Chapter 24

Responses of High Latitude Ecosystems to Global Change: Potential Consequences for the Climate System

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24.1 Introduction

Terrestrial ecosystems of high latitudes occupy approximately one-fourth of the Earth's vegetated surface. Substantial climatic warming has occurred in many high latitude areas during the latter half of the 20th Century (Serreze et al. 2000), and evidence continues to mount that this warming has been affecting the structure and function of terrestrial ecosystems in this region (Stow et al. 2004; Hinzman et al. 2005). It is important to understand these changes because they may have consequences for the functioning of the climate system, particularly in the way that *(a)* radiatively active gases are exchanged with the atmosphere, *(b)* water and energy are exchanged with the atmosphere, and *(c)* fresh water is delivered to the Arctic Ocean (Chapin et al. 2000a; McGuire et al. 2003). The exchange of water and energy has implications for regional climate that may influence global climate, while the exchange of radiatively active gases and the delivery of fresh water to the Arctic Ocean are processes that could directly influence climate at the global scale.

Over the past decade the IGBP-GCTE high latitude transects have become important foci for research on responses of high latitude terrestrial regions to global change (Steffen and Shvidenko 1996; McGuire et al. 2002). This network of transects (Fig. 24.1) includes two in Siberia, the Far East Siberian Transect (FEST) and the East Siberian Transect (EST); one in Scandinavia (SCANTRAN/SCANNET), which has been augmented by carbon storage studies along a transect in Finland; one in Canada, the Boreal Forest Transect Case Study (BFTCS); and one in Alaska.

The high latitude transects generally span substantial temperature gradients (mean annual temperature of 5° to –15°C) both within and among transects (McGuire et al. 2002). Temperature along each transect co-varies with precipitation and photosynthetically active radiation. Disturbance regimes including fire and insects are also variable among the high latitude transects. For example, fire is essentially non-existent in much of Scandinavia, but burns annually an average of approximately 1% of the boreal forest along the EST (McGuire et al. 2002; Fig. 24.2). Similarly, land-use and land-cover change also varies among the high latitude transects (Kurz and Apps 1999; McGuire et al. 2002, 2004).

Each of the transects provides a different perspective into the responses of high latitude ecosystems to global change. In this chapter we first summarize how climate, disturbance regimes, and land cover in high latitudes have changed during the last several decades. We then summarize the results of ecological research along these transects that have contributed towards a richer understanding of high latitude terrestrial responses to these changes. We conclude with a discussion of challenges and opportunities for integration.

24.2 Recent Changes in Climate, Disturbance Regimes, and Land Cover

Temperature. While temperature has changed substantially in high latitudes during recent decades (Serreze et al. 2000), changes have not been uniform. Warming has been most pronounced in continental Siberia and in Alaska, with most of the warming occurring in winter (December–February) and spring (March–May) (Serreze et al. 2000; McBean et al. 2005). During the last century, northern Scandinavia experienced warming during the 1920s and 1930s, cooling from the 1940s until the 1960s, and warming since the 1970s; this pattern mirrors the global mean temperature trend over the last century (IPCC 2001). In recent decades, air temperatures have increased substantially in western Canada (Serreze et al. 2000). While eastern Canada generally cooled since the 1970s (Serreze et al. 2000), the cooling appears to have ceased since the late 1990s (McBean et al. 2005).

Precipitation. The increase in the hydrological discharge of northern Eurasian rivers into the Arctic Ocean over the last century, as documented by Peterson et al. (2002), is largely explained by increased moisture transport into high latitudes (McClelland et al. 2004). Consistent with this observation, Vaganov et al. (1999) documented increased winter precipitation along the FEST during the last century. While precipitation has remained stable in Alaska, several lines of evidence indicate that Alaska is

