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ORIGINAL PAPER

Seeking potential contributions to future carbon budget in conterminous US forests considering disturbances

Fangmin Zhang[1,2] **· Yude Pan**[3] **· Richard A. Birdsey**[3] **· Jing M. Chen**[2] **· Alexa Dugan**[3]

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Abstract Currently, US forests constitute a large carbon sink, comprising about 9 % of the global terrestrial carbon sink. Wildfire is the most significant disturbance influencing carbon dynamics in US forests. Our objective is to estimate impacts of climate change, CO_2 concentration, and nitrogen deposition on the future net biome productivity (NBP) of US forests until the end of twenty-first century under a range of disturbance conditions. We designate three forest disturbance scenarios under one future climate scenario to evaluate factor impacts for the future period (2011–2100): (1) no wildfires occur but forests continue to age (S_{aging}), (2) no wildfires occur and forest ages are fixed in 2010 (S_{fixed_nodis}), and (3) wildfires occur according to a historical pattern, consequently changing forest age ($S_{dis\_age\_change}$). Results indicate that US forests remain a large carbon sink in the late twenty-first century under the S_{fixed_nodis} scenario; however, they become a carbon source under the S_{aging} and $S_{dis\_age\_change}$ scenarios. During the period of 2011 to 2100, climate is projected to have a small direct effect on NBP, while atmospheric CO_2 concentration and nitrogen deposition have large positive effects on NBP regardless of the future climate and disturbance scenarios. Meanwhile, responses to past disturbances under the S_{fixed_nodis} scenario increase NBP regardless of the future climate scenarios. Although disturbance effects on NBP under the S_{aging} and $S_{dis\_age\_change}$ scenarios decrease with time, both scenarios experience an increase in NBP prior to the 2050s and then a decrease in NBP until the end of the twenty-first century. This study indicates that there is potential to increase or at least maintain the carbon sink of conterminous US forests at the current level if future wildfires are reduced and age structures are maintained at a productive mix. The effects of CO_2 on the future carbon sink may overwhelm effects of other factors at the end of the twenty-first century. Although our model in conjunction with multiple disturbance scenarios may not reflect the true conditions of future forests, it provides a range of potential conditions as well as a useful guide to both current and future forest carbon management.

✉ Fangmin Zhang
fmin.zhang@utoronto.ca

[1] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, College of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, Jiangsu 210044, China

[2] Department of Geography, University of Toronto, 100 St. George Street, Toronto, ON M5S 3G3, Canada

[3] Newtown Square Corporate Campus, USDA Forest Service, 11 Campus Blvd, Newtown Square, PA 19073, USA

1 Introduction

Disturbance is an important feature of forests that determines stand age distributions and carbon dynamics across a forest landscape—current growth rates and carbon stocks are directly related to disturbance history (Peichl et al. 2010; Nunery and Keeton 2010; Pregitzer and Euskirchen 2004; http://www.sciencedaily.com/releases/2014/07/140720204326.htm). The future rate of forest carbon sequestration, to a large extent, might depend on disturbances and stand age (Birdsey et al. 2006; Pan et al. 2011a, 2013). For example, Li et al. (2013) quantified fire effects globally in the twentieth century via fire-on and fire-off simulation with the NCAR community Land Model CLM4.5. He concluded that direct fire decreased net carbon gain of global terrestrial ecosystem by 1.9 PgC yr^{-1}, and indirect effect increased by 0.9 PgC yr^{-1} which can be attributed to regrowth after burning. The capacity of carbon sequestration of US forests in the twenty-first century may decline with increasing disturbance events and forest aging; conversely, the carbon sink would be increased by one third if no disturbances occurred (EPA 2015). How non-disturbance factors (such as atmospheric CO2, nitrogen deposition, and climate) will affect carbon sequestration if disturbances continue to determine the amount of carbon that forests will uptake in the future?

