al., 1996) as illustrated in the base case pre-treatment pattern, with a minimum value of less than 10% in 2000 (Fig. 4). Under current climate with no future cutting, long-term simulations indicated that the soil base saturation gradually increased towards the end of the simulation period, but still remained below pre-acid deposition values (26% vs 17.4%). The harvesting of trees resulted in a slight increase in percent soil base saturation the first year after the clear-cut, coinciding with elevated leaching of nutrient cations in soil and stream water (Figs. A4, A5, A6). However, depletion of soil available nutrient cations reduced base saturation below pre-cut levels during the early years after the cut, and then it increased gradually with vegetation regrowth. Long-term harvesting practices were predicted to amplify the depletion of soil base saturation, reducing values to 17–14% by the end of the simulation period, lower than the reference no cut scenario (Fig. 4). For a no harvest scenario under climate change, percent soil base saturation increased from the minimum value at a slower rate than under the constant climate scenario, eventually reaching 15% by 2200. The interaction of climate change with harvesting regimes increased the decline in percent soil base saturation, with values ranging between 10 and 13.7% in 2200. Thus, soil base saturation recovery was projected to be highly sensitive to both climate change and harvest practices.

3.6. Nutrient leaching simulations

Cumulative leaching of nutrients over the 180-year simulation period (2020–2200) indicated slightly higher losses under constant climate than for changing climate for a no future cutting scenario. Cumulative leaching of NO_3^-, Ca^{2+} and Mg^{2+} reached levels of 125 kg N ha^{-1}, 1211 kg Ca ha^{-1} and 322 kg Mg ha^{-1}, respectively, from 2020 to 2200 for stationary climate without cutting, compared to the values of 116 kg N ha^{-1}, 1045 kg Ca ha^{-1} and 293 kg Mg ha^{-1} for changing climate (Fig. 5). Cumulative leaching of nutrients from 2020 to 2200 increased substantially with logging scenarios compared to the reference no cutting scenario for both climate conditions, reflecting the interval of increased leaching following intensive forest harvest. Cumulative stream losses of NO_3^- under climate change exceeded values under constant climate for each of the harvesting conditions. In contrast, the reverse was observed for Ca^{2+} and Mg^{2+} with greater leaching losses under constant climate than changing climate.

4. Discussion

4.1. Interactions between forest harvesting and future climate change alter forest production and nutrient dynamics

Our results are consistent with the literature showing the ability of forests to maintain large stores of carbon and mineral nutrients in various ecosystem pools (e.g., aboveground living biomass, woody debris,