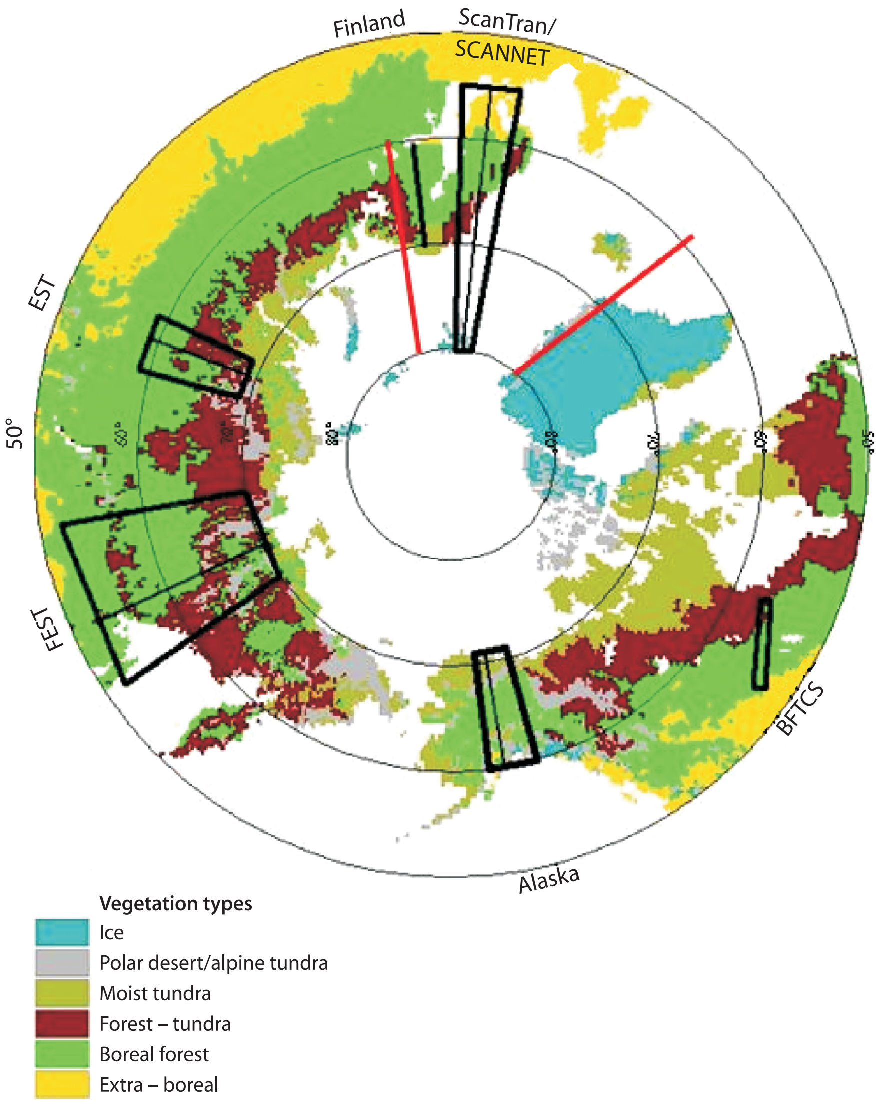

Fig. 24.1. Polar projection vegetation map indicating the location of high latitude transects. This network of transects includes two in Siberia, the Far East Siberian Transect (*FEST*) and the East Siberian Transect (*EST*); one in Scandanvia (*SCANNET*), which has been augmented by carbon storage studies along a transect in Finland; one in Canada, the Boreal Forest Transect Case Study (*BFTCS*), and one in Alaska

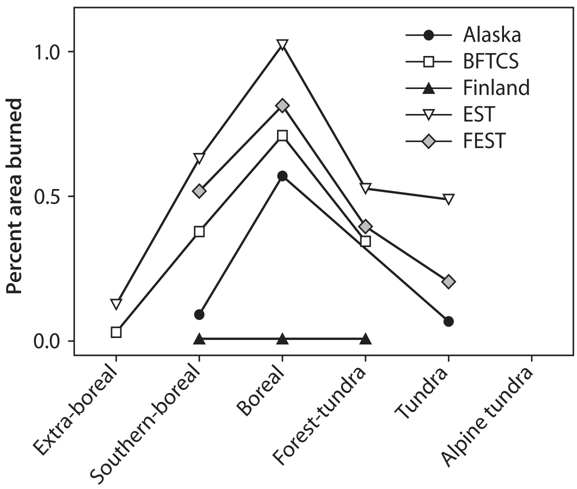

Fig. 24.2. Patterns of historical area burned along each of the high latitude transects as a function of vegetation distribution (reprinted with permission from McGuire et al. 2002)

experiencing increased drought stress because of increased summer water deficits (Oechel et al. 2000; Barber et al. 2000). There is also increased variability in climate in Siberia, and long periods of warm dry weather have become more frequent.

Permafrost. A wealth of evidence indicates that permafrost is warming in the FEST (Hinzman et al. 2005), Canada (Vitt et al. 2000), Alaska (Fig. 24.3; Romanovsky and Osterkamp 1997; Osterkamp and Romanovsky 1999; Hinzman et al. 2005), and Fennoscandia (Christensen et al. 2004; Luoto et al. 2004). While permafrost warming is consistent with regional increases in air temperature, deeper snow cover also plays a roll (Osterkamp and Romanovsky 1999; Stieglitz et al. 2003). In Alaska, warming of permafrost may be causing a significant loss of open water across the landscape, as thawing of permafrost connects closed watersheds with groundwater (Yoshikawa and Hinzman 2003). However, the reduction

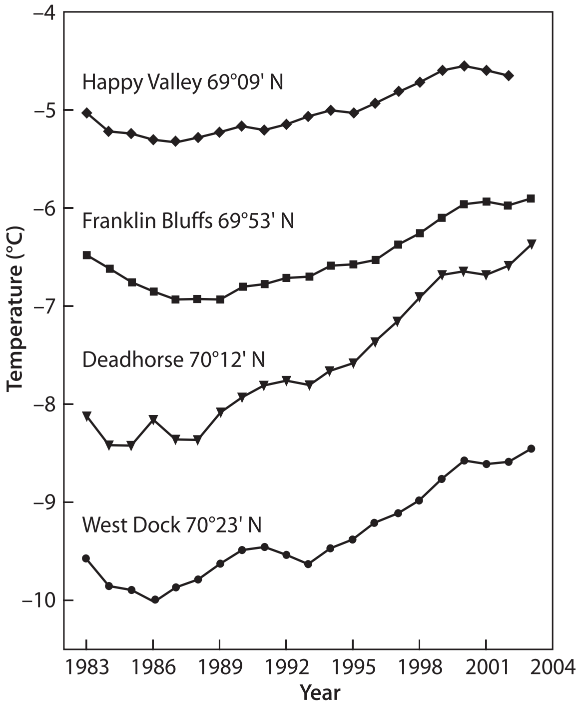

Fig. 24.3. Changes in soil temperature at 20 m depth for several northern sites of the Alaska transect (data courtesy of Tom Osterkamp; see also Romanovsky and Osterkamp 1997)

of open water bodies may also reflect increased evaporation under a warmer and effectively drier climate in Alaska as the loss of open water has also been observed in permafrost-free areas (Klein 2005).

