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Potential influence of climate-induced vegetation shifts on future land use and associated land carbon fluxes in Northern Eurasia

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Abstract

Climate change will alter ecosystem metabolism and may lead to a redistribution of vegetation and changes in fire regimes in Northern Eurasia over the 21st century. Land management decisions will interact with these climate-driven changes to reshape the region's landscape. Here we present an assessment of the potential consequences of climate change on land use and associated land carbon sink activity for Northern Eurasia in the context of climate-induced vegetation shifts. Under a 'business-as-usual' scenario, climate-induced vegetation shifts allow expansion of areas devoted to food crop production (15%) and pastures (39%) over the 21st century. Under a climate stabilization scenario, climate-induced vegetation shifts permit expansion of areas devoted to cellulosic biofuel production (25%) and pastures (21%), but reduce the expansion of areas devoted to food crop production by 10%. In both climate scenarios, vegetation shifts further reduce the areas devoted to timber production by 6–8% over this same time period. Fire associated with climate-induced vegetation shifts causes the region to become more of a carbon source than if no vegetation shifts occur. Consideration of the interactions between climate-induced vegetation shifts and human activities through a modeling framework has provided clues to how humans may be able to adapt to a changing world and identified the trade-offs, including unintended consequences, associated with proposed climate/energy policies.

Keywords: climate-change effects, climate policy, economic feedbacks, land-cover change, land-use change, carbon sequestration, biofuels

S Online supplementary data available from stacks.iop.org/ERL/9/035004/mmedia

1. Introduction

Climate change is likely to alter both the metabolism (e.g. net primary production, decomposition) and species composition of ecosystems in the future [1, 2]. Some of these

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changes in ecosystems dynamics may occur rather slowly as later successional species eventually become more dominant over early successional species as environmental conditions change. However, other changes may occur rather rapidly when unfavorable environmental conditions promote die-back, disease and wildfires [3–9]. These climate-induced changes in ecosystem characteristics may also cause some currently undeveloped areas to become more suitable for economic activity and other areas to be less suitable [10–12]. Furthermore, climate-induced changes in the productive capacity of managed lands may cause changes in the extent and distribution of these lands used to support the production of food, fiber and bioenergy for a growing human population. Thus, it is important to determine what limitations and opportunities may exist in response to climate change for the production of food, fiber and bioenergy in the future and how climate/energy policies might influence these limitations and opportunities. In addition, human and climate-induced changes in the exchange of carbon between land ecosystems and the atmosphere feedback to influence radiative forcing and future climate [1, 13]. Thus, it is also important to know how interactions among climate, ecosystem metabolism, vegetation shifts, and economic activity influence potential future land carbon sinks and how climate/energy policies might affect these interactions.

We focus on Northern Eurasia (figure S3 and table S3 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia) because its ecosystems play a significant role in the global carbon cycle and it has already experienced a number of environmental changes. Besides accounting for about 20% of the earth's land surface, the region contains large amounts of carbon in soils [14, 15] and vegetation [16–18] in a diverse set of ecosystems including peatlands, tundra, boreal forests and woodlands, temperate forests, grasslands, semi-deserts and deserts. Much of this carbon is vulnerable to release to the atmosphere by natural and human disturbances [19, 20]. Winter temperatures have already increased by more than 2 °C and summer temperatures in the Eurasian Arctic show an increase of 1.35 °C since 1881 [21]. Precipitation has also increased over the 20th century in western Russia, but decreased slightly over eastern Russia and China [22]. Satellite data have indicated a shortened period of snow on the ground [23]. However, there has also been an increase in maximum snow depth in some parts of the Eurasian Arctic over the last 40–50 years [24, 25]. Climate model simulations indicate that increases in air temperatures and precipitation will continue into the future [26, 27].

The increases in air temperatures will enhance evapotranspiration [28], which along with the earlier thaw dates and retreat of spring snow cover, may compensate for the increased precipitation in some areas of Northern Eurasia and cause drier conditions to occur during the summer and so increase the fire danger [29]. As a result, wildfires may have already increased in area burned, frequency and severity, but historical changes in the documentation of these fire characteristics make it difficult to define such trends [30]. In Russia, about 30% of the forest areas that have experienced single or repeated catastrophic fires have been converted to more barren lands in a process called 'green desertification' [31, 32]. These climate changes have already been associated with a number of other changes in ecosystem dynamics including a trend in earlier thaw dates of frozen soils, a lengthening of the growing season [33], increased shrub density in tundra [34–36], treeline migration [30, 37], and changes in vegetation productivity [38, 39] and the uptake of atmospheric carbon dioxide (CO_2) by the land surface [40]. All of these changes in ecosystem dynamics are predicted to continue into the future [30].

Besides climate, human activities have also had a large influence on land cover and carbon dynamics in Northern Eurasia [41, 42]. The abandonment of substantial areas of agricultural land as a result of the Chernobyl nuclear accident and the fall of the Soviet Union during the 1980s and 1990s [43–45] have led to carbon sequestration in these areas from regrowth of forests [18, 46–49]. However, illegal logging activities have also increased more recently [50] as these societies transition to a more market-based economy suggesting that land-use pressures may increase in this region in the future. In addition, human activities are also known to alter the fire regime in the region [32, 51].

To examine how climate-induced vegetation shifts may influence land management decisions and the associated consequences on terrestrial carbon dynamics in Northern Eurasia during the 21st century, we conduct simulation experiments with an integrated modeling framework based on two climate policy scenarios, a business-as-usual scenario (*No-Policy*) and a level 1 stabilization policy scenario (*Policy*). These experiments provide insights into the complex interactions of dynamic natural and human systems that are concurrently changing in response to climate change.

2. Methods

The simulation experiments use a modification of the modeling framework used in Reilly *et al* [11]. In the modified modeling framework (figure 1), an equilibrium biogeography model, has been combined with a computable general equilibrium model of the world economy, a biogeochemistry model, and a coupled atmospheric chemistry–climate model. Overall, the linked models capture interactions among ecosystem metabolism, shifts in vegetation structure, land use, atmospheric chemistry, climate, and the economy. Anthropogenic greenhouse gas emissions, as projected by the economic model, drive the coupled atmospheric chemistry–climate model to simulate the future climate that then drives the biogeography and biogeochemistry models. The biogeography model, the Siberian BioClimatic Model (SiBCliM), projects the distribution of natural vegetation based on the simulated climate conditions and the presence of permafrost and the level of fire danger [52, 53]. The biogeochemistry model, the Terrestrial Ecosystem model (TEM) [10], then estimates land carbon fluxes including net primary production (NPP) of vegetation based on the simulated climate, atmospheric chemistry, natural vegetation cover and any managed ecosystems (i.e. croplands, pastures, forest plantations) specified by the economic model, the Emissions Predictions and Policy Analysis (EPPA) model [54, 55].