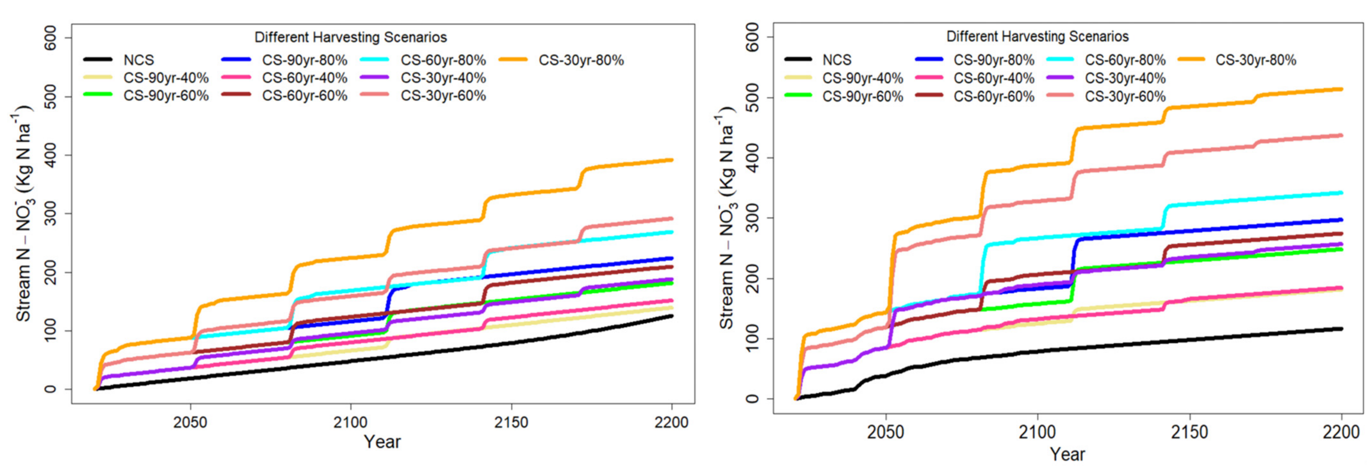

Fig. 5. Simulations of cumulative stream leaching of NO_3^- for ten forest management scenarios for W5, HBEF under stationary climate (left) and future climate change (right).

soil pools) under both stationary and climate change conditions in the absence of forest cutting. Cutting strategies, however, are projected to decrease ecosystem nutrient pools to varying degrees (Aherne et al., 2012; Jiang et al., 2002; Scheller and Mladenoff, 2005; Wu et al., 2017). Under all forest management strategies considered, the rates of carbon sequestration and nutrient assimilation (e.g. N, Ca^{2+}, Mg^{2+}) in aboveground living biomass and woody debris were projected to be significantly higher under changing climate than stationary climate, mainly due to the fertilization effects of CO_2, associated with enhanced water use efficiency and growth rate (Boisvenue and Running, 2006; Ollinger et al., 2008; Pourmokhtarian et al., 2017; Scheller and Mladenoff, 2005). Model simulations suggest this high production could be maintained in face of possible N limitation. The supply of N needed to maintain forest growth is derived primarily from soil organic matter, including the large accumulation of soil N that occurred as a result of historical elevated atmospheric N deposition over much of the 20th and early 21st century. Note, however, that even without N limitation there is evidence that the CO_2 fertilization effect in forests is limited (Mohan et al., 2007). Conversely, for all management scenarios, climate change resulted in a marked loss of soil organic matter and elevated leaching of soil nutrients compared with constant climate conditions, primarily due to higher rates of soil mineralization caused by increases in temperature, precipitation and runoff (Boisvenue and Running, 2006; Creutzburg et al., 2016; Pourmokhtarian et al., 2017; Reich et al., 2006).

Overall, our simulations demonstrated the greater sensitivity of forest ecosystem pools to logging strategies under climate change relative to constant climate conditions. These effects are accentuated with shortening the length of the cutting intervals and increasing forest harvesting intensity. These simulations highlight the challenges in maintaining the long-term productivity of managed forests under changing climate. Simulations under both climate conditions showed greater sensitivity to varying the length of cutting period than altering cutting intensities, consistent with previous reports (Blanco et al., 2005; Jiang et al., 2002; Wei et al., 2003). Under equivalent cutting frequency, the effects of increasing harvesting intensity on the reduction of ecosystem stored carbon, including aboveground biomass, woody debris and soil organic matter, was greater for changing than constant climate.

Field observations of the effects of logging on forest floor organic matter have been inconsistent, including increases, decreases or no change (Creutzburg et al., 2016; Hartmann et al., 2012; Nave et al., 2010b; Palviainen et al., 2004; Yanai et al., 2003). The reasons for these disparities include methodological differences as well as variations in harvesting practices and ecosystem conditions (soil properties, climate, vegetation). Results from our simulations confirm previous analyses suggesting that tree harvesting under constant current climate should affect living tree biomass and woody debris more than soil carbon (Blanco et al., 2005; Creutzburg et al., 2016; Jiang et al., 2002; Wei et al., 2003). However, our simulations suggest that climate change could have negative impacts on soil organic matter pools and eventually on-site fertility. Soil organic matter plays a significant role in supporting soil nutrient availability, which is essential to maintain site productivity, particularly in N-limited forests. Nitrogen is generally a key growth-limiting nutrient in temperate forest ecosystems and lower N availability impacts forest productivity (Aherne et al., 2012; Seely et al., 2002). Our simulations suggest that the soil C:N ratios would be expected to fluctuate slightly with harvesting events (in the range of 15–17), and eventually generally exceed values for the reference no cutting scenario by 2200 under both climate conditions (Fig. A14). This soil C:N result confirms that intensive harvesting could decrease both soil carbon and nitrogen storage, but that soil nitrogen depletion would generally exceed that of organic carbon. Our results suggest that this effect would be heightened under climate change, potentially exacerbating N limitation of the northern forest ecosystem. The only clear exception to this pattern of soil C:N occurred for the 30-year cutting period under climate change, where soil C:N remained below the reference values throughout the simulation period. This effect was likely due to significant reduction of the aboveground biomass and woody debris pool that results in a rapid loss of the soil organic pool, limiting plant growth. This result confirms previous findings that litter pools represent a small fraction of the total ecosystem carbon pool, but rates of litter production have a significant impact upon carbon stored in the SOM pool (Seely et al., 2002). Another explanation might be the combination of progressive N limitation and an interaction of CO_2 and plant available N supply will likely lead to smaller NPP enhancement under increased atmospheric CO_2 than anticipated (Reich et al., 2006).