The climatic effects on forest carbon dynamics depend on the non-linear functions of carbon uptake and release as related to precipitation and temperature (Canadell et al. 2007a; Chmura et al. 2011; van der Molen et al. 2011; Reith et al. 2014). Climate change also affects nitrogen availability which in turn will constrain CO_2 effects on plants (Reith et al. 2014); on the other side, increasing of atmospheric CO_2 concentration primarily can stimulate plant growth to increase carbon sequestration, but the long-term sustainability of carbon storage depends on nitrogen availability (Luo and Weng 2011). Bala et al. (2013) indicated that future warming effects on carbon storage may overwhelm nitrogen deposition effects by sensitivity analysis, but atmospheric CO_2 is still the dominant influence factor. Balshi et al. (2009) highlighted the importance of CO_2 fertilization in the future by comparing simulations from Terrestrial Ecosystem Model (TEM) with and without CO_2 fertilization. However, if nitrogen deposition inputs are more than nitrogen losses, GPP response to CO_2 may be less constrained by nitrogen availability in the simulation of Balshi et al. (2009) (Sokolov et al. 2008). Although Balshi et al. (2009) introduced disturbances (fire) and stand age to evaluate carbon storage changes to wildfires, stand age was only considered as a tool to estimate disturbed areas rather than as a driver of carbon dynamics. De Vries and Posch (2011) suggested that climate change may be the major driver for future carbon sequestration in Europe, and its impact is reduced by nitrogen availability; however, disturbances were ignored. Currently, US forests constitute a large carbon sink (~214 TgC yr^{-1}, Zhang et al. 2012, 2015), comprising about 9 % of the global terrestrial carbon sink (~2400 TgC yr^{-1}, Pan et al. 2011a). Which is the dominant factor for future carbon sequestration needs more exploration when considering disturbance patterns.

Models with climate, disturbance, and vegetation are indispensable tools for future prediction. In the absence of these interactions, ecosystem responses to future changing climate may be misrepresented (Keane et al. 2015). The Integrated Terrestrial Carbon Cycle Model (InTEC) has been verified that can simulate the ecosystem processes interactions (Chen et al. 2000a, b, c; Zhang et al. 2012, 2015).

Wildfire as an important disturbance type, here we investigate changes of future carbon sequestration in US forests to wildfire along with changes in future climate via fire-on, fire-off, and fire-change simulation. We chose the A2 climate scenario since it represents one of the "marker" scenarios developed through IPCC (http://www.ipcc.ch/report/). Moreover, the A2 scenario is at the higher end (although not the highest) of the Special Report on Emissions Scenarios (SRES); so, if ecosystems can adapt to a larger climate change, then they potentially can adapt to the lower ones. In addition, the current actual emission (1990 to present) is at a relatively high level. Three disturbance patterns are designated for the future period: (1) wildfires occur at a rate of 1 % with consequent changes in forest age ($S_{dis\_age\_change}$) based on the recent historical estimates (e.g., Smith et al. 2009), (2) no wildfires occur but forests continue aging from ages observed in 2010 (S_{aging}), and (3) no wildfires occur and forest ages are fixed to ages observed in 2010 (S_{fixed_nodis}). Based on these three disturbance patterns, we examine changes of carbon sequestration to disturbances along with changes in future climate. This could provide important evidences to help understand and predict future US carbon sequestration.

2 Methods and materials

2.1 Overview of model

The Integrated Terrestrial Carbon Cycle Model (InTEC) was designed to investigate the effects of changing climate, atmospheric composition, disturbances, and forest recovery on long-term carbon and nitrogen cycles in forest ecosystems (Chen et al. 2000a, b, c, 2003; Zhang et al. 2012, 2015). The advantage of this model is that it integrates the effects of both non-disturbance (i.e., climate, CO_2 concentration, nitrogen deposition) and disturbance effects (i.e., direct carbon loss from harvest, fire and insect attacks, and subsequent forest recovery following disturbance events) on carbon dynamics. This model has been used to evaluate the relative contributions and uncertainties of both forest disturbance and non-disturbance factors on the net C changes of conterminous (including contiguous 48 states, except Alaska, Hawaii, and other islands) US forests from 1901 to 2010 (Zhang et al. 2012, 2015). These results provide the foundation for estimating future carbon dynamics across the conterminous US forests under different disturbance scenarios.

2.2 Input data

All input data prior to 2010 were described in earlier studies (Zhang et al. 2012, 2015). The derived forest stand age map in 2010 and the relationships between NPP and stand ages (He et al. 2012) were used as a basis to develop disturbed areas and age effects after wildfires during 2011–2100. We treated the average climate, CO2, and nitrogen deposition during 2001–2010 as baseline.

2.2.1 Future non-disturbance data

A control and a projected future climate scenario (A2) from version two of the second generation of Canadian Coupled General Circulation Model (CGCM2) are used for the period of 2011 to 2100 (http://www.cccma.ec.gc.ca/data/cgcm2/cgcm2.shtml). The control scenario represents a potential climate system with the late twentieth century atmospheric concentration of GHGs. The A2 climate scenario is characterized by drastic increases of nitrogen emissions until 2100, which represent potential climate systems with extreme GHG emission rates and aerosol forcing assumption from IPCC SRES "A2" (http://www.cccma.ec.gc.ca/data/cgcm2/cgcm2.shtml). The datasets are at an approximately 3.75° longitude × 3.75° latitude (a 97 × 48 Gaussian grid) spatial resolution.