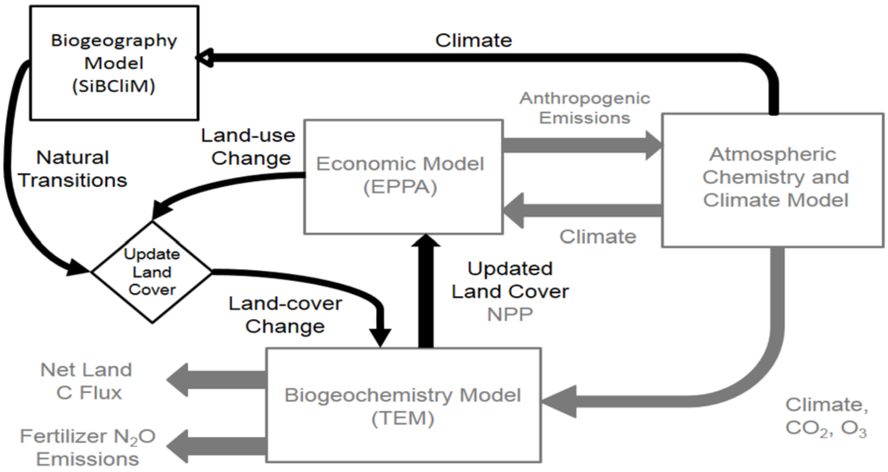

Figure 1. Structure of the EPPA/TEM/SiBCliM modeling framework. It consists of an economic model (EPPA), a biogeography model (SiBCliM), and a biogeochemistry model (TEM) that uses output from a coupled atmospheric chemistry and climate model. Climate-induced shifts in natural vegetation simulated by SiBCliM are combined with downscaled land-use change estimated by EPPA to prescribe land-cover inputs to TEM. Black arrows, shapes and text represent modifications to the modeling framework (gray) described in Reilly *et al* [11].

While EPPA supplies managed land-cover inputs to TEM, it also receives information from TEM. Changes in NPP of crops, pastures, and forests projected by TEM are fed back to the EPPA model to change yields and the areas of the agricultural sectors. Within EPPA, these changes are combined with changes in commodity demands and climate/energy policies to simulate changes in anthropogenic greenhouse gas emissions and further changes in land use.

Because the models within the framework operate at different spatial and temporal resolutions, output from one model must be downscaled, interpolated or aggregated before being used as input by another model. We use a statistical downscaling approach based on the present day distributions of temperature and precipitation [56] to obtain fine-scale (0.5° latitude × 0.5° longitude) climate from the zonally (4° latitudinal bands) averaged climate simulated by the coupled atmospheric chemistry model [57]. The SiBCliM estimates a single type of natural vegetation within each 0.5° latitude × 0.5° longitude grid cell across the region every twenty-five years. These changes in natural vegetation are interpolated to an annual resolution for input to TEM based on the type of land-cover transition (see Supplementary Materials available at stacks.iop.org/ERL/9/035004/mmedia). For successional changes, 4% of a grid cell is assumed to change each year of the 25-year period. For changes associated with wildfires, the entire area of a grid cell changes in a single year, but different grid cells burn in different years within the 25-year period.

The TEM uses a dynamic cohort approach [10, 40] to track the history of vegetation shifts and land use within a 0.5° latitude × 0.5° longitude grid cell. A single grid cell may contain hundreds of cohorts, which are created from both human and natural disturbances. Initially, undisturbed cohorts are distinguished by the various types of potential natural vegetation found within a grid cell. However, the vegetation cover of a particular cohort may change over time as a result of climate-induced vegetation shifts, wildfires, and agricultural conversion or abandonment. In addition, the area covered by a particular cohort may decrease over time as new cohorts are created from disturbances that affect only part of the area of the original cohort. Thus, each cohort represents the area of a particular land cover within a grid cell that experiences exactly the same land-use and disturbance history. A cohort may cover a minimum area of 1 km^2 up to the entire area of the grid cell depending upon the type of natural vegetation in the grid cell and its disturbance history.

The EPPA model estimates the economies for 16 regions across the globe using 5-year time steps. The regionally aggregated transitions among land-use types from EPPA are downscaled to the 0.5° latitude × 0.5° longitude grid level based on a statistical approach [58] and create additional cohorts for use in TEM during the next 5-year period. The resulting pattern of land use is affected by a number of factors including a prescribed population growth, economic growth simulated by EPPA, and the magnitude and regional pattern of NPP simulated by TEM. For input into EPPA, the NPP estimates by TEM are aggregated across the 0.5° latitude × 0.5° longitude grid cells that comprise each of the 16 regions to create 5-year mean annual NPP values for each of the EPPA land sectors [11]. Information is exchanged between EPPA and TEM every 5 years so that economic activities can adjust to short-term changes in environmental conditions. A more detailed description of the coupled atmospheric chemistry–climate model and the modified linkages among SiBCliM, EPPA, and TEM is provided in the supplementary materials (available at stacks.iop.org/ERL/9/035004/mmedia).

In this modified modeling framework, ecosystems can either gain or lose carbon based on changing environmental conditions and disturbance events (wildfires, land-use change). Environmental factors influencing land carbon dynamics include air temperature, precipitation, solar radiation, nitrogen fertilizer applications and atmospheric carbon dioxide and ozone concentrations [10]. Ecosystems gain carbon when the uptake of CO_2 by vegetation during photosynthesis to produce biomass is greater than the combined effects of the release of CO_2 from living organisms, decomposition of dead organic matter, and disturbance-related fire emissions. In an undisturbed ecosystem, the net gain of carbon is represented by net ecosystem production (NEP). Fires may result from either natural or human disturbances to rapidly release land carbon to the atmosphere. For vegetation shifts from a biome with large standing stocks of carbon to a biome with small standing stocks (e.g. boreal forest to grassland), the loss of carbon is attributed to wildfire (E_F). For timber harvests and the conversion of natural vegetation to agriculture, some of the vegetation carbon is lost to the atmosphere from burning part of the plant material on or off site during the year of the disturbance (E_C). The remaining vegetation carbon is transferred either to surface or subsurface soil organic matter pools or to wood products [59]. These wood products along with any agricultural products eventually are consumed or decomposed to return carbon back to the atmosphere (E_P). Thus, the net carbon exchange (NCE) between land ecosystems and the atmosphere is calculated as

$$\mathrm{NCE} = \mathrm{NEP} - E_F - E_C - E_P.$$

A positive value of NCE represents carbon sequestration by land ecosystems whereas a negative value means that land ecosystems are losing carbon. Positive NCE occurs during succession from non-tree to tree species in natural ecosystems or during regrowth of natural vegetation after disturbances, such as forest harvest or wildfire, or the abandonment of agricultural lands.