Our results also show that as more wood is extracted from the forest via harvesting, greater depletion of nutrient cations from the soil exchangeable complex will occur, resulting in a decline in soil base saturation (Aherne et al., 2012; Blanco et al., 2005). Depletion of soil base cations is accelerated under climate change due to increases in soil mineralization, plant uptake and enhanced biomass accumulation. Previous findings by Aherne et al. (2012) also show that increasing harvest intensity from stem-only harvest to whole-tree harvest approximately doubled the removal of biomass, tripled the removal of base cations and quadrupled the removal of N from forest catchments in Finland under constant climate. However, their study indicated that climate change would compensate for the depletion of soil base cations caused by harvesting, mainly due to increased weathering rates associated with warmer temperature. It is difficult to compare the results as we did not consider the effects of enhanced weathering with increases in temperature and they did not depict the effects of CO_2 fertilization on enhanced tree growth and nutrient uptake. The effects of nutrient cation loss are particularly problematic for sites like Hubbard Brook, which is characterized by naturally low rates of mineral weathering and depleted low soil pools of exchangeable nutrient cations (Nezat et al., 2004).

Few studies have evaluated the effects of forest harvesting under changing climate. Moreover, those studies have largely focused on the dynamics of carbon. Hence, there are few studies to compare with our work. Creutzburg et al. (2016) found patterns inconsistent with our projections, suggesting that climate change would decrease carbon sequestration in aboveground biomass and woody debris relative to current climate due to increases in heterotrophic respiration. They suggested that long-term impacts of forest harvesting on forest carbon would be less evident under changing climate than stationary climate, and they projected a slow increase in soil C accumulation (by 8% until 2100) with harvesting under both stationary and changing climate conditions due to the contribution of decomposition of roots from the harvested trees. One reason for the discrepancies between their study and ours is that the effects of CO_2 fertilization on biomass productivity were not considered in their work. Wu et al. (2017) concluded that climate change could increase C stock in forest biomass; however, they also pointed out that land-use change (i.e., deforestation, development) would be more likely to reduce forest C stocks in their study area in China by the middle of the 21st century.

Forest harvesting resulted in elevated export of N and base cations in the stream water immediately after harvesting (Dahlgren and Driscoll, 1994). These impacts were relatively greater under climate change mainly because of increases in organic matter mineralization associated with higher temperature. However, long-term cumulative leaching of base cations would likely be mitigated under climate change relative to stationary climate, due to the higher nutrient uptake of regrowing vegetation, as long as the consequent effects on base cation availability does not directly or indirectly reduce forest growth. Again PnET – BGC does not simulate individual tree species (only distinguishing conifer vs. hardwood forest) although some tree species in the northern forest are clearly sensitive to low availability of nutrient cations (e.g., red spruce, sugar maple, (Cleavitt et al., 2018)). Moreover, nitrogen is the element which is simulated to experience the greatest relative loss in the stream water over both short- and long- periods under different harvesting strategies, particularly under changing climate. In model calculations the current level of atmospheric N deposition was carried forward through the simulation period. However, air quality management efforts are resulting in declines in atmospheric N deposition with possible consequences for N availability that are not considered here (Lloret and Valiela, 2016). Previous studies have also showed that overexploitation of biomass leads to greater loss of nutrients particularly nitrogen and phosphorus, compared to the other nutrients (e.g. Ca^{2+}, Mg^{2+}, K^{+}) (Aherne et al., 2012; Blanco et al., 2005).