To adjust the climate bias between current and future data, the departures of current monthly climate during 1991–2010 relative to the contemporary monthly climate from Climate Research Unit (CRU) data were applied to time series of future climates from 2011 to 2100 by:

$$CGCM2_{adjusted\ monthly} = \overline{CRU_{h\ monthly}} - \overline{CGCM2_{h\ monthly}} + CGCM2_{f\ monthly} \quad (2)$$

where $CGCM2_{adjusted\ monthly}$ is the adjusted monthly future climate data during 2011–2100, $\overline{CRU_{h\ monthly}}$ is the mean monthly values during 1991–2010 from CRU, $\overline{CGCM2_{h\ monthly}}$ is the mean monthly values during 1991–2010 from CGCM2, and $CGCM2_{f\ monthly}$ is the monthly future values during 2011–2100. This method forces future climate variability to be in agreement with current climates, facilitating a continuous time series of future climate variability from 2011 to 2100.

Anlysis of the CGCM2 A2 climate scenario used shows that the mean annual temperature will rise up from 11.3 °C (1990–2015) to 16.4 °C by the end of the twenty-first century. Meanwhile, precipitation trends do not change greatly, but its geographic patterns vary considerably. Under the A2 climate scenario, by the end of the twenty-first century, temperature will increase by over 6 °C in part of the North Rocky Mountain region (referring to regional divisions of US forests from http://www.fs.fed.us/research/rpa/regions.php) compared to the period of 2001–2010. Meanwhile, precipitation will increase more than 30 % in the Pacific Southwest region but decrease more than 30 % in the Southeast region compared to the period of 2001–2010.

The corresponding CO_2 concentration ($[CO_2]$) and GHG concentration ([GHG]) were used from the CGCM2 A2 climate scenario. It assumes that the $[CO_2]$ rises up to 850 ppm and [GHG] to 1320 ppm CO_2 eq. in 2100.

2.2.2 Future disturbance scenarios: wildfire and stand age

Wildfire is only the disturbance type we used in the model simulation after 2010. We define three different future disturbance scenarios based on wildfires and stand age. The first scenario (S_{aging}) assumes no wildfires for the entire conterminous US forests after 2010, therefore forests continue to age annually from their current age in 2010. The second scenario (S_{fixed_nodis}) is that there are no wildfires after 2010 but forests keep their current age in 2010 until the end of the twenty-first century. Currently, it is estimated that the average area burned by fires from 2002 to 2010 is about 0.9 % of the forest area (6.8 million acres) in the USA, with large inter-annual variability (http://www.nifc.gov/fireInfo/nfn.htm). Zhuang et al. (2006) studied CO_2 and CH_4 exchanges between land ecosystems and the atmosphere by assuming that the area burned each year at a fixed rate of 1 % per year from 2000 to 2100. Thus, based on Zhuang et al. (2006) and the current wildfire rate in US forests (Smith et al. 2009), in the third scenario ($S_{dis\_age\_change}$), we assume a constant wildfire rate of 1 % per year for the whole conterminous US forests and then assign wildfires to pixels in different regions based on forest inventory age classification information (Pan et al. 2011b).

2.3 Simulation strategy performed

Three disturbance simulations were designed to predict potential carbon dynamics sensitive to future disturbance patterns. We first run a scenario without considering disturbances but baseline with current climate conditions, atmospheric CO_2, and nitrogen deposition, i.e., $S0_{aging}$, $S0_{fixed\_nodis}$, and $S0_{dis\_age\_change}$. For each of the three disturbance scenarios, we also run following eight simulations: (S1) baseline with current climate conditions, atmospheric CO_2, and nitrogen deposition; (S2) future climate, future atmospheric CO_2, and baseline nitrogen deposition; (S3) future climate, baseline atmospheric CO_2, and future nitrogen deposition; (S4) future climate, baseline atmospheric CO_2, and baseline nitrogen deposition; (S5) future air temperature, baseline precipitation, future atmospheric CO_2, and future nitrogen deposition; (S6) baseline temperature, future precipitation, future atmospheric CO_2, and future nitrogen deposition; (S7) baseline climate, future atmospheric CO_2, and future nitrogen deposition; and (S8) future climate, future atmospheric CO_2, and future nitrogen deposition. S8 is also called the combined overall effect including disturbance and non-disturbance factors. Thus, under each disturbance pattern, nitrogen effect by S8–S2, CO_2 effect by S8–S3, combined CO_2 and nitrogen effect by S8–S4, precipitation effect by S8–S5, temperature effect by S8–S6, climate effect by S8–S7, and the combined non-disturbance effect by S8–S1 have been investigated. The disturbance effects for three disturbance patterns are determined by S1–$S0_{aging}$, S1–$S0_{fixed\_nodis}$, and S1–$S0_{dis\_age\_change}$, respectively.

