The changing effects of Alaska's boreal forests on the climate system[1]

E.S. Euskirchen, A.D. McGuire, F.S. Chapin III, and T.S. Rupp

Abstract: In the boreal forests of Alaska, recent changes in climate have influenced the exchange of trace gases, water, and energy between these forests and the atmosphere. These changes in the structure and function of boreal forests can then feed back to impact regional and global climates. In this manuscript, we examine the type and magnitude of the climate feedbacks from boreal forests in Alaska. Research generally suggests that the net effect of a warming climate is a positive regional feedback to warming. Currently, the primary positive climate feedbacks are likely related to decreases in surface albedo due to decreases in snow cover. Fewer negative feedbacks have been identified, and they may not be large enough to counterbalance the large positive feedbacks. These positive feedbacks are most pronounced at the regional scale and reduce the resilience of the boreal vegetation – climate system by amplifying the rate of regional warming. Given the recent warming in this region, the large variety of associated mechanisms that can alter terrestrial ecosystems and influence the climate system, and a reduction in the boreal forest resilience, there is a strong need to continue to quantify and evaluate the feedback pathways.

Résumé : Dans la forêts boréale de l'Alaska, les récents changements climatiques ont influencé les échanges de gaz à l'état de trace, d'eau et d'énergie entre ces forêts et l'atmosphère. Ces changements dans la structure et la fonction des forêts boréales peuvent en retour avoir un impact sur le climat régional et mondial. Dans cet article, nous examinons le type et l'ampleur des rétroactions climatiques des forêts boréales de l'Alaska. De façon générale, les travaux de recherche indiquent que l'effet net d'un réchauffement climatique est une rétroaction régionale positive au réchauffement. Actuellement, les principales rétroactions climatiques positives sont probablement reliées à la diminution de l'albédo en surface due à la réduction du couvert nival. Moins de rétroactions négatives ont été identifiées et elles ne sont peut-être pas assez importantes pour contrebalancer les importantes rétroactions positives. Ces rétroactions positives sont les plus fortes à l'échelle régionale et réduisent la résilience du système végétation – climat boréal en amplifiant le taux de réchauffement régional. Étant donné le récent réchauffement dans cette région, la grande variété de mécanismes associées qui peuvent modifier les écosystèmes terrestres et influencer le système climatique, et une réduction de la résilience de la forêt boréale, il est impératif de continuer à quantifier et à évaluer les modes de rétroaction.

[Traduit par la Rédaction]

Introduction

Recent warming in northern high latitudes by 2–3 °C over the last 50 years has been about five times greater than the global mean (Arctic Climate Impact Assessment 2004). The boreal forest is the northernmost forested biome, so it is expected to be sensitive to this warming. Climatically sensitive processes include permafrost dynamics, snowfall, fire regimes, plant productivity, forest succession, and the outbreak patterns of forest insects. While ecosystems are usually resilient to stochastic variation or directional change in driving variables, such as changes in temperature and precipitation patterns, they may shift to a new state when some threshold is exceeded. Resilience theory postulates that important negative feedbacks tend to maintain the system within certain bounds (e.g., repeating successional cycles) until it exceeds critical thresholds, at which point positive feedbacks push the system into a new state (Gunderson 2000). Novel boreal landscape patterns may emerge when climate change leads to disturbance regimes that alter permafrost integrity, plant productivity, successional patterns, and abundances of key functional types. Furthermore, changes in local and regional resilience may have consequences to society through changes in the ecosystem services provided by boreal forests, including both local (e.g., subsistence resources) and global (e.g., climate regulation through carbon sequestration) resources (see also Chapin et al. 2010).

Because the biosphere and the atmosphere are a coupled system, changes in the structure and function of terrestrial

Received 26 August 2009. Accepted 21 December 2009. Published on the NRC Research Press Web site at cjfr.nrc.ca on 17 June 2010.

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[1]This article is one of a selection of papers from The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming.
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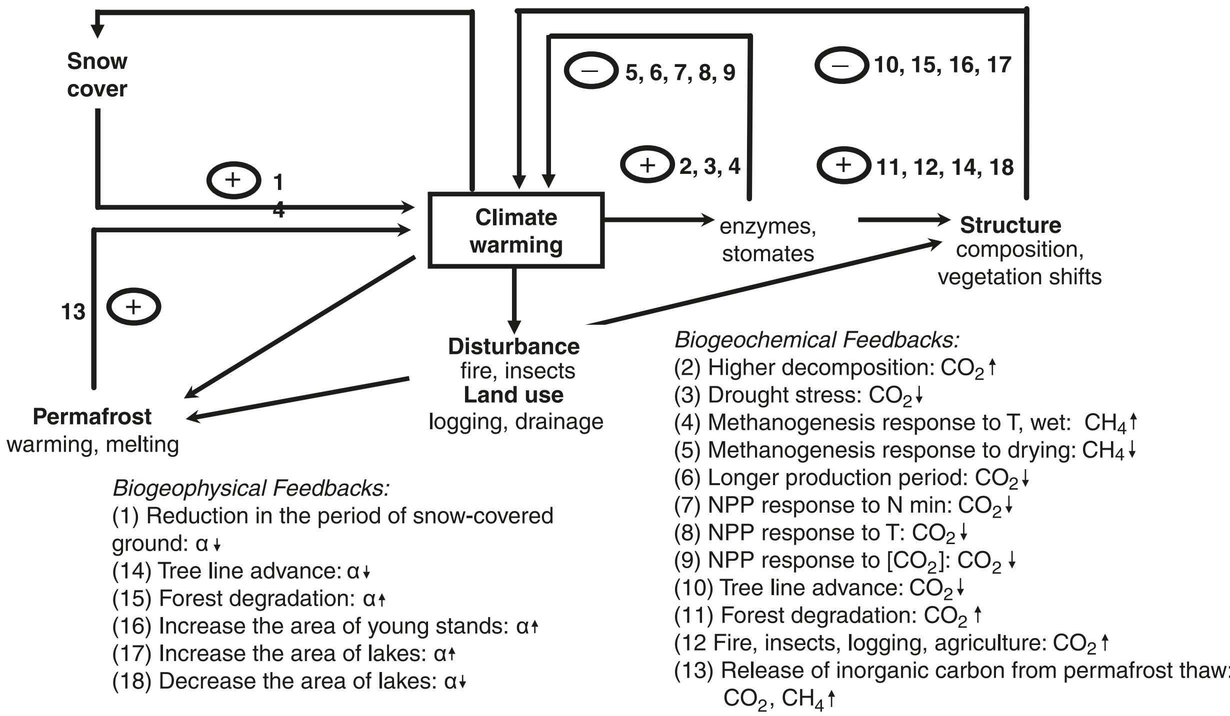
Fig. 1. Conceptualization of the climate feedbacks in Alaska's boreal forests. α, albedo; +, positive feedback to climate; –, negative feedback to climate. T, temperature; NPP, net primary productivity; N, nitrogen. Modified after McGuire et al. 2006.