Growing Season. Several studies based on remote sensing indicate that growing seasons are changing in high latitudes regions (Dye 2002; McDonald et al. 2004; McGuire et al. 2004; Smith et al. 2004). These studies identify earlier onset of thaw in both northern North America and northern Eurasia, but the magnitude depends on the study. Putting together the trends in the onset of both thaw and freeze, Smith et al. (2004) indicate that the trend for longer growing seasons in northern North America (3 days per decade) is primarily because of later freezing, while the trend in northern Eurasia (1 day per decade) is because the trend for earlier thaw is slightly greater than the trend for earlier freezing. However, in the EST Vaganov et al. (1999) found delays in the onset of the growing season associated with increases in winter precipitation. Data from the Scandinavian transect also indicate that that growing season changes may be complex at the regional scale (Callaghan et al. 2004).

Fire Disturbance. Important changes in land cover that have occurred in high latitudes include changes associated with disturbance (e.g., fire, insect outbreaks, timber harvest, cropland establishment/abandonment, and industrial activities like oil and gas extraction) and large-scale changes in the distribution of vegetation (e.g., the advance of tree line in regions now occupied by tundra). During the 1970s and 1980s, the area burned annually in northwest Canada increased substantially (Kurz and Apps 1999; Stocks et al. 2000, 2003). There is also evidence that fire frequency in Northern Eurasia has increased in recent decades. Analyses of fire frequency data from Russia suggest a long-term average of annual area burned of about 10 million ha yr^{-1} including low-severity surface fires (Conard and Ivanova 1997; Wirth 2004). Satellite-based analyses also suggest increased area burned with an average exceeding 10 million ha yr^{-1} from 1998 through 2003, with a peak of 22 million ha in 2003 (Soja et al. 2004). After fire, soil temperatures typically warm and the active layer becomes deeper, but soils cool again as mosses grow back during succession. However, severe fires or more frequent fires can lead to the degradation of permafrost, which may result in substantial mortality of forests.

Insect Disturbance. On average insect infestations annually affect an area almost as large as does fire in the forests in Canada (Kurz and Apps 1999) and Alaska (Werner et al. 2005). Since approximately 1920, between 1–2 million ha yr^{-1} of forests in Canada have annually experienced insect-induced stand mortality (Kurz and Apps 1999), while the long-term annual fire area in Canada averages 2 million ha yr^{-1} (Stocks et al. 2003). Large outbreaks seem to occur at intervals of approximately thirty years. In Russia, the area affected by insect disturbance is about 2 million ha yr^{-1} (Shvidenko and Nilsson 2003), which is less than the area affected by fire. Similarly, northern Fennoscandia experiences outbreaks approximately every decade during which thousands of square kilometers of mountain birch forests are defoliated (Tenow 1996). There is concern that some of the recent large outbreaks that have been observed in Siberia (Siberian gypsy moth), Canada (Mountain pine beetle), and Alaska (Spruce bark beetle, Larch sawfly, Eastern spruce budworm; Werner et al. 2005) are associated with warm dry weather in the summer. For example, the Siberian gypsy moth is estimated to have affected 10 to 11 million ha of forests in the taiga of Siberia in 2001 and 2002, which is much higher than previously observed rates of infestation. Thus, insect outbreaks that are linked to climate change appear to be increasing in a number of areas spanned by the high latitude transects.

Forest Harvest. Annual forest harvest in Canada approximately doubled from ~0.5 million ha in 1970 to ~1 million ha in 1990 (Kurz and Apps 1999). More dramatically, timber harvest in Alaska increased over sixfold from 1952 to 1992 (McGuire et al. 2004). Recent trends of forest harvest rates in Canada and Alaska are substantially influenced by economics of the global forest sector, as much of the harvested wood is exported out of the region to markets in Asia and the conterminous United States. Concern over conservation issues and the collapse of Asian economies in the 1990s have had substantial impacts in decreasing forest harvest in Alaska and the U.S. Pacific northwest during the 1990s. In Russia, forest harvest between 1950 and 1990 was relatively steady at about 2 million ha yr^{-1}. The harvested areas were mostly concentrated in the European North (about two-thirds of the total) and in the most populated regions of Siberia. With the breakup of the Soviet Union, forest harvest during the last 15 years decreased substantially to around 1 million ha yr^{-1} for the years 2000–2002. This estimate of recent harvest rates should probably be increased by 15 to 20% because of illegal harvest in the Russian Far East.