HBEF streams are highly sensitive to inputs of acid deposition and have negative or near zero acid neutralizing capacity (ANC) (Likens et al., 1996). Our simulations show that forest harvesting can significantly influence stream ANC, with projected reductions of 7% and 20% by 2200 under stationary climate and changing climate, respectively. These estimated reductions in ANC appear to be driven by decreases in soil base saturation associated with harvesting and elevated leaching of strong acid anions coupled with increases in runoff. These patterns suggest that long-term forest sustainability would require ensuring adequate supply of major nutrients over the long-term to maintain forest health and mitigate against stream acidification.

Increased demand for timber production has encouraged forest managers to develop guidelines to satisfy multiple criteria that not only maintain forests as carbon reservoirs but also to consider the ability of forests to sequester carbon (Creutzburg et al., 2016; Seely et al., 2002; Wang et al., 2014). As our results demonstrate, undisturbed mature forests can store significantly greater quantities of carbon in tree biomass and soils compared with those managed for timber production. However there are potential management strategies that can mitigate against this loss of carbon (Creutzburg et al., 2016; Scheller and Mladenoff, 2005; Seely et al., 2002). Many studies have reported that the ability of a forest to store carbon declines with increasing age when the rate of ecosystem respiration approaches primary production (Scheller and Mladenoff, 2005; Seely et al., 2002). Our results suggest that under both stationary and climate change conditions the rate of carbon sequestration in forest biomass depends upon the cutting interval, with a sharp increase from the intervals of 30–60 years, but only a modest increase from 60 to 90 years (Fig. A3).

We examined the trade-offs between timber production and long-term carbon storage under both stationary and climate change conditions. Total carbon storage at the end of the simulation interval (2200) and its relation to cumulative harvested stemwood carbon for the 180-year hypothetical simulation period are depicted using a diagonal line that denotes the 1:1 relationship between the variables (Fig. 6). Management options falling above the line favor carbon use for timber production while management scenarios falling below the line favor ecosystem carbon storage and nutrient retention. Simulations show that all management options under climate change enhance both timber production and carbon storage in comparison to stationary climate, but with greater potential for a reduction in long-term soil fertility.

4.2. Sources of model uncertainty

Although the PnET-BGC model used in this study was previously parameterized using direct field measurements and tested using comprehensive observations of vegetation, soil and stream water chemistry at a variety of field sites (Pourmokhtarian et al., 2017), some important limitations are acknowledged, especially its application across large time scales. First, PnET-BGC does not directly account for changes in tree species composition following forest harvest or with changing climate that might significantly influence the dynamics of forest biomass, hydrology and biogeochemistry. Second, weathering rates of elements through the simulation period and atmospheric deposition rates for the future years were assumed to be constant, but both may be influenced under changing climate, altering the supply and availability of nutrient sources (Aherne et al., 2012; Vadeboncoeur et al., 2014). Third, indirect effects of climate change, such as increases in wildfire, insect defoliation and diseases were not considered but are clearly potentially important (Creutzburg et al., 2016; Wei et al., 2003).

An additional important source of uncertainty that demands attention is the simulation of biomass accumulation under changing climate and CO_2 fertilization. First, the model projects aboveground biomass values under changing climate with no harvest that exceed values observed in any existing old-growth northern hardwood forests in the region; for example, Keeton et al. (2011) report upper-end values below 250 Mg C/ha while the model projects over 300 Mg C/ha (Fig. 1). Whether such high biomass could be attained in a changed climate on sites like the HBEF is questionable as a variety of site and species limitations might exist. Second, the sustained biomass accumulation in the long-term model simulations under changing climate suggests that the forests could overcome progressive nitrogen limitation (PNL) that has been associated with CO_2 fertilization (Luo et al., 2004). Note that the model assumed that enhanced levels of atmospheric N deposition would continue into the future, whereas recent observations suggest that pollution controls are significantly decreasing N deposition (Gilliam et al., 2019; Lloret and Valiela, 2016). Moreover, Luo et al. (2004) indicated that N deposition would be insufficient to overcome PNL. Most importantly, the soils at the HBEF have relatively large soil