ecosystems, as expected under a changing climate, may in turn feed back to the climate, both positively and negatively. Since the boreal region is one of the largest biomes on Earth, it plays a major role in the global climate system. Boreal forests cover much of southcentral and interior Alaska, and while detailed descriptive information concerning the boreal forests of Alaska is contained in the papers of this special issue and elsewhere (Van Cleve et al. 1983; Chapin et al. 2006), we give a brief overview here. The landscape consists of evergreen and deciduous needle-leaved forests, deciduous broad-leaved forests, bogs, fens, and lakes, with the primary tree species of these forests, including black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.), white spruce (*Picea glauca* (Moench) Voss), quaking aspen (*Populus tremuloides* Michx.), Alaska paper birch (*Betula neoalaskana* Sarg.), larch (*Larix laricina* (Du Roi) K. Koch), and balsam poplar (*Populus balsamifera* L.). The presence or absence of permafrost is probably the most important threshold regulating forest structure and function, with permafrost occurring primarily on north-facing hill slopes and valley bottoms. The sensitivity of permafrost to changes in climate is well documented. Permafrost temperatures have warmed since the 1970s in response to regional warming and are now very close to thawing (generally greater than –2 °C), warming by 0.7 °C per decade (Osterkamp et al. 2009; Jorgenson et al. 2010). Fire is the primary disturbance agent and the second major regulator of threshold change. Recent studies suggest that the fire duration, size, and severity have changed in recent decades (Kasischke et al. 2010), resulting in a landscape with a greater proportion of young stands. Disturbance associated with insect outbreaks can also act as a regulator of threshold change and may become an increased risk in the future.

In addition to changes in permafrost, the snow season has decreased by approximately 2.5 days·decade^{-1}, and the growing season has generally increased by about the same amount (Euskirchen et al. 2006, 2007). These changes in the snow season and growing season lengths may change the vegetation distribution, including treeline advancement in some areas and retreat in other areas, resulting in new landscape patterns. Cumulatively, these changes in permafrost integrity, disturbance, and landscape pattern may then feed back to influence the climate. These feedbacks can be grouped into changes in biogeophysical (changes in energy and water exchange, aerosols) and biogeochemical (carbon dioxide (CO_2) and methane (CH_4) exchange) mechanisms. The magnitude and direction of these feedbacks remain uncertain.

In light of this uncertainty and the vulnerabilities of the climate system to responses in northern high-latitude regions (McGuire et al. 2006), it is important that we improve our understanding of how integrated regional changes in the boreal forest will likely influence the global climate system. Here, we first provide a brief overview of the biogeophysical and biogeochemical feedbacks to climate, including the surface energy balance and CO_2 and CH_4 dynamics of this boreal region (Fig. 1). We then examine the various issues of change presented in this special issue in regard to climate feedbacks, including changes in permafrost integrity (Jorgensen et al. 2010), insect outbreaks, fire regimes (Johnstone et al. 2010), and vegetation (Yarie et al. 2010; McGuire et al. 2010). Finally, we examine climate feedbacks in relation to changes in snow cover and land use in boreal Alaska. Changes in the number of positive versus negative feedbacks to climate may influence the resilience of the boreal forest (Chapin et al. 2010).

Table 1. Albedo and energy flux ratios based on data from boreal ecosystems in Alaska, with sensible and latent heat determined by eddy covariance methodology.