To evaluate how climate-induced vegetation shifts may influence land management decisions and the associated consequences for terrestrial carbon dynamics in Northern Eurasia during the 21st century, we conducted six simulations. We used the median results of an ensemble of climate projections by the MIT Earth System Model (MESM) for two climate policy scenarios, a *No-Policy* scenario and a level 1 stabilization *Policy* scenario [60, 61]. In the *No-Policy* scenario, the cumulative emissions of 8.0 trillion metric tons CO_2-eq cause mean atmospheric CO_2 concentrations to reach 870 ppmv and a 5.1 °C increase in mean annual surface temperatures from current conditions. These emissions are based on region specific projections of population and economic growth, increased agricultural productivity, and growing energy use in the developing world [11]. In the *Policy* scenario, a carbon tax is applied to all fossil fuel emissions, which favors the expansion of cropland used for biofuel production. Under the *Policy* scenario, cumulative emissions are limited to 2.3 trillion metric tons CO_2-eq which cause mean atmospheric CO_2 concentrations to reach 480 ppmv and a 1.6 °C increase in mean annual surface temperatures from current conditions. For each scenario, we conducted three simulations. In the first, no vegetation shifts occur with climate change, but land use is allowed to change. In the second, no land-use change occurs, but vegetation shifts are allowed to occur with climate change. And in the third, both land-use change and climate-induced vegetation shifts are allowed to occur.

3. Results

3.1. Contemporary conditions

At the beginning of the 21st century, managed lands are estimated to cover about 1132 million hectares or 39% of Northern Eurasia (table 1). This managed land includes pastures (51%), croplands (40%), and managed forests (9%). Croplands are concentrated in southwestern Russia, northeastern China, the Ukraine, Kazakhstan, Poland, Belarus, and Romania (figure S5 and table S3 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia). Pastures are primarily in Kazakhstan, Mongolia, southwestern Russia, northeastern China and Turkmenistan. Managed forests are concentrated in Finland, Sweden and northwestern Russia. Currently, no areas are estimated to be devoted to the production of cellulosic biofuels as this technology is assumed to still be under development. The unmanaged lands of Northern Eurasia are dominated by forests (44%), but grasslands (32%) and tundra (24%) also cover vast areas of the region.

We estimate that 0.5 Pg C yr^{-1} were sequestered in Northern Eurasian ecosystems at the beginning of the 21st century (2001–2005) with food crops, natural forests, grasslands, and tundra accounting for 69%, 16%, 10% and 5%, respectively of this carbon sink. The large carbon sink in croplands is a result of soil carbon accumulation associated with the application of nitrogen fertilizers, no-till practices, the type of land converted to agriculture (e.g., forests versus grasslands), and the time since conversion (see supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia).

3.2. Future land use without climate-induced vegetation shifts

Without climate-induced vegetation shifts, managed lands are estimated to cover a larger proportion of Northern Eurasia (1523 million hectares or 53% under the *No-Policy* scenario, 1572 million hectares or 55% under the *Policy* scenario) by the end of the 21st century (table 1). Under the *No-Policy* scenario, the areas devoted to food crops and pastures increase by 73% and 17%, respectively. Under the *Policy* scenario, the use of 309 million hectares for the production of cellulosic biofuels limit the expansion of food crops and pastures so that these areas increase by only 28% and 7%, respectively. In both scenarios, food crops replace pastures in Kazakhstan and Mongolia (figures 2(a), (b), (d), and (e), see also table S4 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia). In contrast, pastures replace food production in the western part of the region. The expansion of pastures, croplands and biofuel production areas occur at the expense of natural grasslands and managed forests (table 1, figure 2, see also tables S4 and S5 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia).

The dominant types of land-cover changes vary over time. With the exception of biofuel production, most of the change in land cover induced by land-use change occurs during the first half of the 21st century for both climate policy scenarios (figures S6(a) and (b) in Supplementary Materials available at stacks.iop.org/ERL/9/035004/mmedia). Biofuel production

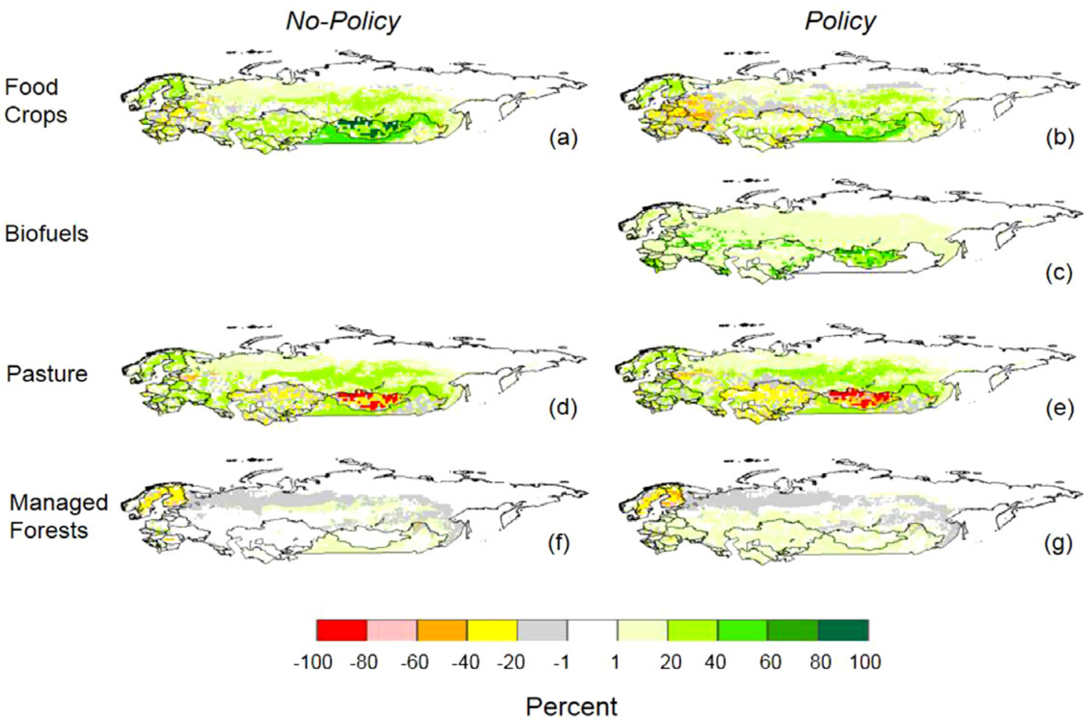

Figure 2. Changes in the distribution of managed ecosystems over the 21st century with and without a climate policy when no shifts of vegetation occur. Values represent the change in coverage from year 2000. No cellulosic biofuels are assumed to grow in the region under a scenario without a climate policy.