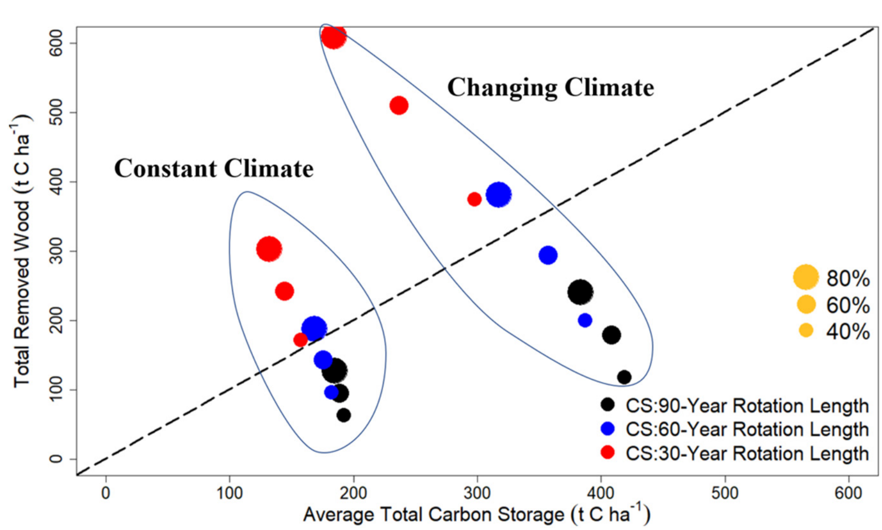

Fig. 6. Simulation of total stored carbon in the forest ecosystem at the end of simulations (2200 year) and its relation to cumulative harvested stemwood carbon over the 180-year simulation period for various cutting regimes (from 2020 year until 2200 year) under stationary and changing climate conditions for W5, HBEF. The diagonal line denotes a 1:1 relationship between variables.

organic C and N stocks that the model projects would be significantly mineralized under changing climate (Fig. 2); this soil organic N stock provides most of the N that maintains forest biomass accumulation in the long -term simulations. Short-term empirical studies have not detected a CO_2 fertilization effect on soil N mineralization (Graaff et al., 2006; Liang et al., 2016), but whether such a mechanism could overcome long-term PNL is unknown. The current version of PnET-BGC simulates soil organic matter as a single pool functionally equivalent to the "active" pool in Century (Parton et al., 1993). This simplified approach probably allows the mineralization of N from some highly resistant SOM pools that might not be mineralized even over very long-time scales (Ollinger et al., 1997). Nevertheless, some empirical CO_2 fertilization studies indicate that greater exploitation of untapped soil N by tree roots may be capable of accessing the N supplies necessary to overcome PNL (Finzi et al., 2006; Norby et al., 2010). Further understanding of this effect is certainly needed so that models can more accurately project climate change and forest harvest effects on ecosystem C and N dynamics.

Few studies have evaluated the long-term effects of CO_2 emissions and its interaction with other global-change drivers (e.g. harvesting) (Pourmokhtarian et al., 2017). Uncertainty in predictions of greenhouse gas emission and climate data in any climate change scenario can affect model simulations. The limitations and uncertainties noted above warn against over interpreting our quantitative predictions. In addition, forestry practices are highly site dependent. Hence, we suggest caution when extrapolating results from one site to another without proper evaluation of specific impacts. Nevertheless, our work shows how a multi-element soil-layer model can be used as a useful diagnostic tool to gain a better understanding of the complex interactions of ecological process and their response to multiple ecosystem stressors. The results of different combinations of harvesting and climate scenarios provide important insight into the relative importance of different factors on key ecosystem processes including carbon sequestration, nitrogen cycling, and biomass accrual.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.144881.

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