				Energy flux ratio*			
Ecosystem type	Geographical coordinates	Season	Albedo	R_N/K_{down}	G/R_N	H/R_N	LE/R_N
Liu and Randerson 2008							
3–5 years postfire (grasses)	63°N, 145°W	Spring	0.44	0.42	0.08	0.29	0.29
		Summer	0.13	0.61	0.04	0.35	0.33
		Autumn	0.24	0.25	–0.27	–0.55	0.82
		Winter	—	–1	0.29	1.21	–0.14
15–17 years postfire (aspen and willow)	63°N, 145°W	Spring	—	0.41	0.06	0.49	0.29
		Summer	—	0.59	0.07	0.33	0.50
		Autumn	—	0.20	–0.22	–0.11	1
		Winter	—	–1.36	0.21	–0.95	–0.10
80–85 years postfire (black spruce forest)	63°N, 145°W	Spring	0.16	0.61	0.01	0.53	0.24
		Summer	0.08	0.72	0.05	0.40	0.37
		Autumn	0.14	0.41	–0.06	–0.28	0.72
		Winter	—	–0.71	–0.60	1.1	–0.3
Beringer et al. 2005							
100 years postharvest (white spruce forest)	64°N, 163°W	Summer	0.10	0.73	0.05	0.44	0.37
Chambers and Chapin 2003							
0 years postfire	63°N, 145°W	Summer	—	0.67	0.12	0.59	0.23
3–4 years postfire (grasses)	63°N, 145°W	Summer	—	0.66	0.09	0.41	0.32
7 years postfire (grasses and small shrubs)	63°N, 142°W	Summer	—	0.63	—	0.42	0.35
12 years postfire (aspen and willow)	63°N, 145°W	Summer	—	0.71	0.09	0.45	0.34
14 years postfire (black spruce and small shrubs)	63°N, 148°W	Summer	—	0.59	—	0.40	0.37
80–85 years postfire (black spruce forest)	65°N, 147°W	Summer	—	0.75	0.08	0.52	0.35

Note: Further site descriptions can be found in the reference given for each set of measurements.
*K_{down}, incoming short-wave radiation; R_N, net radiation; G, soil heat flux; H, sensible heat flux; LE, latent heat flux.

Background — biogeophysical and biogeochemical feedbacks

Surface energy balance across boreal ecosystems and over the full annual cycle

To understand the feedbacks to climate from boreal ecosystems, it is essential to understand both the seasonal changes in energy exchange within an ecosystem and the differences in energy exchange across ecosystems. In boreal Alaska, time since fire is the defining feature of differences in surface albedo and energy balance across ecosystems (Table 1), since fire often causes stand-replacing mortality and thus opening closed canopies.

The first year after fire is marked by a low value of summer albedo similar to that found in mature coniferous forests due to black carbon on the surface caused by the fire (Amiro et al. 2006; Randerson et al. 2006). Subsequently, an herbaceous ground cover develops, increasing summer albedo. During the period of snow covered ground in the first years after fire, the open surface has a high value of albedo (Table 1; Amiro et al. 2006; Liu and Randerson 2008). Soil heat flux and active layer depth (the layer of soil above permafrost that annually freezes and thaws) increase after fire (Yoshikawa et al. 2003; Liu and Randerson 2008). Latent and sensible heat fluxes remain lower in the recently burned areas than in those dominated by mature forest because of decreases in net radiation and ground heat flux, which are caused by a decrease in surface roughness and turbulent exchange due to the loss of canopy structure (Chambers and Chapin 2003; Liu and Randerson 2008).

As the forest continues to recover in the years after fire, the ecosystem usually follows a process known as ‘‘relay succession’’ whereby the forest goes through one or more successional stages before returning to the same ecosystem type (e.g., coniferous forest) as was there before the fire (Johnstone et al. 2010). A mixture of deciduous shrubs (e.g., willow) and trees (e.g., aspen, birch) establishes, with a summer albedo in these deciduous ecosystems that is greater than in the coniferous ecosystems that dominate the final successional stage of postfire recovery (Amiro et al. 2006; Liu and Randerson 2008). The albedo during the snow season in these deciduous stands is generally lower than that during the years immediately after a fire, but is greater than that in the coniferous ecosystems. Throughout this early- to mid-successional period, canopy conductance and evapotranspiration rates are higher than in both the recently burned stands and the coniferous sites (Liu and Randerson 2008). Therefore, a greater percentage of net radiation is transferred as latent heat, with a parallel decrease in sensible heat in these deciduous ecosystems (Table 1). In the fire disturbance section below, we examine how a loss of resilience in fire-disturbed ecosystems may alter successional trajectories and climate feedbacks.

Measurements of summer albedo over the course of forest succession after fire show differences depending on whether they are remotely sensed or ground-based (Amiro et al. 2006; Lyons et al. 2008). The remotely sensed and ground-based measurements both show a general increase in albedo postfire and a decline in the later successional forests. However, the timing of this decline differs. In a synthesis of ground-based measurements of boreal albedo, the albedo increases until approximately year 10 and then declines thereafter (Amiro et al. 2006), while in the remotely sensed collected data, the albedo peaks at 25–30 years postfire and declines thereafter (Lyons et al. 2008). Furthermore, the values of albedo differ between the two data sets, ranging between ~0.05 and ~0.12 in functions based on the synthesized ground-based data set (Amiro et al. 2006) versus between ~0.11 and ~0.14 in the function based on the remotely sensed data (Lyons et al. 2008). These differences may be attributed to a combination of scaling and remote sensing issues associated with satellite retrievals (Lyons et al. 2008) and indicate that modeling studies that use albedo data should carefully consider how to best account for these variations in albedo across data sets.

Ground heat exchange and permafrost

Permafrost is a strong heat sink that reduces surface temperature and, consequently, heat flux to the atmosphere. Ground heat flux in the boreal forest is 5%–10% of net radiation (Table 1), whereas it is negligible on a daily or longer time scale in most ecosystems (Oke 1987). Predicting the response of permafrost thaw to climate warming in boreal Alaska is complicated by the wide variety of factors that influence soil temperature, including air temperature, snow depth, topographic effects on insolation, soil texture, organic layer depth, surface water and runoff, groundwater movement, and soil moisture. In ice-rich flat areas, permafrost thaw leads to an increase in surface water, with lower albedo that increases heat absorption, and in turn increases permafrost thaw and surface water. However, vegetation succession leads to lower mineral soil surface temperature and a decline in thermal conductance of the organic horizon, making the permafrost more resilient to climate warming (Jorgensen et al. 2010). The depth of the organic layer that remains after fire can have a strong impact on the response of permafrost to fire. Studies suggest that if an organic layer of more than 7–12 cm remains after fire, the thermal impact to permafrost will be minimal in interior Alaska boreal forest (Yoshikawa et al. 2003). We discuss changes in permafrost as they relate to changes in biogeochemistry and vegetation dynamics in more detail below. Jorgensen et al. (2010) analyzes in detail the issue of permafrost resilience and vulnerability in Alaska's boreal forests in a changing climate.