Agricultural Land Use. In the prairie provinces of Canada, there was an estimated net deforestation of 12.5 million ha between 1860 and 1992 (based on Ramankutty and Foley 1999). Since 1950, Canadian forests have had a net gain of 3.0 million ha at the expense of agriculture. While this is a small proportion of the total forest base (<1%), it is important to recognize that most of the afforestation has occurred in eastern Canada and deforestation continues to occur in western Canada. In Russia, abandonment of arable lands between 1988 and 2001 was approximately 30 million ha. Abandonment is most pronounced in the zone of the boreal forest because the low productivity lands were unprofitable in the transition to a market economy. Recent land-use changes in Fennoscandia primarily include expansion of some of the larger towns in the region, but at the cost of the rural areas where depopulation is at an advanced stage as 32 000 Norwegian northern coastal farms have been abandoned since 1955 (Eilertsen 2002). Habitat fragmentation as a result of increased infrastructure and transport route development has proceeded rapidly since the 1940s and is expected to accelerate.

Treeline responses. The transects differ in the presence or absence of barriers to coniferous forest movement northward into areas occupied by tundra. The Brooks Range separates boreal forest in interior Alaska from arctic tundra on the north slope of Alaska, and there are ocean barriers to vegetation shifts in the SCANNET region. In contrast, geography is not a significant barrier to treeline migration along the Siberian and Canadian transects. The replacement of tundra with boreal forest occurred in earlier warm periods of the Holocene in northern Eurasia (MacDonald et al. 2000) and western Canada (Spear 1993). Over the last half century, treeline advances into tundra have been documented in Russia (Esper and Schweingruber 2004), Canada (Scott et al. 1987; Lavoie and Payette 1994), and Alaska (Suarez et al. 1999; Lloyd et al. 2003; Lloyd and Fastie 2003). However, fire and human activities in Russia have moved treeline to the south (Vlassova 2002). In Fennoscandia, treeline advanced at some sites during the first half of the 20th Century (Hustich 1958; Kullman 1986), but changed tree growth form at treeline at other sites (e.g., shifts from stunted krummholz trees to upright trees) without substantial changes in position of the tree species' limit (Kullman 1995). In mountainous areas of Scandinavia, several studies documented that elevational treeline has moved upslope during the last half of the 20th century in association with increases in temperature (Juntunen et al. 2002). However, in Scandinavia there are other issues besides climate affecting the position of treeline such as land use and browsing by reindeer and moose (Callaghan et al. 2004).

24.3 Responses of Radiatively Active Gases

24.3.1 General Issues

High latitude ecosystems contain approximately 30% of the world's vegetation carbon (McGuire et al. 1995) and about 40% of the world's soil carbon (Melillo et al. 1995). Much of the soil carbon in high latitude ecosystems is highly labile and has accumulated simply because of cold and/or anaerobic soils conditions. Thus, high latitude ecosystems could substantially affect atmospheric concentrations of CO_2 and CH_4. Likely changes in the fluxes of CO_2 and CH_4 could both enhance warming (positive feedbacks) and mitigate warming (negative feedbacks) (Smith and Shugart 1993; Chapin et al. 2000a; Clein et al. 2002; Zhuang et al. 2004). As summarized below, studies of carbon and methane dynamics along the high latitude transects have provided new insights on how CO_2 and CH_4 exchange respond to changes in climate and disturbance.

24.3.2 Responses of CO_2 Exchange to Climatic Change

Aerobic vs. Anaerobic Decomposition. Warming could cause release of carbon as CO_2 from aerobic boreal soils, i.e., soils that are not saturated with water, through enhanced decomposition (McGuire et al. 1995, Arneth et al. 2002). In anaerobic boreal soils, warming could affect carbon storage by altering soil drainage patterns. Although soil drainage may be especially vulnerable to the response of permafrost to climatic warming, the net effect on CO_2 exchange is not clear because drainage can either be enhanced or retarded by permafrost degradation. For example, the release of CO_2 from aerobic decomposition is likely to be enhanced if permafrost warming results in a drop of the water table (Oechel et al. 1995; Christensen et al. 1998) or thaws soil in areas of discontinuous permafrost (Goulden et al. 1998). In contrast, CO_2 emissions from soils are likely to be reduced if permafrost thaws in situations where drainage is impeded and decomposition is diminished because of aneorobic conditions (Christensen et al. 1998, 2004) and moss production is increased (Turetsky et al. 2000).

Experimental Warming of Aerobic Soils. In general, the warming of aerobic soils is expected to increase decomposition in high latitude ecosystems. This warming effect may be constrained by increases in leaf area index, which shade the soil surface. For this reason summer soil temperatures in arctic sites can be higher than those in the shade of subarctic birch forests (Callaghan et al. 2005). Although the warming of aerobic soils will tend to increase the release of CO_2 from high latitude ecosystems, the net effect of warming depends on the balance between production and decomposition. A recent meta-analysis of experimental warming studies indicates that an increase in productivity is approximately compensated by an increase in decomposition rates (Rustad et al. 2001).