The historical climate, CO_2 concentration, nitrogen deposition, disturbances (including harvest, insect, and fire), and forest stand age were used to initialize the model simulation so that all carbon pools can attain an equilibrium state in the beginning year (Zhang et al. 2012). In all simulations, historical disturbance and non-disturbance effects were explicitly considered in the historical carbon dynamics prior to 2011 (Zhang et al. 2012). We assume that forest areas and forest species do not change during the simulation period. In a wildfire year, the amount of carbon directly emitted from the stand-replacing fire was estimated as the sum of 100 % of foliage carbon, 25 % of woody carbon, and 100 % of carbon in surface structural and metabolic detritus pools (Kasischke et al. 2000). Forest stands are reset to zero year old, start to regenerate immediately in the year after wildfire, then continue to age until the next wildfire.

3 Results and discussion

3.1 Carbon sink and source estimates under disturbance scenarios

Figure 1 shows the trend of carbon sinks and sources in three disturbance scenarios under A2 climate scenario, starting 2010 until 2100. When forests are disturbed and stand ages are changed ($S_{dis\_age\_change}$), NBP shows a decreasing trend from the 2010s to the 2060s, and then increases to 284 TgC yr^{-1} in 2100 s. NBP decreases when forests continue to age without any wildfires (S_{aging}), but forests still remain a carbon sink (about 70 TgC yr^{-1}) in 2100 s. When 2010 stand ages are maintained and there are no wildfires (S_{fixed_nodis}) from 2011 to 2100, NBP increases from the 2010s and reaches its maximum value (750 TgC yr^{-1}) in the 2070s. From then on, NBP decreases and maintains an average of 570 TgC yr^{-1}.

To better understand the changes of carbon sources and sinks in the late twenty-first century, Fig. 2 illustrates the spatial deviation of the average NBP during the period from 2081 to 2100 relative to the period of 2001–2010 under three disturbance patterns. The NBP deviations vary greatly under different disturbance scenarios (Figs. 2a–c). Relative to the period of 2001–2010, during the period of 2081–2100 NBP under the $S_{dis\_age\_change}$ scenario shows a decrease in the northern Great Lakes, Northeast, South, and western West Coast regions (Fig. 2a). However, NBP shows an increase in the Mid-Atlantic and western Rocky Mountain regions, reaching the maximum rate of up to 400 gC m^{-2} yr^{-1}. In contrast, the change patterns of NBP under the S_{aging} scenario are similar to the patterns of NBP under the $S_{dis\_age\_change}$ scenario, but the change magnitudes are rather moderate (Fig. 2b). Under the S_{fixed_nodis} scenario, NBP increases in most areas across the conterminous US forests relative to the period of 2001–2010 (Fig. 2c). Comparisons of NBP changes

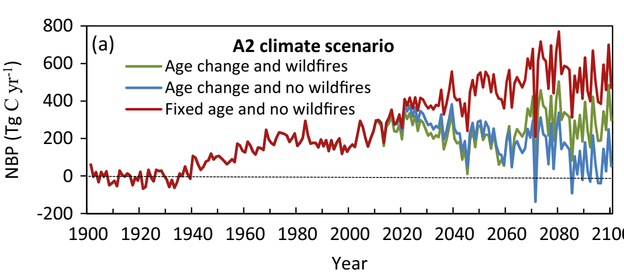

Fig. 1 Changes of net biome productivity (NBP) responses to three disturbance scenarios under A2 and control climates. See details about disturbance scenarios in Section 2.2.2. *Negative values* indicate carbon sources