Biogeochemical feedbacks

Both CO_2 and CH_4 are increasing in the atmosphere, causing an increased heating of the Earth. Increases in CO_2 and CH_4 are estimated to have caused ~1.66 and ~0.48 $W \cdot m^{-2}$ increases in radiative forcing globally since 1750, respectively (Forster et al. 2007). Methane is a relatively potent greenhouse gas with a high global warming potential and is 21 times more effective per molecule than CO_2 at absorbing long-wave radiation on a 100-year time scale. Since terrestrial ecosystems fix CO_2 through photosynthesis and release it through respiration, any change that impacts these processes will feed back to climate. Model estimates indicate that the boreal forest soils of Alaska are responsible for 45% of the total CH_4 consumption in Alaska, where current net emissions (emissions minus consumption) of CH_4 are estimated as ~3 Tg $CH_4 \cdot year^{-1}$ (Zhuang et al. 2007). However, in the future, under a changing climate, emissions of CH_4 from wet soils in the Alaskan tundra are likely to be enhanced more than the CH_4 consumption of dry soils and will play a large role in Alaska by acting as a net source of greenhouse gas (considering both CO_2 and CH_4) flux to the atmosphere. In the sections following, we discuss several changes in the boreal forest of Alaska that may influence the exchange of CO_2 and CH_4 with the atmosphere, including the climate sensitivity of boreal forest growth, changes in permafrost depth and distribution, changes in disturbance regimes including fire regimes and insect outbreaks, CH_4 emissions from wetlands and lakes, and land use.

Vegetation dynamics: climate feedbacks due to the climate sensitivity of boreal forest growth

The growing season length across the circum-arctic/boreal region in general, and in boreal forests in particular, has been shown to be increasing by approximately 2.5 $days \cdot decade^{-1}$, with most of this increase occurring in the spring (Euskirchen et al. 2006). The interplay between changes in climate and vegetation growth has been shown to generate a range of responses in Alaskan boreal forests under an increased growing season. The climate controls over vegetation in Alaskan boreal forests are temperature and moisture. Nitrogen can be a primary growth-limiting nutrient in boreal forests. Recent research in Alaskan boreal forests suggests that nutrient limitations may only occur during the early spring period, after which moisture availability may become the dominant limitation at warm mid-successional sites (Yarie et al. 2010). However, this research also found that in warm old-growth sites, tree growth is less sensitive to climate variables and more sensitive to the amount of available nitrogen. At cooler floodplain locations, forest growth was most sensitive to changes in soil moisture, indicating that summer rainfall plays a dominant role in tree growth (Yarie et al. 2010). Other research (McGuire et al. 2010) finds negative correlations between white spruce growth and summer warming due to increased drought stress under high temperatures in white spruce occupying the warmest and driest environments of boreal Alaska. Yet, populations of white spruce growing in areas where the summers are cooler with more abundant precipitation show a positive growth response to climate warming. Consequently, the changes in forest growth may result in both positive and negative feedbacks to climate, with positive climate feedbacks occurring in drought-stressed trees that absorb less CO_2 and negative climate feedbacks occurring in regions where the tree growth responds positively to changes in temperature. It is also important to note that increases in tree productivity under a warming climate may be counterbalanced by increases in respiration, which would again act as a positive climate feedback (Ueyama et al. 2009). Furthermore, climate-induced permafrost thaw may influence the hydrological cycle (Jones and Rinehart 2010) and soil moisture regimes in the region, affecting both tree growth and respiration.

Some studies have indicated that warmer conditions and longer growing seasons favor treeline advance, either in latitude or elevation, in Alaska and the western Arctic (Lloyd et al. 2003; Danby and Hik 2007). This replacement of tundra with boreal forest may result in greater carbon uptake by the boreal trees, thus acting as a negative feedback to climate. However, any event that causes an advance of treeline will likely reduce albedo, causing an increase in sensible heat and a positive feedback to warming; model-based studies show that the location of treeline has a substantial effect on global climate because of changes in albedo and energy fluxes. Research has also shown that the net uptake or release of carbon associated with changes in treeline is likely a much smaller feedback to climate than is the feedback resulting from changes in surface energy balance (Betts 2000). Nevertheless, latitudinal treeline advance in Alaska may proceed quite slowly because of limitations related to seed dispersal and establishment and barriers such as the Brooks Range (Rupp et al. 2001).

Other research suggests that climate warming may lead to a decline of forest extent. The negative effects of warming on white spruce described above may interact with slow recruitment and reduced seed sources to decrease the success rate of spruce regeneration after disturbance (McGuire et al. 2010). Eventually, this may result in an increased proportion of forests that regenerate to open forests or shrubland after disturbance. In addition to forest decline due to drought stress, permafrost degradation may also cause a decline of forest extent, as forests may be replaced by bogs. These open forests, shrublands, or bogs would store less vegetation carbon but more soil carbon than a forest with the net carbon feedback depending on the relative magnitude of these effects. However, the land surface of these less vegetated ecosystems would have a generally high albedo and would act as a negative feedback.