Responses to Extension of the Growing Season. Climate warming is lengthening the growing season throughout much of the region occupied by high latitude ecosystems (Dye 2002; McDonald et al. 2004; Smith et al. 2004; Euskirchen et al. 2006). In temperate forests, annual carbon storage is enhanced by approximately 6 g C m^{-2} for every day that the growing season is lengthened (Baldocchi et al. 2001), and modeling analyses suggest that carbon storage in high latitude ecosystems may have a similar level of sensitivity to changes in growing season length (Euskirchen et al. 2006). The start of the growing season, as defined by photosynthetic activity of the canopy, is tightly coupled to the thawing of the soil in conifer stands of the BFTCS in Canada because frozen soil prevents transpiration (Frolking et al. 1999). Eddy covariance studies of Scots pine stands in the EST indicate that photosynthetic capacity at the beginning of the growing season is less than expected from relationships of assimilation vs. light and temperature during the peak of the growing season (Lloyd et al. 2002). One possible cause is a high respiration cost in needles for restructuring the photosynthetic apparatus (Shibistova et al. 2002) and for repairing damage of early season photoinhibition (Ensminger et al. 2004). Deciduous stands begin net carbon uptake following leafout, which is also sensitive to the timing of snowmelt. Studies in Siberia and Alaska indicate that deciduous forests become net CO_2 sinks much later in the season than coniferous stands, but that the delay is compensated for by higher assimilation rates and results in annual carbon balances that are similar between deciduous and coniferous stands (Röser et al. 2002; Lui et al. 2005).

Evidence from Inventory and Remote Sensing Studies. While site-specific studies do not clearly show whether experimental warming or lengthening of the growing season augments carbon storage, analyses of forest inventory data for Russia suggest that Russian forests are generally sinks for carbon (Schulze et al. 1999, 2002; Shvidenko and Nilsson 2002, 2003). Analyses based on satellite data suggest that both production and vegetation carbon storage have generally been enhanced in high latitude ecosystems during recent decades (Myneni et al. 1997, 2001; Randerson et al. 1999; Zhou et al. 2001; Nemani et al. 2003; Jia et al. 2003), although there are extensive areas in high latitudes that exhibit decreases in production (Goetz et al. 2005).

The Role of Soil Nitrogen Cycling. One hypothesis for the mechanism of increased production is that warming increases decomposition of soil organic matter to release nitrogen in forms that can be taken up by plants. Since production is often limited by plant nitrogen supply in boreal forests (Van Cleve and Zasada 1976; Van Cleve et al. 1981; Chapin et al. 1986; Vitousek and Howarth 1991; Schulze et al. 1995; Wirth et al. 2002a), an increase in nitrogen availability to plants should increase production. Several warming experiments and modeling studies have provided support for this mechanism (Van Cleve et al. 1990; Bonan and Van Cleve 1992; Bergh et al. 1999; Stromgrem and Linder 2002; Clein et al. 2002). One hypothesis is that the transfer of soil nitrogen released by decomposition to plants should result in greater carbon storage in plants because plants have a higher carbon to nitrogen ratio than soils (Shaver et al. 1992). Whether the capacity for increased plant growth can offset decomposition losses largely depends on the degree to which nitrogen released through enhanced decomposition is transferred to plants vs. immobilized in soil organic matter or lost from the terrestrial ecosystems in aquatic or gaseous pathways (McGuire et al. 1992; Stieglitz et al. 2000). If warming enhances production of high latitude ecosystems, soil carbon storage could increase if the transfer of carbon from vegetation to the soil is greater than the enhancement in decomposition from warming. If this condition occurs, then the long-term rate of soil carbon storage depends on whether the carbon that is transferred to the soil decomposes quickly or slowly (Hobbie et al. 2000; Clein et al. 2000). Our understanding of soil carbon and nitrogen transformations in response to warming is incomplete and is a key gap that limits our ability to make projections of the long-term response of soil carbon to warming in high latitude ecosystems (Clein et al. 2000).

Drought Stress. Warming-induced increases in production may not occur if other factors limit production. For example, forests on coarse-textured soils are among the most severely nitrogen-limited boreal ecosystems, but are also frequently subject to drought stress because of low water retention in the soil and superficial root systems (Kelliher et al. 1999). Warming has reduced growth in old white spruce trees growing on south-facing aspects in interior Alaska because of drought stress (Barber et al.

2000), and remote sensing analyses suggest that drought stress may be affecting a substantial portion of the North America boreal forest (Goetz et al. 2005). At treeline in Alaska, the growth of trees located in warm dry sites below the forest margin declined in response to recent warming, whereas the growth of trees located at treeline, particularly in wet regions, increased (Lloyd and Fastie 2002). Thus, there appears to be substantial spatial variability in the response of white spruce growth to recent warming in Alaska, and studies conducted elsewhere on other species throughout the boreal forest suggest that growth responses of warming depend on interactions between temperature and the timing and amount of precipitation (Briffa et al. 1998; D'Arrigo and Jacoby 1993; Jacoby and D'Arrigo 1995; Linderholm et al. 2003).

Winter Decomposition. Warming can also promote the loss of carbon as CO_2 from high latitude terrestrial ecosystems through higher rates of winter decomposition and through the increased decomposition of terrestrially derived carbon in aquatic ecosystems. A number of studies, which have primarily been conducted in the vicinity of the FEST and Alaska transects, have concluded that winter decomposition represents an important component of the annual budget of CO_2 exchange between high latitude ecosystems and the atmosphere (Coyne and Kelley 1974; Waelbroeck and Louis 1995; Hobbie and Chapin 1996; Zimov et al. 1993, 1996; Oechel et al. 1997; Fahnestock et al. 1999; Grogan and Chapin 1999; Shibistova et al. 2002; Michaelson and Ping, 2003). In general, winter decomposition is expected to increase with increases in soil temperature. One particularly interesting hypothesis involves the degree to which the heat of microbial activity might further enhance decomposition from high latitude soils (Zimov et al. 1993, 1996). The nitrogen released by winter decomposition may be less accessible to plants than nitrogen released in summer because of plant dormancy in winter, immobilization of nitrogen by soil microbes during winter, and loss of nitrogen from terrestrial ecosystems in spring runoff.