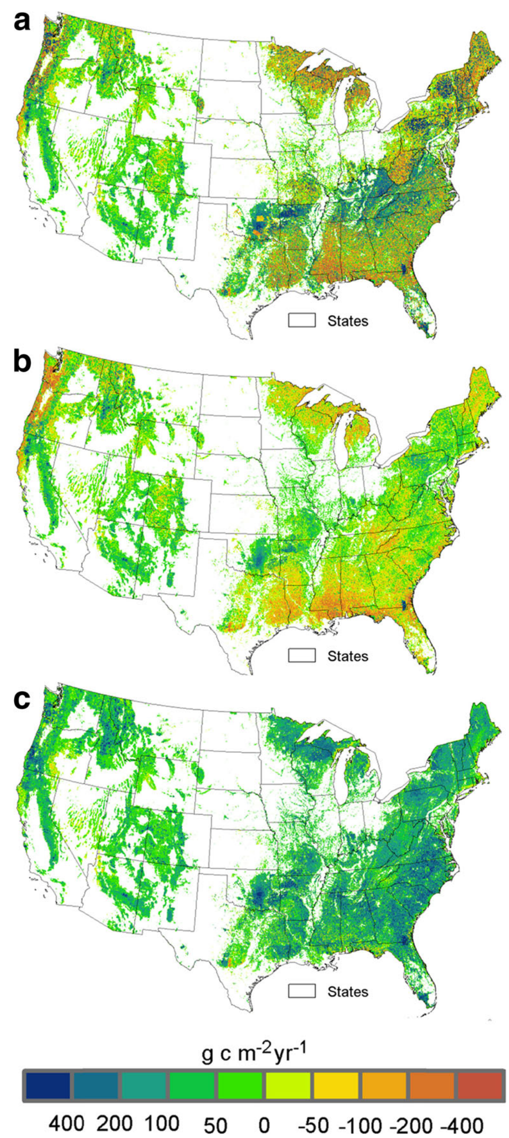

Fig. 2 Mean departures of net biome productivity (NBP) across the conterminous US forests calculated for the period of 2081–2100 relative to the 2001–2010 contemporary mean values under the A2 climate scenario in combination with the following three disturbance scenarios: **a** "age change and wildfires" ($S_{dis\_age\_change}$), **b** "age change and no wildfires" (S_{aging}), and **c** "fixed age and no wildfires" (S_{fixed_nodis}). *Negative values* indicate carbon sources

under three disturbance scenarios show that the increase of NBP under the S_{fixed_nodis} scenario is the largest.

3.2 Potential contributions to carbon sinks and sources under disturbance scenarios

The future CO_2 concentration under the A2 climate scenario will increase NBP under the three disturbance scenarios but at varying magnitudes and with differing trends under each disturbance scenario (Fig. 3a). The contribution of CO_2 to NBP is higher under the S_{fixed_nondis} scenario than under the $S_{dis\_age\_change}$ and S_{aging} scenarios during 2011 to 2060; however, it is higher under the $S_{dis\_age\_change}$ scenario than under the S_{aging} and S_{fixed_nondis} scenarios during 2061 to 2100.

Nitrogen deposition shows positive effects on NBP with different increasing rates under three disturbance scenarios (Fig. 3b). The impact is particularly remarkable under the $S_{dis\_age\_change}$ scenario. It saturates in the 2080s with the maximum increase in NBP of 210 TgC yr^{-1} under the $S_{dis\_age\_change}$ scenario, while it saturates in the 2070s with NBP increased by 80 TgC yr^{-1} under the S_{aging} scenario. The effect of nitrogen deposition on NBP does not saturate under the S_{fixed_nodis} scenario, which results in an increase of NBP in 2100.

Impacts of climate change on NBP are relatively smaller (−100 to 75 TgC yr^{-1}) than impacts of CO_2 and nitrogen deposition on NBP (Fig. 3c). Under the $S_{dis\_age\_change}$ scenario, effects of climate on NBP are negative during the periods of 2011–2060 and 2081–2090. Under the S_{aging} scenario, climate effects do not noticeably influence NBP from 2011 to 2050. However, climate increases NBP from 2051 to 2080, and then the effects of climate become negative from 2081 to 2100. Under the S_{fixed_nodis} scenario, climate changes do not have an obvious effect on NBP except for the period of 2061 to 2090. However, climate increases NBP in the 2070s but decreases NBP in the 2060s and 2080s.

Disturbance effects on NBP from all three disturbance scenarios show decreasing trends (Fig. 3d), but effects under the $S_{dis\_age\_change}$ and S_{aging} scenarios become negative after the 2050s while the effect under the S_{fixed_nodis} scenario is always positive during the period of 2011 to 2100. It indicates that disturbances could increase carbon sink, but as forest stands are aging or consecutively disturbed, disturbance might induce carbon sinks to become carbon sources by the end of the twenty-first century.