Disturbance regimes: fires regimes and insect outbreaks

Fire regime changes in boreal Alaska

As described above, changes in the fire regime lead to changes in vegetation structure and function and, subsequently, to changes in albedo and energy fluxes. Climate feedbacks resulting from changes in the fire regime depend on a number of factors, including changes in fire severity, fire size, and fire duration and timing. Johnstone et al. (2010) argue that in boreal Alaska strong connections between soil conditions and plant traits result in plant communities that are resilient to fire disturbance, with postfire communities reassembling on successional trajectories similar to those of the prefire community (e.g., “relay succession”, as described above). During stable conditions and fire regimes, these cycles will likely remain stable on the landscape. However, this resilience may be weakened when changes in the fire regime interact with directional changes in environmental variables, potentially switching the system to a new state. For example, regeneration of black spruce forests may be disrupted under a severe fire that consumes the thick organic layers and creates high-quality seedbeds dominated by mineral soils. Consequently, the resulting forest may be primarily deciduous (Johnstone et al. 2010). This deciduous forest would have a greater albedo than the coniferous forests, so an increase in fire severity would act as a negative feedback from the perspective of albedo and surface energy balance (Goetz et al. 2007). From the perspective of vegetation carbon storage, deciduous forests after high severity fires have a greater net uptake of carbon in the vegetation over the first 50 years of succession because of the large deciduous component compared with coniferous forests. However, as succession continues, the productivity of the vegetation in these forests may decline and remain lower in these forests because of the low density of black spruce. Soil carbon storage may also be lower over the course of succession after high severity fires. Harden et al. (2006) found much larger stores of soil carbon in mesic sites than dry sites, and dry sites tend to burn more severely. Therefore, an increase in the frequency of mixed spruce – deciduous stands under an increase in fire severity may lead to a reduction in carbon storage in both the vegetation and the soils.

The increase in deciduous stands across the landscape because of changes in fire frequency and area leads to an overall increase in albedo and a decrease in sensible heating relative to coniferous stands (Table 1). This negative feedback to atmospheric heating (–4.2 $W \cdot m^{-2}$ radiative forcing for the global atmosphere; Randerson et al. 2006) has been shown to be larger than the positive feedback from fire-emitted greenhouse gases over the course of an 80-year fire cycle in boreal Alaska (+1.6 $W \cdot m^{-2}$ radiative forcing averaged globally; Randerson et al. 2006). Another study shows that taking into account changes in successional dynamics associated with a change in the future fire regime (2003–2100) results in a decrease in atmospheric heating of –0.9 $W \cdot m^{-2} \cdot decade^{-1}$ due to an increase in early successional stands with a greater albedo in the boreal forests of Alaska and western Canada (Table 2; Euskirchen et al. 2009). These results again underline a generally greater significance of changes in albedo on climate feedbacks than those associated with changes in trace gases and biogeochemistry.

The smoke and haze aerosols from boreal forest fires in Alaska may feedback to the climate in other regions. While the impacts of aerosols on climate are not well understood (Forster et al. 2007), it is generally accepted that smoke cools the surface, acting as a negative feedback to climate. During the summer of 2004 when fires burned for weeks in Alaska and northwestern Canada, large quantities of smoke from these forests were dispersed throughout the Northern Hemisphere. Recent studies have found that this smoke did have a cooling effect in regions outside of boreal Alaska, although this effect was partially dampened by the absorp-

Table 2. Summary of changes in atmospheric heating due to changes in land surface albedo and CO_2 and CH_4 uptake and (or) emissions in boreal Alaska, from available estimates.

	Change in energy ($W \cdot m^{-2} \cdot decade^{-1}$) due to changes in:					
	Albedo associated with:		Atmospheric exchange of C associated with:			
Years	Snow cover	Fire regime	Climate and CO_2*	Fire regime	Methane	Total
1970–2000	+1.90[†]	—	–0.10[‡]	+0.74[‡]	+0.28[§]	+1.34 + ?
2003–2100	+4.30[‖]	–0.90[‖]	–2.02[¶]	+0.50[¶]	+0.56[§]	+2.44

Note: A negative sign represents a negative feedback for a sink term and a positive sign represents a positive feedback for a source term. Values are converted between Pg C to $W \cdot m^{-2}$ based on the methodology in Zhuang et al. 2006. —, data not available.

*Climate and CO_2 refers to model simulations incorporating transient data pertaining to climate and atmospheric concentrations of CO_2.

[†]Euskirchen et al. 2007.

[‡]Balshi et al. 2007.

[§]Zhuang et al. 2007.

[‖]Euskirchen et al. 2009.

[¶]Balshi et al. 2009.

tion of solar radiation by black carbon fire aerosol and by the greenhouse gas emissions from the fires (Pfister et al. 2008; Stone et al. 2008).

Insect outbreaks

Another disturbance agent that may impact carbon uptake by boreal ecosystems in Alaska is insect outbreaks, which can be triggered by high temperatures. Reduced carbon uptake by boreal forests due to tree mortality or reduced growth associated with insect outbreaks can transform regions that have acted as carbon sinks to carbon sources (Kurz et al. 2008), acting as a positive climate feedback. In the boreal forest of Alaska, recent outbreaks of bark beetles in the Kenai Peninsula resulted in an increase in salvage timber harvest in this region, likely reducing carbon storage in these systems (Jones 2008). However, it is also likely that these areas that have experienced insect outbreaks have an increased albedo and decreased sensitive heating due to grass and deciduous regrowth, which would in turn reduce atmospheric heating. Furthermore, since tree mortality influences leaf stomatal conductance, it is possible that insect damage will change the partitioning of available energy into sensible and latent heat — increasing sensible heat and decreasing latent heat. The strength of the particular feedbacks in terms of changes in energy balance and insect outbreaks has not been quantified in boreal Alaska or elsewhere.