Table 1. Changes in land-cover distribution (million hectares) of Northern Eurasia over the 21st century for two climate policies with and without land-use change and vegetation shifts.

		No-Policy (2100)			Policy (2100)		
Land cover	Current (2000)	Land-use change only	Veg shifts only	Land-use change + veg shifts	Land-use change only	Veg shifts only	Land-use change + veg shifts
Food crops	453	784	453	834	579	453	566
Biofuel crops	0	0	0	0	309	0	386
Pasture	575	671	575	708	618	575	627
Managed forests	104	68	104	66	66	104	63
Natural forests	764	736	826	800	730	864	779
Tundra	417	401	37	37	399	203	202
Grasslands	555	208	873	423	167	669	245

under the *Policy* scenario does not occur in the region until 2063, but rapidly expands after 2080.

With no climate-induced vegetation shifts, we estimate that Northern Eurasia will sequester carbon under both climate scenarios over the 21st century (table 2). The largest carbon sink is in natural forests under the *No-Policy* scenario and in food croplands under the *Policy* scenario. Under both scenarios, the carbon sinks are located in the northern part of the region, Mongolia and Siberia (figures 3(a) and (b)) with larger carbon sinks in the tundra and boreal forest areas under the *No-Policy* scenario. The replacement of pastures with fertilized food and biofuel crops in Mongolia has enhanced carbon sequestration in this region. In contrast, pastures are the largest source of carbon in both scenarios (table 2). Carbon is lost from areas dominated by croplands and pastures in southwestern Russia, northeastern China, the Ukraine, Poland, Belarus, Romania, Hungary, Slovenia and Croatia with more carbon generally lost in the *No-Policy* scenario.

The temporal pattern of carbon sequestration over the 21st century varies between the two scenarios (figures 4(a) and (b)) and is dominated by the carbon dynamics of food croplands. Carbon sequestration in food crops decreases with increases in ozone pollution across the region and increases with decreasing ozone pollution (see Supplemental Materials available at stacks.iop.org/ERL/9/035004/mmedia). Carbon sequestration in forests and tundra is compensated by carbon losses from pastures in the *Policy* scenario throughout the 21st century and in the *No-Policy* scenario before the 2080s. At the end of the 21st century under the *No-Policy* scenario, however, the carbon gains in forests, tundra and food croplands increase

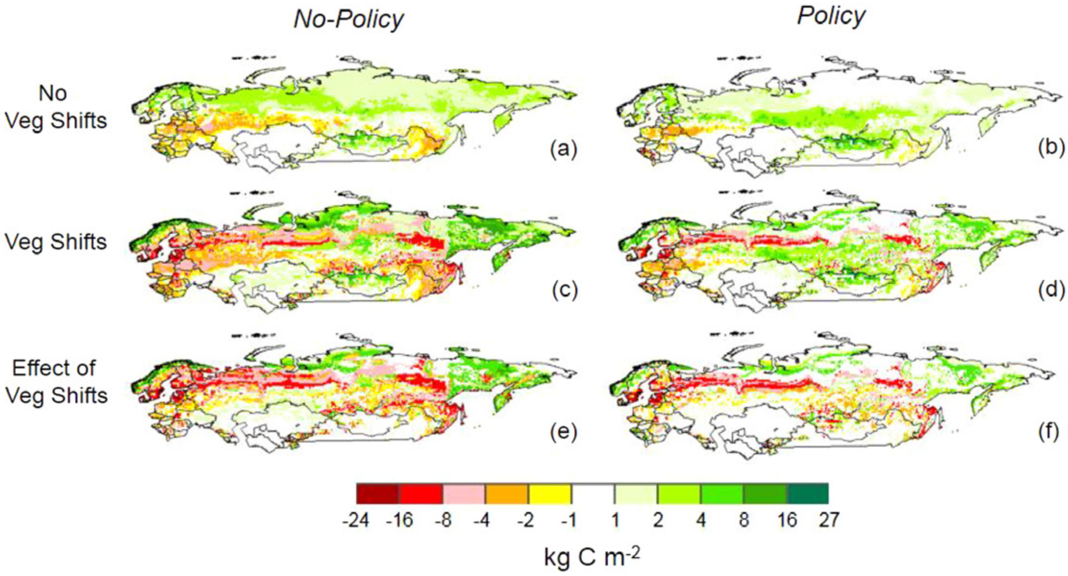

Figure 3. Influence of vegetation shifts on atmospheric carbon sinks (positive values) and sources (negative values) over the 21st century with and without a climate policy.

Table 2. Cumulative changes in carbon storage (Pg C) in land covers of Northern Eurasia over the 21st century for two climate policies with and without land-use change and vegetation shifts.

	No-Policy (2100)			Policy		
Land cover	Land-use change only	Veg shifts only	Land-use change + veg shifts	Land-use change only	Veg shifts only	Land-use change + veg shifts
Food crops	+8.9	−9.8	+8.9	+26.5	+4.6	+21.9
Biofuel crops	0.0	0.0	0.0	+3.6	0.0	+3.4
Pasture	−19.4	−3.8	−21.4	−22.9	−3.0	−20.8
Managed forests	+5.3	−0.8	+3.2	+4.7	+1.4	+3.8
Natural forests	+18.7	+26.4	+25.2	+12.8	+13.5	+12.4
Tundra	+7.1	+2.4	+2.3	+3.8	+2.1	+2.1
Grasslands	−1.2	−40.2	−34.8	+0.8	−19.0	−15.0
Total	+19.4	−25.8	−16.6	+29.3	−0.4	+7.8

carbon sequestration in the region because little additional carbon is lost from pastures.

3.3. Climate-induced vegetation shifts

In our simulations, climate change causes biomes to generally shift northwards (figure 5) with a loss of tundra (−91% under *No-Policy*, −51% under *Policy*) and a gain of natural forests (13% under *No-Policy*, 8% under *Policy*), and grasslands (57% under *No-Policy*, 21% under *Policy*, see table 1). Although boreal forests advance north and east into tundra, these forests, in turn, are invaded from the south by temperate forests and grasslands. Overall, the area of boreal forests decrease by 151 million hectares (−19%) under the *No-Policy* scenario and 15 million hectares (−2%) under the *Policy* scenario. In contrast, the area of temperate forests increases by 214 million hectares (258%) under the *No-Policy* scenario and 116 million hectares (140%) under the *Policy* scenario. As a result, forested land increases overall by 62 million hectares (7%) under the *No-Policy* scenario and by 100 million hectares (12%) under the *Policy* scenario. No changes occur in food croplands, pastures, or managed forests in these simulations because the distribution of land use is held constant throughout the 21st century.