Terrestrial-Aquatic Linkages. High latitude streams and lakes can act as conduits for CO_2 via the decomposition of dissolved and particulate carbon derived from terrestrial ecosystems (Kling et al. 1991). After spring runoff, concentrations of dissolved and particulate organic carbon in high latitude aquatic ecosystems are highly correlated with precipitation as water is flushed through the organic layer (Prokushkin et al. 2005). There is also a significant increase in the carbon concentrations of streams after fire. Therefore, increases in precipitation or increases in the frequency of fire disturbance in high latitudes might enhance delivery of soil organic carbon to and subsequent decomposition in aquatic ecosystems. Arctic rivers also deliver a substantial amount of organic carbon to the Arctic Ocean (Romankevich and Vetrov 2001). A key uncertainty about increases in this flux is whether this will increase the release of CO_2 from immediate decomposition in coastal ecosystems or whether the carbon will be sequestered in marine sediments. About half of the carbon entering the Arctic Ocean from terrestrial ecosystems is from river inputs and about half from the erosion of coastal soils along the Arctic Ocean. While some of this carbon may become buried in ocean sediments, some of this material will likely be immediately decomposed in coastal Arctic ecosystems. Coastal erosion has increased in recent decades (Are 1999) associated with reduced summer cover of sea ice on the Arctic Ocean. It is expected that erosion of organic matter from soils along the coast of the Arctic Ocean will increase over the next century if sea ice continues to retreat and that this will enhance the CO_2 flux to the atmosphere from the Arctic.

24.3.3 Responses of CH_4 Exchange to Climatic Change

In general, CH_4 emissions of wetlands are expected to increase dramatically in response to warming (Zhuang et al. 2004). A study of CH_4 emissions from wetlands in Greenland, Iceland, Scandinavia and Siberia showed that annual mean emissions were strongly dependent on temperature (Fig. 24.4; Christensen et al. 2003), which indicates that high latitude CH_4 emissions could increase in response to climate warming. Emissions of CH_4 will also depend on changes in the water table. For example, while the release of CO_2 from aerobic decomposition is likely to be enhanced if permafrost warming results in a drop of the water table (Oechel et al. 1995; Christensen et al. 1998), emissions of CH_4 are likely to decrease because methanogenesis is an anaerobic process (Roulet 2000). In contrast, if the thawing of permafrost results in the expansion of lakes and wetlands, then releases of CH_4 are likely to be enhanced (Zimov et al. 1997; Christensen et al. 2004).

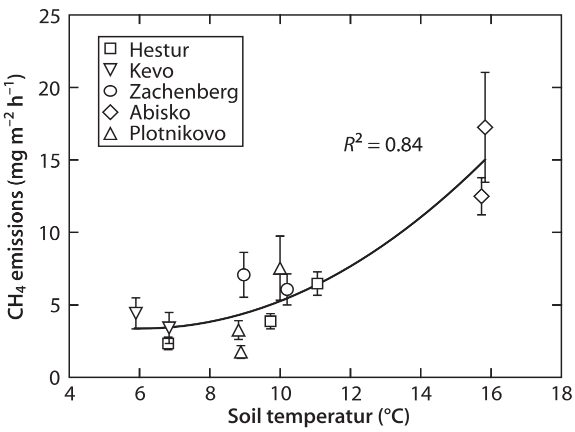

Fig. 24.4. The sensitivity of tundra CH_4 emissions in Greenland and Eurasia to soil temperature (reprinted with permission from Christensen et al. 2003)

The balance of changes in CO_2 exchanges vs. CH_4 emissions in terms of their radiative forcing is, however, complicated and difficult to assess. The current emissions of CH_4 from high latitude ecosystems, which are in the range 20–60 Tg CH_4 yr^{-1} (Zhuang et al. 2004), play a significant role in the global methane budget. In eastern Canadian peatlands, the enhanced CH_4 emissions associated with the creation of wetlands will likely result in a positive feedback to warming for up to 500 years until the enhanced storage of carbon in the wetlands (i.e., uptake of CO_2 from the atmosphere) offsets the enhanced radiative forcing associated with CH_4 emissions (Roulet 2000). In the southern end of the EST, recent studies of wetland trace gas exchange have shown that the radiative forcing of the CH_4 emissions are stronger than the substantial uptake of CO_2 (Friborg et al. 2003). For tundra regions of the high latitude transects, the balance of evidence suggests that tundra is currently a source of greenhouse warming due to substantial CH_4 emissions (Callaghan et al. 2005; Zhuang et al. 2004) that represent a radiative forcing effect that is much greater than small source/sink activity associated with the exchange CO_2 (Sitch et al. 2006). It is also likely that this source strength will increase in the future due to enhanced CH_4 emissions regardless of the strength of the carbon sink in tundra regions (Callaghan et al. 2005).