Carbon and methane release from permafrost degradation

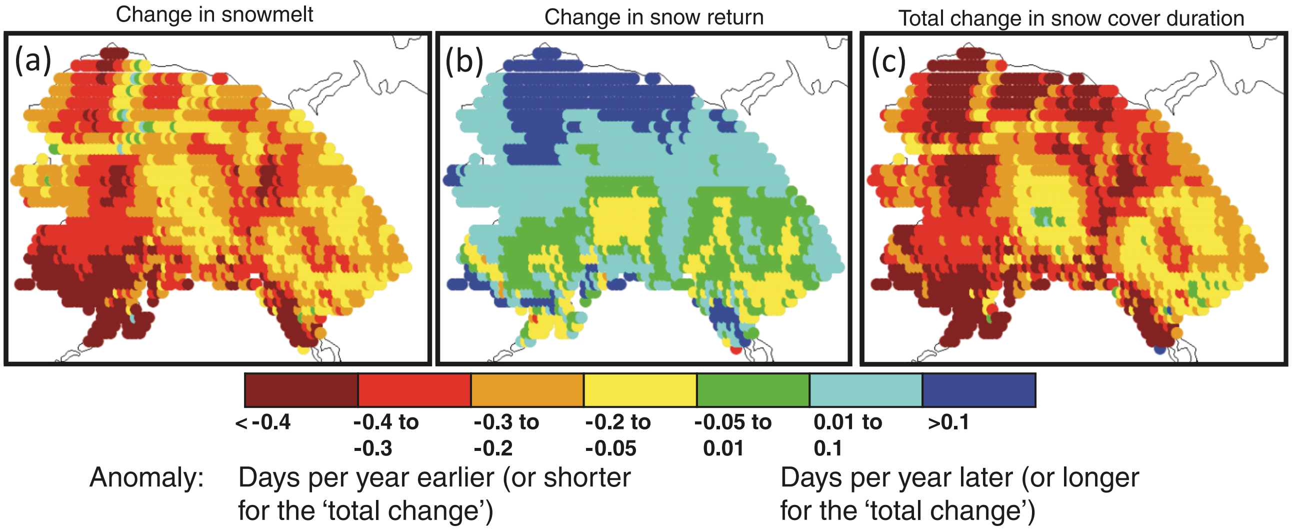
Climate feedbacks associated with CO_2 and CH_4 release from microbial decomposition related to permafrost degradation are likely substantial. Recent research suggests that pool sizes of carbon stored deep in the permafrost are much larger than previous estimates of high-latitude permafrost carbon. Consequently, carbon releases from thawing permafrost act as a much larger positive climate feedback than previously thought (Schuur et al. 2008). This carbon release includes greater microbial CO_2 respiration as well as anaerobic CH_4 production. In upland ecosystems, the age of the thermokarst (e.g., the land surface that forms from the thawing of permafrost) determines if an area is a carbon source or carbon sink (Schuur et al. 2009).

Extremely warm, dry years with more extensive or severe fires are also years when more permafrost thaws than normal. This combination of thawing and fires may expose and rapidly transfer large amounts of carbon to the atmosphere, exacerbating the positive climate feedback. As mentioned above, permafrost thaw can also result in forests being replaced by peatlands and bogs. These peatlands may accumulate more CO_2 but emit more CH_4 than forests, although accumulation of carbon in the peatlands may be reduced under drought conditions (Myers-Smith et al. 2007). In areas where forests remain, the CO_2 released from permafrost thaw and the resulting positive climate feedback may be only slightly compensated for by the negative climate feedback associated with an increased growing season and greater carbon uptake by these forests (Schuur et al. 2008).

Changes in lake area

Methane emissions from lakes in Alaska may also be substantial and may act as a positive feedback to global climate (Walter et al. 2007). Changes in lake area due to permafrost thaw have been documented in boreal Alaska. Consequently, in the future, the amount of these emissions may be highly dependent on changes in lake area. Although these studies have generally documented a decrease in lake area in southern areas of warm permafrost due to lake drainage after permafrost thaw (Smith et al. 2005; Riordan et al. 2006), lake area tends to increase with permafrost thaw in northern ice-rich zones of cold permafrost (Smith et al. 2005). These increases or decreases in lake area would also impact albedo, with increases in lake area generally resulting in an increase in albedo and a negative climate feedback. Decreases in lake area would likely result in a lighter surface as vegetation colonized the area, with an increase in albedo and negative climate feedback, although the magnitude of this feedback would be dependent on the type of vegetation filling that occurs and the size of the lakes that are replaced

Fig. 2. Spatial distribution of changes in snow cover (days·year^{-1}) for changes in (*a*) snowmelt, (*b*) snow return, and (*c*) the total length of the snow cover duration in the western Arctic between 1970 and 2000. Further details are in Euskirchen et al. 2007.



(Rouse et al. 2005). Overall, while the magnitude of the climate feedback as a result of changes in lake area has not been quantified, it would depend on the relative changes of CH_4 emissions versus albedo.