Overall, these vegetation shifts cause Northern Eurasia to become a source of carbon to the atmosphere over the 21st century rather than a carbon sink (table 2). More carbon is sequestered in the larger area covered by natural forests than in the land-use change only simulations for both climate scenarios, but less carbon is sequestered in the smaller area covered by tundra. The expansion of grasslands in these simulations, however, causes more carbon to be lost from this biome than is added to natural forests and tundra. This loss is caused by the wildfires that are assumed to occur as forests are converted to grasslands.

3.4. Future land use with climate-induced vegetation shifts

Climate-induced vegetation shifts during the 21st century allow a modest additional expansion of managed ecosystems

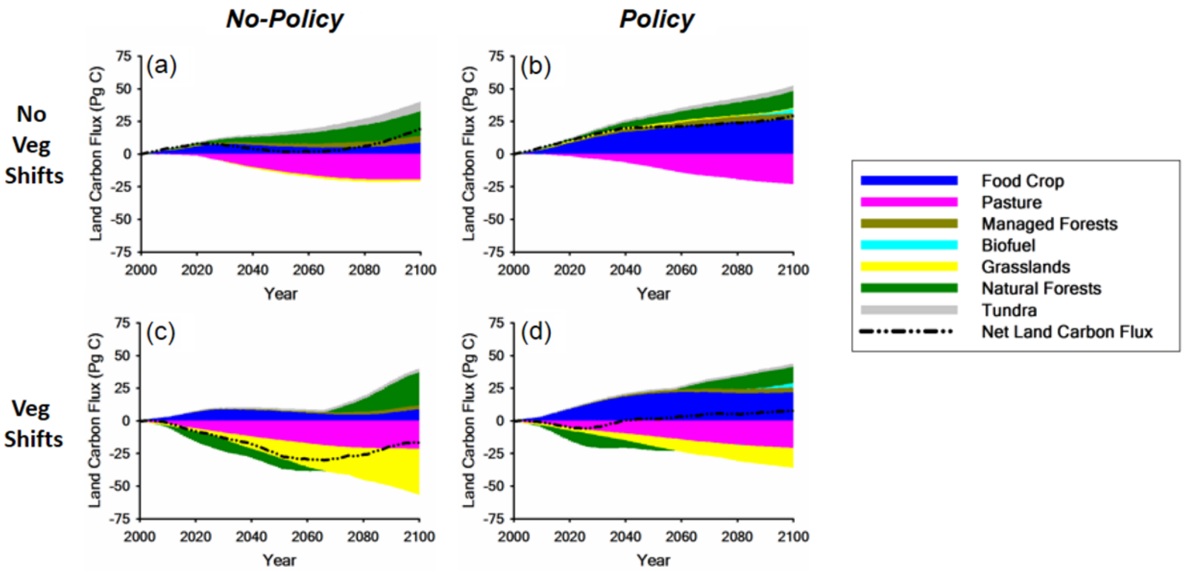

Figure 4. Net changes in carbon stored in managed and natural ecosystems of Northern Eurasia with and without vegetation shifts over the 21st century for the *No-Policy* and *Policy* scenarios.

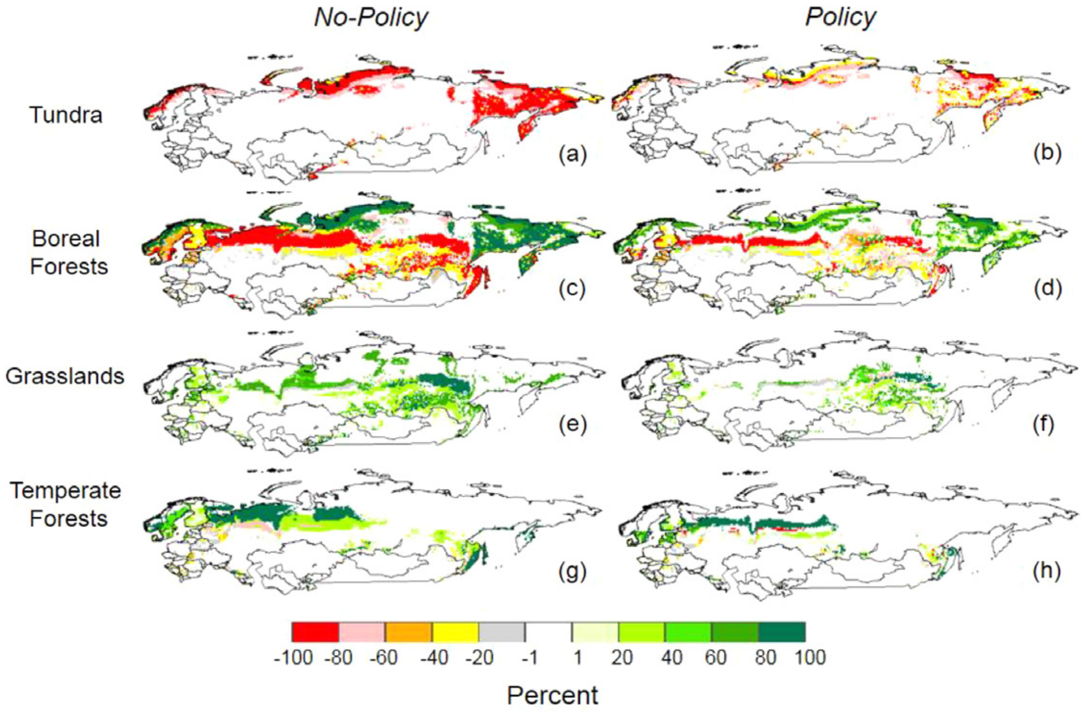

Figure 5. Shifts in tundra, boreal forests, grasslands, and temperate forests over the 21st century projected by SiBCliM with and without a climate policy. Values represent the changes in vegetation coverage from year 2000.

in Northern Eurasia over that estimated by the land-use only simulation (table 1). Managed lands cover 1608 million hectares (56% of Northern Eurasia, a 3% increase over the land-use only estimate) under the *No-Policy* scenario by the end of the 21st century. Under the *Policy* scenario, managed lands cover 1642 million hectares (57% of Northern Eurasia, a 2% increase over the land-use only estimate).