24.3.4 Responses to Changes in Disturbance and Land Cover

General Issues. A number of regional analyses suggest that carbon storage in high latitude forests is largely determined by how stand-age distribution changes at the regional scale. For stand-replacing disturbance, the temporal course of carbon storage in forests is largely controlled by wood increment and decomposition of coarse woody debris. Disturbance is generally characterized by a period of ecosystem carbon loss, during which production is less than decomposition, followed by a period of ecosystem carbon gain once production exceeds decomposition. If disturbances in high latitude regions become more frequent or more severe, carbon could be released from some ecosystem carbon pools (Kasischke et al. 1995; Wirth et al. 2002b), although the carbon stored in dead wood initially increases after disturbance (Shvidenko and Nilsson 2002).

Changes in Fire and Insect Disturbance Regimes. Together, both fire and insect disturbance have likely released substantial amounts of carbon into the atmosphere from forests in Canada (Kurz and Apps 1999; Chen et al. 2000; Amiro et al. 2001) and Russia (Shvidenko and Nilsson 2000a,b; Kajii et al. 2003). The degree to which increased fire frequency could release carbon from high latitude ecosystems depends, in part, on fire severity. Fires in most of the southern Eurasian boreal forest, which is dominated by Scots pine and Sibierian larch, tend to be surface fires in which most trees survive because of thick bark. In contrast, fires in the permafrost zone of far eastern Russia (Gmelin's larch), in Siberian dark taiga forests (spruce, fir, stone pine) and in boreal North America (mainly spruce), tend to be stand-replacing fires (Wirth et al. 1999; Shvindenko and Nilsson 2000a; McGuire et al. 2002; Wirth 2004; Csiszar et al. 2004). Analyses of the effects of climate change projections on fire weather suggest that climate change could increase fire frequency in Canada (Flannigan et al. 2001; Csiszar et al. 2004). In contrast, palaeoecological work in Canada revealed that colder and wetter periods were associated with higher fire frequencies (Lesieur et al. 2002). Nevertheless, of disturbance regime responses to climate change, fire is the disturbance agent that has the greatest potential to quickly release large amounts of carbon from high latitude regions.

The Influence of Disturbance Severity. Disturbance severity may substantially affect the temporal dynamics of carbon release and storage of high latitude ecosystems. For example, severe fires can lead to a complete destruction of organic soils. In these cases there is a large loss of up to 60 t C ha^{-1} CO_2 in fire emissions, but the ecosystem could come into positive carbon balance sooner if post-fire decomposition rates are low and vegetation recovery is high. The severity of fire disturbance also could affect the trajectory of vegetation succession after fire. Insect disturbance that causes partial or complete stand mortality leads to immediate post-fire carbon loss because of lowered production. In stands that have suffered substantial mortality, subsequent additional loss of carbon may occur if stands are then salvage logged. Also, stands affected by insect disturbance may be more vulnerable to fire because tree mortality generally increases the flammability of forest stands.

Changes in Forest Harvest Regimes. Forests of high latitude regions represent a wood resource of global significance. In general, forest harvest and management results in lower vegetation and soil carbon stocks than equivalent unmanaged forests. In the Russian Far East, carbon loss from illegal logging in the transboundary areas (Rosencranz and Scott 1992) results in the export of wood to China and other Asian countries, but this activity has not offset the drop in legal commercial logging associated with the breakup of the Soviet Union. Thus, it is expected that the change in the degree of forest harvest in the Russian boreal forest will result in net carbon storage over the next few decades unless harvest rates return to previous levels.

Changes in Treeline. Although rapid tree migration rates of up to 25 km yr^{-1} (Ritchie and MacDonald 1986) have been suggested for warming periods in the early Holocene, there are major uncertainties concerning the future rate of forest movement and the extent of range expansion that can take place. It is estimated that the potential increase in ecosystem carbon storage by replacing tundra with boreal forest is likely to proceed at a very slow pace because of inertia associated with the ability of boreal forests to migrate into regions of arctic tundra (Starfield and Chapin 1996; Chapin and Starfield 1997; Lloyd et al. 2003). The replacement of arctic tundra with boreal forest could increase ecosystem carbon storage substantially (Smith and Shugart 1993; Betts 2000).

24.4 Responses of Water and Energy Exchange

24.4.1 General Issues

Most of the energy that heats Earth's atmosphere is first absorbed by the land surface and then transferred to the atmosphere. The energy exchange properties of the land surface therefore have a strong direct influence on climate. High latitude ecosystems differ from more southerly biomes in having a long period of snow cover, when white surfaces might be expected to reflect incoming radiation (high albedo) and therefore absorb less energy for transfer to the atmosphere. Observed winter albedo in the boreal forest varies between 0.11 (conifer stands) and 0.21 (deciduous stands) (Betts and Ball 1997). This is much closer to summer albedo (0.08–0.15) than to the winter albedo of tundra (0.6–0.8), which weather models had previously assumed to be appropriate for boreal forests. The incorporation of true boreal albedo into climate models led to substantial improvements in medium-range weather forecasting and in climate re-analyses (Viterbo and Betts 1999). There is substantial spatial variability in winter albedo within high latitude ecosystems due to the spatial mosaic of conifer forests, deciduous forests, non-forested wetlands, burn scars, and tundra (Chapin et al. 2000a). The latter three have an albedo of approximately 0.6 when the short-statured vegetation is snow covered.