4 Discussion

4.1 Carbon dynamics of conterminous US forest in the twenty-first century

Comparison of NBP changes related to stand age suggests that forest aging reduces the carbon sink of conterminous US forests to a carbon source in 2100 under the A2 climate scenario. However, even if the forests are kept at the current stand ages, the carbon sink still drops in the 2080s likely due to climate effects (Fig. 1). The forest carbon

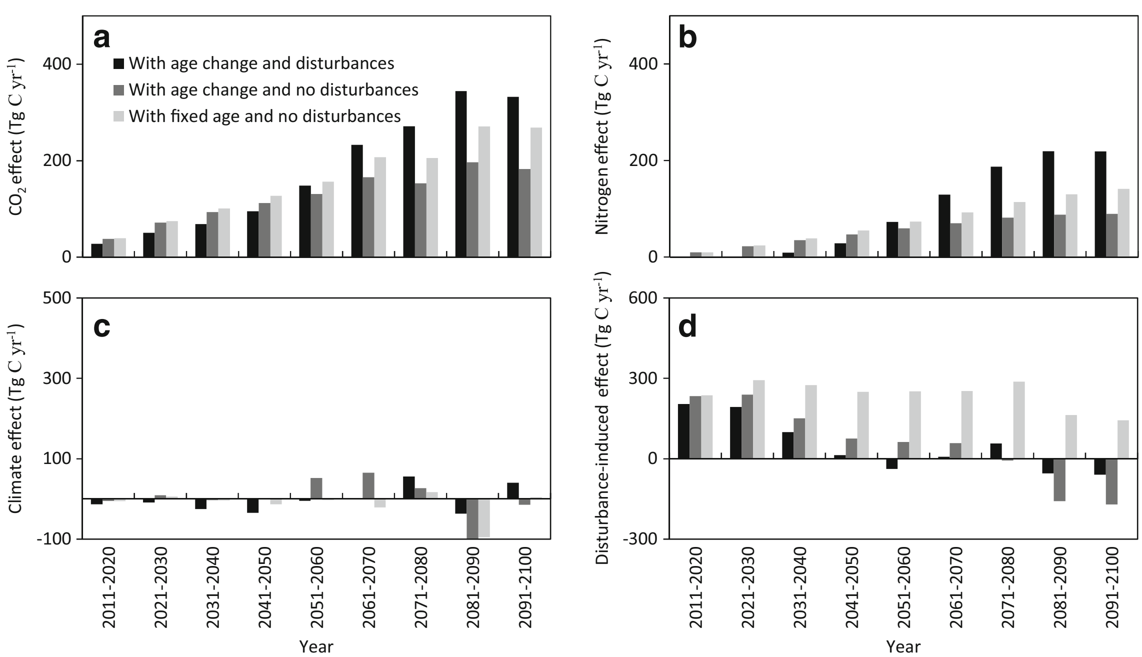

Fig. 3 Relative decadal contributions of atmospheric CO_2 concentrations, nitrogen deposition, climate variability, and disturbance factors to net biome productivity (NBP) of conterminous US forests from 2011 to 2100 under the following three disturbance scenarios: **a** "age change and wildfires" ($S_{dis\_age\_change}$), **b** "age change and no wildfires" (S_{aging}), and **c** "fixed age and no wildfires" (S_{fixed_nodis})

sink would be larger than the current level under the $S_{dis\_age\_change}$ and S_{fixed_nodis} disturbance scenarios but would be smaller or even become a carbon source under the S_{aging} scenario. This suggests that forests would have a smaller carbon sink if they continue aging without disturbances initiating regrowth than if forest ages change with disturbances. Generally, young forests accumulate carbon at higher rates with peak accumulation in middle ages (He et al. 2012), whereas old-growth stands are carbon neutral, or small carbon sinks based on forest carbon-flux estimates (such as Song and Woodcock 2003; Knohl et al. 2003; Luyssaert et al. 2008), which might help explain why the S_{aging} scenario may result in smaller carbon sinks. On the other hand, forests have been rebounding from previous disturbances, becoming net carbon sinks (Birdsey et al. 2006) over much of the twentieth century, which also explains why further aging from current productive ages without disturbances prompting establishment of young forests may eventually lead to smaller carbon sinks or carbon sources (Figs.1 and 4).