These climate-induced vegetation shifts allow for more intensive use of these managed lands. Overall, the area of food crops increases by 84% (an 11% increase over the land-use only estimate) and the area of pastures increases by 23% (a 6% increase over the land-use estimate) under the *No-Policy* scenario. Under the *Policy* scenario, the use of 386 million hectares for the production of cellulosic biofuels (a 25% increase over the land-use only estimate) again limits the expansion of food crops and pastures. Cropland areas increase by only 25% (a 3% decrease from the land-use only estimate) and pasture areas increase by 9% (a 2% increase over the

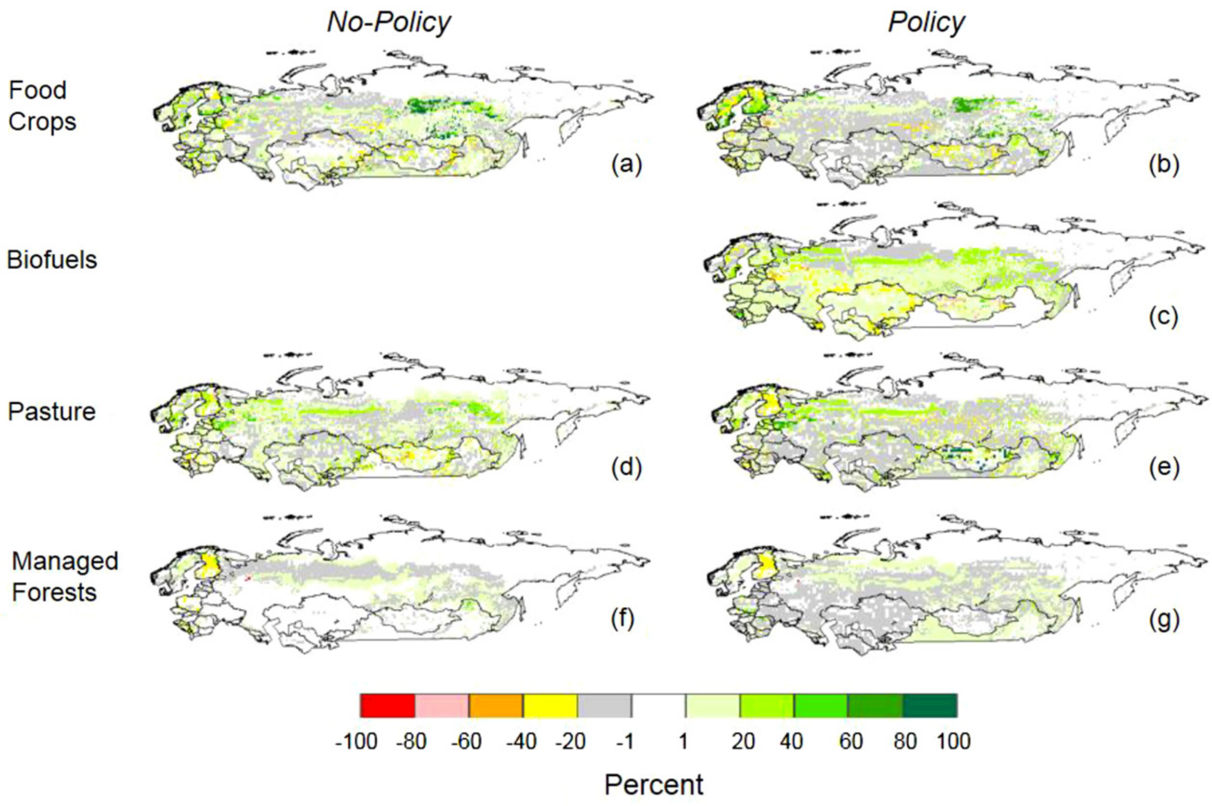

Figure 6. Effect of vegetation shifts on the distribution of food crops, biofuels, pasture, and managed forests at the end of the 21st century with and without a climate policy. No cellulosic biofuels are assumed to grow in the region under the *No-Policy* scenario.

land-use only estimate). The area of managed forest decreases by 37% (a 2% larger loss than the land-use only estimate) over the 21st century under the *No-Policy* scenario and 39% (a 2% larger loss than the land-use only estimate) under the *Policy* scenario.

The additional expansion of managed lands occurs primarily in Russia and is divided between croplands and pastures in the *No-Policy* scenario (figure 6, see also table S8 in supplementary material available at stacks.iop.org/ERL/9/035004/mmedia). In the *Policy* scenario, the expansion of managed lands is dominated by biofuel production. In contrast, the area of land devoted to agriculture in some of the southern parts of the region shrinks slightly.

With consideration of both climate-induced vegetation shifts and land-use change, the land ecosystems in Northern Eurasia are a carbon source (−16.6 Pg C) under the *No-Policy* scenario and a somewhat reduced carbon sink (+7.8 Pg C) under the *Policy* scenario when compared to the land-use only simulation (table 2). Twice as much carbon is lost from grasslands under the *No-Policy* scenario than under the *Policy* scenario. The large loss of carbon from grasslands and pastures overwhelm the concurrent carbon sequestration in forests, tundra and food croplands such that the region becomes a carbon source under the *No-Policy* scenario. In contrast, the smaller loss of carbon from grasslands under the *Policy* scenario combined with pasture carbon losses compensate for only a portion of the concurrent carbon sequestration in forests, tundra, and food and biofuel croplands such that the region remains a carbon sink.

Vegetation shifts also influence the temporal trajectory of carbon sequestration in Northern Eurasian ecosystems (figures 4(c) and (d)). Unlike the land-use only simulations (figures 4(a) and (b)), the loss of carbon from pastures, forests, and grasslands is estimated to dominate the region's net carbon balance until 2026 in the *Policy* scenario and until 2066 in the *No-Policy* scenario. Under the *Policy* scenario, Northern Eurasia begins to sequester carbon after 2026 because the carbon gains in food croplands and managed forests overcome the carbon losses in pastures, forests and grasslands. This regional carbon sequestration is then supplemented later by carbon gains in natural forests after 2057. Under the *No-Policy* scenario, Northern Eurasia begins to sequester carbon after 2066 because the carbon gains in natural and managed forests along with food croplands overcome the carbon losses in pastures and grasslands.

4. Discussion

In this study, we conduct the first in-depth analysis of how climate-induced vegetation shifts in Northern Eurasia interact with the global economy and climate/energy policies to influence land-use change and land carbon dynamics in the region. With climate-induced vegetation shifts, the large decrease in tundra (−364 million hectares under the *No-Policy* scenario, −196 million hectares under the *Policy* scenario) in our simulations indicate that a large area of currently unsuitable lands in Northern Eurasia may become more suitable for agriculture in the future. We estimate that the expansion of managed lands in Northern Eurasia over the 21st century is allowed to increase by an additional 16–22% from climate-induced vegetation shifts. The additional expansion of managed lands is not as great under the implementation of a climate policy because there is less change in environmental conditions. In addition, the implementation of a climate policy has a large influence on how the new managed lands created from vegetation shifts are used. With no climate policy, climate-induced vegetation shifts allow the additional expansion of areas devoted to food crop production by 15% and pastures by 39% over the 21st century. With a climate stabilization policy, however, climate-induced vegetation shifts allow the additional expansion of areas devoted to cellulosic biofuel production by 25% and pastures by 21%, but reduce the expansion of areas devoted to food crop production by 10%.