Land use

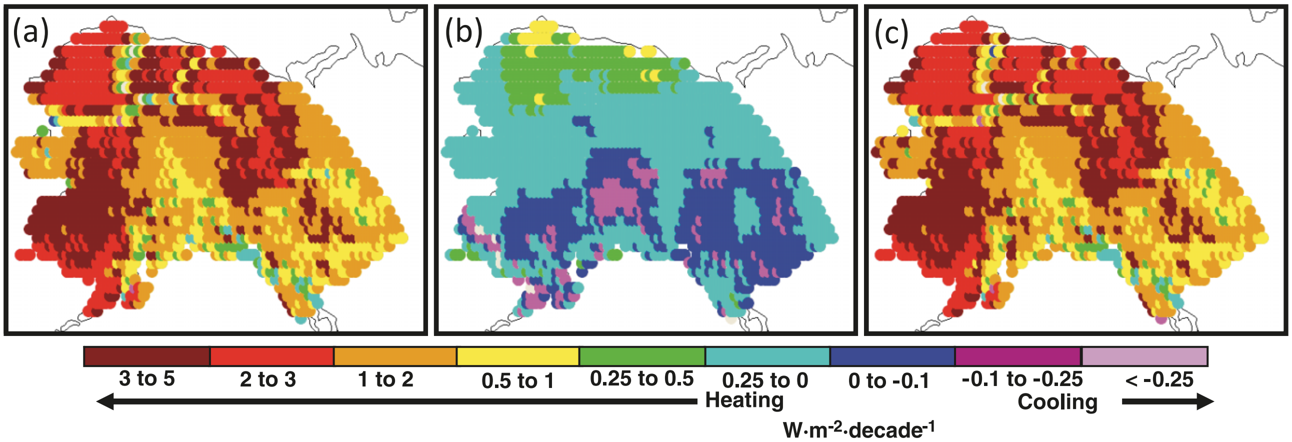
Changes in land use in boreal Alaska will likely have a much smaller feedback to climate than changes in land use in other regions. While the population of Alaska has doubled over the last 50 years, the land surface remains sparsely populated. Large-scale changes in the land surface are more likely due to changes in permafrost, wildfire, snow cover, insect outbreaks, and the other processes discussed in this paper. Aside from the increase in salvage timber harvest after insect outbreaks (discussed above), boreal forest timber harvest has been more of a factor historically (e.g., clear-cutting in interior Alaska during the early 20th century) than currently, with little planned for the future (Wurz et al. 2006). Any increase in logging activity in boreal forests reduces evapotranspiration and increases soil heat flux, with little influence on sensible heat, since the ratio of sensible heat to net radiation is already large in the mature forests that are logged (Eugster et al. 2000). Consequently, a significant climate feedback from timber harvest would be in the atmospheric moisture budget and hydrological balance, with little direct feedback to air temperature.

If timber harvest and forest clearing were to increase in the future under a warming climate and longer growing season, the main reason for this may be due to an intensification of agriculture or agroforestry for fuelwood production. This would likely have a direct impact on the carbon budget, with research showing large losses of soil carbon during the first years of agriculture after deforestation and a positive climate feedback (Grünzweig et al. 2004). These losses of soil carbon may be greater than those after land clearing in other biomes because of the higher soil carbon content per unit area in these boreal forests. Reductions in vegetation carbon uptake due to logging activity would also be reduced, acting again as a positive climate feedback. It is also possible that the increase in albedo in the areas cleared for agriculture may be large in the spring when the logged lands are covered in snow and would cause a negative climate feedback (Bala et al. 2007). In summary, there are two main sources of uncertainty in terms of climate feedbacks due to changes in land use: (1) the actual amount of agriculture and agroforestry that may occur in this region in the future, and (2) the amount of soil carbon that may be lost due to this conversion to agriculture.

Snow season changes

Understanding and predicting snow dynamics in boreal regions are important because, as snow retreats, less solar energy is reflected to space and more energy is absorbed and transferred to the atmosphere, causing a positive snow–albedo feedback loop that reinforces warming. A positive feedback to atmospheric heating may occur as a result of a decrease in the period of snow-covered ground that is observed and expected under a warming climate (Dye 2002; Euskirchen et al. 2006, 2007). Snowmelt in the western Arctic occurred approximately 3.0 days·decade^{-1} earlier during the last several decades of the 20th century (Fig. 2*a*), while the return of snowfall occurred approximately 0.3 days·decade^{-1} later during this same period (Fig. 2*b*; Euskirchen et al. 2007), meaning that the snow season was shortened by a total of 3.3 days·decade^{-1} (Fig. 2*c*). The change in snowmelt of 3.0 days·decade^{-1} earlier resulted in an estimated increase in atmospheric heating of 2.0 W·m^{-2}·decade^{-1} in the western Arctic (Fig. 3*a*), while the later return of snowfall of 0.3 days·decade^{-1} resulted in an estimated increase in atmospheric heating of 0.1 W·m^{-2}·decade^{-1} (Fig. 3*b*), for a total increase in atmospheric heating of 2.1 W·m^{-2}·decade^{-1} (Fig. 3*c*; Euskirchen et al. 2007). Because of differences in the warming impacts between the tundra and boreal biomes, approximately 40% of this change in atmospheric heating occurred in areas occupied by boreal forest, while the remaining 60% occurred in areas occupied by tundra. This is because there are large seasonal contrasts in the snow-free and snow-covered value of albedo in the tundra

Fig. 3. Changes in energy (W·m^{-2}·decade^{-1}) due to changes in (*a*) the timing of snowmelt, (*b*) the timing of snow return, and (*c*) the length of the snow cover duration in the western Arctic between 1970 and 2000. Further details are in Euskirchen et al. 2007.



(e.g., 0.3 summer albedo versus 0.6 winter albedo) compared with the forest (e.g., 0.2 summer albedo versus 0.3 winter albedo), where the seasonal contrast is lower.

The importance of changes in albedo across ecosystem types in high latitude boreal forests is illustrated by the substantially enhanced predicative powers of climate models that incorporate a more realistic parameterization of boreal and high-latitude albedo (e.g., Betts and Ball 1997; Viterbo and Betts 1999). There is a long history of including seasonal changes of albedo in climate models (Viterbo and Betts 1999), but the concept that vegetation types may differ substantially in these seasonal changes in albedo between snow-free and snow-covered ground received little attention until the past decade. Large-scale interdisciplinary field campaigns, such as the Boreal Ecosystem–Atmosphere Study (BOREAS), collected information pertaining to vegetation-specific albedo over snow-free and snow-covered ground (Betts and Ball 1997). This information was later included in climate models, greatly increasing their predicative capacities in snow-covered regions (e.g., Viterbo and Betts 1999).