4.2 Atmospheric CO_2, nitrogen, and climate effects

As mentioned above (Section 2.2.1), both of CO_2 and nitrogen deposition increase in the future under the CGCM2 A2 climate scenario. Our simulations for the twenty-first century indicate that atmospheric CO_2 and nitrogen fertilization play an important role in the carbon changes for conterminous US forests under the assumption that CO_2 and nitrogen deposition will increase. However, the nitrogen deposition started to decline in recent 10 years in the USA (http://nadp.sws.uiuc.edu/data/). If this is true, the simulated US carbon sink should be shrunk (Fig. 4). Currently, forests that are less than 100 years old account for 97 % of the conterminous US forests. These young forests have strong capability to sequester carbon, making current US forests as a large carbon sink (~300 TgC yr^{-1}, Pan et al. 2011a). If current (2010) forest ages (S_{fixed_nodis}), atmospheric CO_2 levels, and nitrogen levels were held constant, the current carbon sink in US forests may be reduced to a smaller sink (~50 TgC yr^{-1}) or even to a small source by the end of the twenty-first century under A2 climate scenario. If forests aged without any disturbances in the future (S_{aging}), the carbon sink of US forests would become a source without CO_2 and nitrogen fertilization under the A2 climate scenario.

In this study, the CO_2 effect is larger than the nitrogen effect and both get saturated by the end of the twenty-first century (Figs. 1 and 4). However, the nitrogen effect limiting CO_2 effect vary among vegetation and soil conditions (Thomas et al. 2009; Luo and Weng 2011; de Vries and Posch 2011; Bala et al. 2013). We found that the contributions of CO_2 to NBP under the A2 climate scenario for three disturbance scenarios become saturated towards the end of the twenty-first century (Figs. 1 and 4). However, the CO_2 effect from simulations of Balshi et al. (2009) under A2 climate scenario did not saturate in the end of the twenty-first century. Such differences between our results may be attributed to model structures.

Our results indicate that the effects of nitrogen deposition on carbon are smaller than the effects of CO_2 but larger than the effects of climate (Fig. 3). However, previous studies indicated that future forest growth is estimated to be dominated by climate change (de Vries and Posch 2011) or that climate warming effects may overwhelm the nitrogen deposition effects on carbon in the future (Bala et al. 2013). Conversely, contributions of climate to overall NBP are less than 10 % in our study, which incorporates the effects of CO_2, nitrogen deposition, disturbance, and stand age on carbon dynamics. It is suggested that uncertainties about the responses of NEP to climate, CO_2, nitrogen, and other factors are primarily due to differences in how modeled NPP responds to a changing climate (Cramer et al. 2001).

In this study, the increased carbon sink as a result of climatic change is generally associated with the increase of

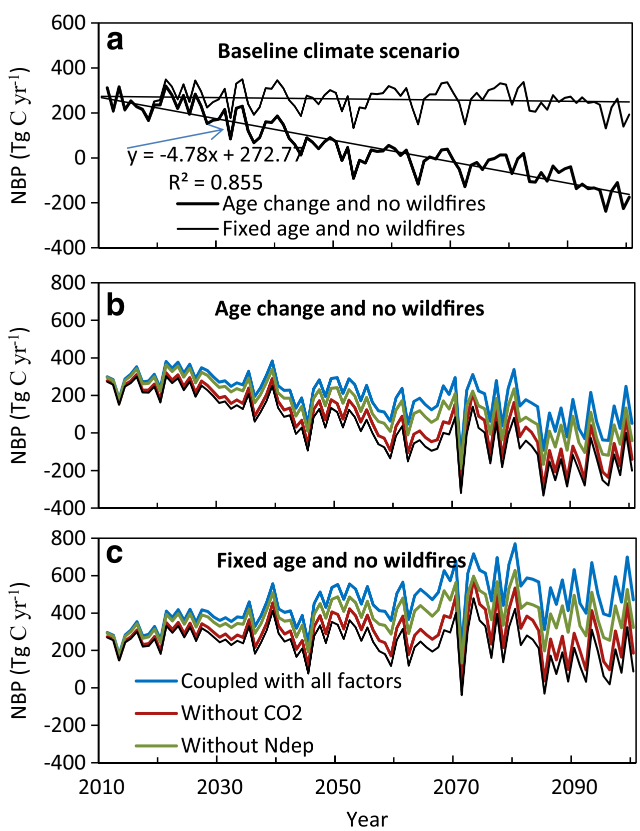

Fig. 4 Changes of net biome productivity (NBP) under baseline climate scenario with the disturbance scenarios of "age change and no wildfires" (S_{aging}) and "age fixed and no wildfires" (S_{fixed_nodis}) from 2011 to 2100 (**a**), in response to with/without CO_2 concentration and nitrogen deposition under the A2 climate scenario with the disturbance scenarios of "age change and no wildfires" (S_{aging}) and "age fixed and no wildfires" (S_{fixed_nodis}) from 2011 to 2100 (**b**–**c**)