These differences are consistent with the need to use cellulosic biofuels to help moderate future climate change, but also indicate that the relationship between the countries within the region and their global trading partners may change to satisfy human needs of food, fiber and energy in the future. In both climate scenarios, vegetation shifts further reduce the areas devoted to timber production by 6–8%. In addition, the types of food crops grown in the region may also change and influence global trade as environmental conditions become more favorable for some crops, but less favorable for other crops [62].

The simulated increase in grasslands associated with climate-induced vegetation shifts (table 1, figures 5(e) and (f)) indicate that large parts of Northern Eurasia may become drier, more susceptible to wildfires, and perhaps less suitable for land use in the future under both climate scenarios, which is consistent with the results of previous studies [29, 30, 52]. Although the *No-Policy* scenario projects larger increases in annual precipitation than the *Policy* scenario (figure S4 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia), the projected larger increases in mean annual air temperature enhance evapotranspiration such that twice as much area burns each year under the resulting drier environmental conditions [29] of the *No-Policy* scenario than under the more moderate conditions of the *Policy* scenario at the end of the 21st century (figure S2 in the supplementary material available at stacks.iop.org/ERL/9/035004/mmedia).

Wildfires associated with the vegetation shifts simulated by SiBCliM and the land-use changes simulated by EPPA will change the age structure of the forests in Northern Eurasia by 2100 to create younger and more temperate forests (figure S7 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia). These changes in forest structure also modify the carbon dynamics within these forests. After a disturbance, forests will initially lose carbon for the first few years as the rate of decomposition overwhelms the rates of vegetation productivity, but then regrowth of these forests will begin to sequester carbon as the rates of vegetation productivity overcome decomposition and respiration rates [63]. Carbon sequestration in forests, however, declines as the forests get older. In a synthesis of forest NPP and NEP across the globe, Pregitzer and Euskirchen [63] have found that temperate forests generally have NEP rates that are almost six times those of boreal forests and that intermediate aged (30–120 years) forests in both boreal and temperate biomes have the highest rates of carbon sequestration. Overall, our simulated estimates of mean NEP for boreal forests (0.1 Mg C hectares^{-1} yr^{-1}) and temperate forests (1.6 Mg C hectares^{-1} yr^{-1}) in Northern Eurasia under contemporary conditions are comparable to the biome-level estimates by Pregitzer and Euskirchen [63] (0.3 ± 1.1 Mg C hectares^{-1} yr^{-1} for boreal forests; 1.7 ± 3.2 Mg C hectares^{-1} yr^{-1} for temperate forests). In addition, similar to Pregitzer and Euskirchen [63], we estimate that our highest NEP rates for temperate forests occur within the 11–30 year age class (table S10 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia). However, we estimate that the highest NEP rates in boreal forests may occur within an earlier age class (31–70 years old) than that study (71–120 years old).

With the implementation of a climate policy, enhanced carbon uptake by younger and more temperate forests exceeds the carbon losses from wildfire caused by vegetation shifts resulting in Northern Eurasia becoming a net carbon sink at the end of the 21st century (table 2). Larger carbon losses from wildfires without climate policy, however, cause the region to be a net carbon source. Because our simulations assumed that carbon loss from wildfires occurred only with vegetation shifts, we may have overestimated the carbon sinks and underestimated the carbon sources in the region as carbon losses from wildfires can occur without vegetation shifts in reality [19, 40, 41, 64].

Several previous studies [65–69] have included the effects of vegetation shifts in their analyses of climate change and land-use change on terrestrial carbon dynamics. However, with one exception, the effects of climate-induced vegetation shifts have been convoluted with the effects of changing economic demands on land-use distribution and the associated carbon dynamics in these studies. In the exception, Van Minnen *et al* [66] found that climate-induced vegetation shifts resulted in about a 1% increase in the area of managed lands globally using the IMAGE 2 model with a single climate change scenario. In that study, vegetation shifts generally enhanced carbon sequestration throughout the 21st century, particularly at the higher latitudes (60–90° N). While wildfires may have been considered in these previous studies [65–69], it has not been clear how wildfires influence their estimates of land carbon fluxes nor how vegetation shifts may be related to the carbon emissions by wildfires.

Because our simulations allowed vegetation shifts to occur only in Northern Eurasia, the increased area of managed ecosystems in Northern Eurasia with climate-induced vegetation shifts indicate that these shifts can help to alleviate the land-use pressures in other parts of the globe associated with satisfying the needs of a growing human population. Currently, tropical forests are being cleared to make way for the production of food and biofuels [70, 71]. Without vegetation shifts, the land-use pressures on these tropical forests are expected to continue to grow in the future [10, 11, 72, 73] because most of the remaining extra-tropical lands are currently unsuitable for agriculture (e.g. deserts, mountains, tundra). The expansion of managed lands in Northern Eurasia associated with climate-induced vegetation shifts, however, helps to alleviate the land-use pressures on tropical forests. Even within Northern Eurasia, the ability of agriculture to expand further north helps to alleviate land-use pressures in the southern parts of the region such as China, Mongolia and Kazakhstan. The land-use pressures in the tropics and Northern Eurasia may be alleviated even further if similar vegetation shifts also occur in North America. Thus, based on the results of the Van Minnen *et al* [66] study described above, climate-induced vegetation shifts may not necessarily result in a significant expansion of managed lands across the globe, but may instead provide more flexibility in where and how these lands are managed.

Climate-induced vegetation shifts may also help societies to moderate problems imposed by future air pollution. When land use is not allowed to change, both food croplands and managed forests lose carbon in the *No-Policy* scenario and become reduced carbon sinks in the *Policy* scenario when compared to the land-use only simulations (table 2). These results indicate that environmental conditions become less favorable for vegetation growth and carbon sequestration in these areas. The influence of ozone on carbon sequestration in food croplands over the 21st century without vegetation shifts (figure 4(a), supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia) indicate that ozone pollution is contributing to these worsening environmental conditions. By making more land suitable for agriculture, vegetation shifts allow food production to move to areas where crop productivity and carbon sequestration are much less limited by ozone pollution. The potential benefits from these climate-induced vegetation shifts, however, depend on the climate policy being implemented. Although the implementation of a level 1 stabilization climate policy results in less vegetation shifts, the policy has the side benefit of limiting the increases in future atmospheric ozone concentrations (figure S4(b) in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia). As a result, crop productivity and carbon sequestration in the *Policy* scenario are less damaged by ozone than in the *No-Policy* scenario and there is less need to seek out new lands for producing food.