Regional comparisons

Modeling simulations over boreal Alaska have documented changes in albedo as a result of changes in the duration of the snow season (as described in the previous section) and in the amount of young forest stands on a landscape due to changes in the fire regime (Euskirchen et al. 2007, 2009). In addition, changes in the exchange of the radiatively active gases (CO_2, CH_4) have also been estimated due to changes in climate, atmospheric CO_2 concentrations, fire regimes, and CH_4 emissions (Table 2; Balshi et al. 2007, 2009; Zhuang et al. 2007). The sum of these feedbacks indicates that changes in boreal Alaska acted as a positive feedback to climate with at least 1.34 W·m^{-2}·decade^{-1} of atmospheric heating between 1970 and 2000 and with ~2.44 W·m^{-2}·decade^{-1} of atmospheric heating between 2003 and 2100. The strongest feedback to climate was based on the snow–albedo feedback between 2003 and 2100 (4.3 W·m^{-2}·decade^{-1} of atmospheric heating; Euskirchen et al. 2009), and this was only partially counterbalanced by an increase in the amount of young stands in the landscape under changes in fire regimes (0.90 W·m^{-2}·decade^{-1} of atmospheric heating; Euskirchen et al. 2009) and by increases in carbon uptake by terrestrial ecosystems between 2003 and 2100 (2.02 W·m^{-2}·decade^{-1} of atmospheric heating; Balshi et al. 2009). Furthermore, under a warmer, wetter climate the amount of CH_4 released from Alaska's peatlands increased between 1970 and 2000 and between 2003 and 2100, acting as a positive climate feedback to warming of 0.28 W·m^{-2}·decade^{-1} of atmospheric heating during the first period and 0.56 W·m^{-2}·decade^{-1} of atmospheric heating during the latter period (Zhuang et al. 2007). Overall, these analyses indicate that changes in atmospheric heating due to changes in these carbon stocks in these boreal ecosystems will play a minor role in the feedback to the climate over the 21st century, with the changes in snow cover estimated to play a larger role in changes in atmospheric heating.

Role of earth system models in representing climate feedbacks from Alaskan boreal forests

Establishing the influence of the boreal forest on climate through direct observations is a challenging endeavor. For example, through an analysis of air temperature and evapotranspiration, it may be possible to discern the timing of leaf-out in the spring, but generally, a broader understanding of the influence of boreal forests on climate requires sophisticated modeling approaches (see also Bonan 2008). Without a synergistic modeling approach that integrates all major feedbacks and relationships between these terrestrial ecosystems and climate, reliable projections of environmental and climate changes are not possible. There are a number of challenges for earth system models in representing these feedbacks. For example, past and future changes in cloud cover over the boreal forest of Alaska, and all of Alaska in general, have a large impact on climate feedbacks, but cloud representation is still a key uncertainty in climate models (Vavrus et al. 2009). Climate models predict future increases in cloudiness in the boreal forest of Alaska, particularly in the summer, although these predictions are subject to wide uncertainty (Spracklen, et al. 2008). Other challenges for earth system models in representing climate feedbacks in boreal forests are (1) including nitrogen feedbacks on carbon uptake; (2) incorporating key disturbance processes such as fire and insect outbreaks; (3) tracking other greenhouse gases in addition to CO_2, such as CH_4; and (4) tracking aerosols. Furthermore, given that recent changes in climate, atmospheric CO_2, land cover, species composition, and element inputs and losses alter the relationship between climate drivers and ecosystem carbon dynamics, net primary productivity and decomposition may differ in their rate or pattern of response. Chapin et al. (2009) recommend a three-phased approach for deciding which biogeochemical complexities to include in global-scale climate–carbon cycle models. This includes (1) incorporating ecologically important responses into stand-level ecological models, and comparing results with whole-system carbon-flux measurements; (2) incorporating at the regional scale those processes that when included at the stand level improve the fit between the model and observations, and comparing these regional model simulations with appropriate data; and (3) incorporating into climate–carbon models those processes that when included in regional-level models improve the fit to observations (e.g., coupling of the carbon and nitrogen cycles).

Conclusion

This manuscript has identified the primary feedbacks to climate from changes in Alaska's boreal forests. While the boreal forest provides climate regulation as an ecosystem service, we do not yet understand if the net effect of the climate feedbacks from Alaska's boreal forests would enhance or mitigate warming. The interactions of positive and negative feedbacks to climate warming in the boreal forest have important implications for resilience both regionally and globally. The largest and most rapid climate feedbacks are positive feedbacks to warming associated with earlier snowmelt. These effects are most pronounced at the regional scale and reduce the resilience of the boreal vegetation–climate system by amplifying the rate of regional warming. The subsequent slower changes caused by changes in fire regime, vegetation, permafrost, and trace gas fluxes constitute a complex mixture of positive and negative feedbacks, whose net effects are uncertain. The results presented in this paper indicate that assessment of boreal forest resilience requires inclusion of climate feedbacks that link boreal forests to changes occurring throughout the planet.

Acknowledgements

This research was supported by the Bonanza Creek Long-Term Ecological Research Program (funded jointly by National Science Foundation grant DEB-0423442 and USDA Forest Service Pacific Northwest Research Station grant PNW01-JV11261952-231). Support was also provided by a National Science Foundation Cooperative Agreement on Circumpolar Synthesis and Integration with the International Arctic Research Center.

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