growing season length due to warming, greater availability of soil nitrogen due to warming and/or wetting enhanced nitrogen fixation and mineralization, and the decline of decomposition rate due to wetter conditions. Taking the simulation S_{fixed_nodis} as an example, the climate contribution to NBP is primarily attributed to the increase of temperature in the North Plains region (Fig. 5a). NBP would be higher without considering the slight increase in precipitation in this region. In contrast, the climate effect on NBP is mainly due to the increase of precipitation (≥30 %) in the Pacific Southwest region although warming also increases NBP (Fig. 5b). Without considering the increase of precipitation, NBP would be reduced by 26 % while by 12 % without temperature effect. Meanwhile, a future drier climate in the Southeast region results in a decline in NBP (Fig. 5c). This indicates that increase in precipitation can enhance carbon sequestration for mesic plants but reduce carbon sequestration for xeric plants, which is partly due to nonlinear functions of carbon uptake and release, and temperature and water availability.

This study stimulated future carbon dynamics of the conterminous US forests by integrating the effects of disturbances and stand age along with environmental variables. Disturbances can change forest stand age, which is considered to be a dominant driver of forest growth and carbon sequestration in the past (Birdsey et al. 2006; Pan et al. 2011b; Canadell et al. 2007b; Zhang et al. 2012). Our study indicates that the contribution of stand age may be reduced by climate effect although stand age is a dominant factor of the current carbon sink of conterminous US forests (see S_{fixed_nodis} scenario in Fig. 3d). On the other hand, as forests age or when forest growth due to stand age cannot offset the carbon release from frequent disturbances (1 % per year in this study), the conterminous US forests will become a carbon source if the effects of CO_2 and nitrogen deposition are ignored (see S_{aging} and $S_{dis\_age\_change}$ scenarios in Fig. 3d). It indicates that the forest carbon sink of conterminous US forests will not decline if the current forest stand ages are maintained regardless of the climate change in the future.

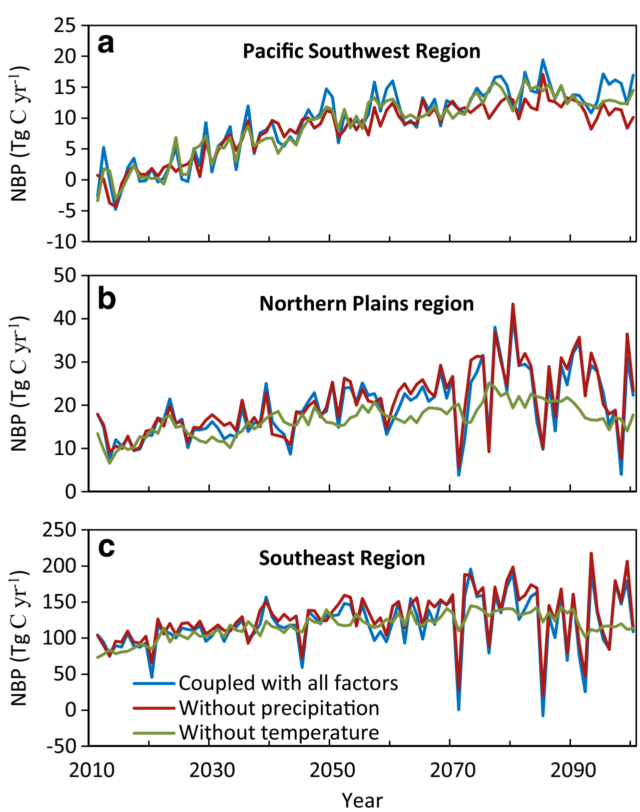

Fig. 5 Time series of net biome productivity (NBP) of three sub-regions in response to with/without precipitation and temperature under A2 climate scenario with the disturbance scenario of "age fixed and no wildfires" (S_{fixed_nodis}) from 2011 to 2100

5 Conclusions

This study projected the future carbon dynamics of conterminous US forests under the A2 climate scenario with three disturbance scenarios, which is trying to explore the potential contributions of climate and disturbance interactions to carbon sequestration. Results suggest that the effect of CO_2 and nitrogen deposition can overwhelm the other effects, enhancing the carbon sink by 2100 under the A2 climate scenario. Our simulations also suggest that the effects of CO_2 may become the dominant contributor to the future carbon sink under warming and disturbed conditions in the future. Meanwhile, stand age structures shifted by disturbances may sequester more carbon to offset carbon release. The influence of disturbances on carbon sequestration of forest vary greatly with disturbance scenarios. The conterminous US forests are likely to become a carbon source if the enhancing effects of CO_2 and nitrogen deposition are ignored under certain disturbance scenarios.

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