A comparison of the carbon sink dynamics among food croplands, pastures, and managed forests between the land-use only and vegetation-shift only simulations (table 2) indicate that the expansion of food croplands are displacing some pastures and leading indirectly to carbon losses from Northern Eurasia. As described above, unfavorable environmental conditions cause food croplands and managed forests to either lose carbon or become reduced carbon sinks when land use is not allowed to change. In contrast, pastures become a reduced carbon source in the vegetation-shift only simulations. The carbon sinks estimated in food croplands and managed forests in the land-use only simulations, therefore, could only occur by converting grasslands or pastures in areas with more favorable environmental conditions. As the areas of pastures are larger in the land-use only simulations than the corresponding vegetation-shift only simulations for both climate scenarios (table 1), the loss of pastures to food croplands and managed forests (figure 2) is more than compensated by the conversion of other lands to pastures. The larger carbon sources from pastures in the land-use only simulations than the corresponding vegetation-shift only simulations, however, indicate that forested areas are being converted to pastures. Thus, although food croplands of Northern Eurasia are estimated to sequester carbon in our study, the expansion of food croplands has indirectly contributed to regional carbon losses by the displacement of pastures (see also [10, 12]).

Although our study has provided several new insights into how climate-induced vegetation shifts can interact with the global economy and climate/energy policies to influence land use and land carbon dynamics in Northern Eurasia, there are several issues that could be addressed in future work to improve our understanding of these interactions. As described by Balshi *et al* [6], studies that use process-based models to analyze fire effects (including more recent studies [74–76]) have focused primarily on retrospective analyses of carbon dynamics. This is because the large interannual variability in area burned and severity make it difficult to predict wildfire effects on future carbon storage. In their evaluation of the role of fire on the future exchanges of carbon dioxide and methane fluxes between northern high latitude ecosystems and the atmosphere, Zhuang *et al* [64] assume that the area burned increases at a fixed rate of 1% yr^{-1} over the 21st century such that twice as much area is burned during 2100 than 2000. In this study, the area burned is determined by the area associated with forests-to-grasslands and some forests-to-forests transitions over a 25-year period simulated by SiBCliM (see supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia). Although there is an attempt to account for some of the effects of the interannual variability in precipitation on area burned, the rate of area burned is fairly constant over each 25-year period, but varies among the four 25-year periods during the 21st century (figure S2 in supplementary materials available at stacks.iop.org/ERL/9/035004/mmedia). With a wildfire disturbance associated with a vegetation shift, we assume that 67% of the carbon in tree biomass and 50% of the carbon in grass biomass is lost to the atmosphere. Thus, there has been no attempt to account for variations in fire severity, which may alter the amount of carbon to be released by a wildfire to the atmosphere than indicated by our estimates. Future studies should explore how interannual variability in area burned and fire severity could be better represented in climate change assessments.

In addition to wildfire–forest regrowth dynamics, agriculture has a large influence on carbon dynamics in Northern Eurasia in our simulations. To improve understanding of the regional carbon dynamics associated with agriculture, some of our assumptions about farming practices in the region should be re-examined in future studies. In our analyses, our assumption of optimum fertilization of food and biofuel crops and no-till practices allows simulated croplands to sequester carbon in agricultural soils. The ability of nitrogen fertilizers to enhance carbon sequestration in agricultural soils is still being hotly debated [77–85]. As the amount and timing of fertilizer applications are rarely 'optimum' in reality [78], we may have overestimated these fertilizer effects on carbon sequestration in cropland soils. In addition, we do not account for the loss of carbon associated with the burning of crop residues. In this region, crop residues are burned to clear fields, fertilize the soil, and eliminate pests and weeds. Between 2001 and 2003, the Russian Federation accounted for 31–36% of all cropland burning across the globe [86]. The ability of no-till or conservation tillage to enhance carbon sequestration is also being debated [85, 87–89]. Thus, we may have overestimated carbon sequestration in cropland soils. Conversely, we also assume that all of our croplands are rain-fed so that we do not capture the potential effects of any irrigation on carbon dynamics in arid areas which may have increased the estimated carbon sink [84, 90].

Future changes in climate and atmospheric chemistry have been simulated in our study using a 2-dimensional coupled atmospheric chemistry and climate model. The limitation of such an approach is that it does not account for possible changes in longitudinal patterns of climate variables or atmospheric chemistry. A better approach would consider the effects of more regionalized changes in climate and atmospheric chemistry on vegetation shifts, land-use change and land carbon dynamics.

Finally, while our modeling framework attempts to account for the influence of some important environmental factors on carbon storage (i.e. CO_2 fertilization, climate change, ozone pollution, agriculture and timber harvest), the version of TEM used in the framework does not account for other environmental factors that may important effects. The addition of nitrogen from atmospheric nitrogen deposition may increase carbon sequestration in these nitrogen-limited ecosystems [40, 91]. Insect outbreaks may kill trees and enhance the susceptibility of forests to wildfire to decrease carbon sequestration [92]. Haze, which may be caused from wildfires and burning of crop residues, may limit the amount of sunlight available to vegetation to reduce carbon sequestration [93]. Urbanization may release carbon during the creation of urban and suburban areas and then later limit carbon sequestration by the presence of large areas of impervious surfaces [94–96]. Finally, permafrost thaw and thermokarst dynamics will influence the temporal trajectory of carbon sequestration or loss by influencing soil thermal dynamics and changes in water drainage [20, 97]. The effects of these other environmental factors on carbon sinks in Northern Eurasia should be considered in future studies.

5. Conclusions

Climate-induced vegetation shifts allow for the potential penetration of agricultural activities further north with the creation of an additional 72–87 million hectares of agricultural land in Northern Eurasia, which is 15–20% more land in agriculture than if no vegetation shifts were to occur. Less additional land from vegetation shifts is available for agriculture when a climate policy is implemented because there is less change in environmental conditions than without a climate policy. Climate policy also has a large influence on how this new agricultural land is used. The new agricultural land is devoted entirely to food production with no climate policy, but is instead devoted to the production of cellulosic biofuels with the implementation of a climate policy. These climate-induced vegetation shifts also result in a net increase of forests in Northern Eurasia; a decrease of 2–3 million hectares in managed forests and a concurrent increase in natural forests of 48–64 million hectares. Despite the net increase in forest area, the increase in wildfires associated with vegetation shifts releases large amounts of carbon to the atmosphere. As a result, the region is projected to become a source of atmospheric carbon when no carbon policy is implemented and a small carbon sink when a climate policy is implemented. Our analyses have provided insights into the complex interactions of dynamic natural and human systems that are concurrently changing in response to climate change. These insights have provided clues to how humans may be able to adapt to a changing world and identified the trade-offs, including unintended consequences, associated with proposed climate/energy policies.

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