During summer, albedo of boreal vegetation is lower than in winter, with deciduous stands and boreal non-forested wetlands having approximately twice the albedo of conifer forests (Chapin et al. 2000a; Chambers and Chapin 2003). This difference in albedo leads to fluxes of sensible heat in conifer stands that are 2 to 3 times those of deciduous stands, whereas the latent energy fluxes (i.e., evapotranspiration) of deciduous forest stands in the boreal forest are 1.5 to 1.8 times greater than those of conifer forest stands (Schulze et al. 1999; Baldocchi et al. 2000; Chapin et al. 2000a). Because transpiration is tightly linked to photosynthesis, latent heat exchange tends to be dominated by transpiration in boreal forest stands with high productivity (e.g., deciduous forests). In contrast, evaporation plays a more important role than transpiration in the latent energy exchange of forest stands with low productivity (e.g., black spruce and pine forests), where surface evaporation from mosses or lichens can account for up to half of total evaporation (Baldocchi et al. 2000; Kelliher et al. 1999). The substantial sensible heating over conifer stands leads to thermal convection and may contribute to the frequency of thunderstorms and lightning (Dissing and Verbyla 2003), which plays an important role in the fire regime of the boreal forest as a source of ignition.

24.4.2 Responses to Changes in Climate, Disturbance, and Land Cover

Responses to Changing Growing Seasons. Responses of high-latitude ecosystems to global change could influence water and energy exchange with the atmosphere in several ways. Because there are substantial seasonal and spatial differences in sensible and latent energy exchange in high latitude ecosystems, climate warming could affect regional climate by altering both positive and negative feedbacks. One positive feedback associated with climate warming may result from lengthening of the growing season, which leads to earlier snowmelt and later snow cover. This effectively reduces annual albedo and should lead to substantial heating of the atmosphere (Chapin et al. 2005). Besides the extension of the snow-free period, the extension of ice-free periods on lake surfaces and the reduction in the area occupied by glaciers and continental ice sheets may also enhance atmospheric warming.

Responses to Changes in Vegetation. Positive feedbacks that involve changes in vegetation include more shrubs in tundra (Sturm et al. 2001; Silapswan et al. 2001), expansion of boreal forest into regions now occupied by tundra (Chapin et al. 2005), and replacement of summergreen conifers (larch) with evergreen conifers (pine; Kharuk et al. 2005). These changes would lead to substantial heating of the atmosphere, a response that could possibly accelerate the replacement of tundra by boreal forest (Table 24.1; Bonan et al. 1995; McFadden et al. 1998; Chapin et al. 2000a,b). Studies conducted with general circulation models indicate that the position of northern treeline has a substantial influence on global climate, with effects extending to the tropics (Bonan et al. 1992; Thomas and Rowntree 1992; Foley et al. 1994).

Table 24.1. Energy budget feedbacks to regional summer climate

Energy feedbacks	W m^{-2}
Feedback from vegetation change: tussock to shrub transition	3.9
Feedback from vegetation change: tundra to forest transition	5.0
2% change in solar constant	4.6
Doubling atmospheric CO_2	4.4

Responses to Changes in Disturbance Regimes. Disturbance and logging may also affect energy exchange with the atmosphere. For example, while fire disturbance often reduces albedo shortly after the fire, it also provides the opportunity for herbs, shrubs, and eventually deciduous broadleaf trees to develop, which will generally raise albedo. Thus, disturbance regimes that increase the proportion of non-forested lands and deciduous forests could reduce energy absorption and represent a negative feedback to atmospheric warming (Chapin et al. 2000a). In Siberia, self-replacing pine and larch in light taiga forests occur on dry upland soils and on permafrost, respectively (Furyaev et al. 2001). After these vegetation types are disturbed by fire or logging, a sometimes sparse post-fire vegetation and the lack of a deciduous pioneer phase result in a high and sustained production of sensible heat (Schulze et al. 1999). Severe fires in the Russian Far East can cause the collapse of permafrost and prevent the recovery of trees, effectively increasing albedo by converting conifer forests into ecosystems dominated by deciduous herbs and shrubs for hundreds of years. In general, post-fire deciduous broadleaf stands have a higher summer albedo (0.14) than do conifer stands (0.09) which they replace and therefore transfer less energy to the atmosphere (Chambers et al. 2003), as described above. Thus, the degree to which the response of vegetation dynamics to climate warming influences regional climate depends on the interaction of factors that may both enhance and mitigate warming.

24.5 Delivery of Freshwater to the Arctic Ocean

24.5.1 General Issues

The delivery of freshwater from high latitude ecosystems is of special importance because the Arctic Ocean, which contains only about 1% of the world's ocean water and receives about 11% of world river runoff (Forman et al. 2000; Shiklomanov et al. 2000), is the most river-influenced and land-locked of all oceans. Changes in freshwater inflow, which currently contribute as much as 10% to the upper 100 meters of the water column for the entire Arctic Ocean (Barry and Serreze 2000), could alter salinity and sea ice formation to affect the strength of the North Atlantic Deep Water Formation (Aagaard and Carmack 1989; Broecker 1997). Modeling studies suggest that maintenance of thermohaline circulation is sensitive to fresh-water inputs to the North Atlantic (Manabe and Stouffer 1995).

High latitude ecosystems play a significant role in the hydrology of the circumpolar north because they dominate the land-mass that contributes to the delivery of freshwater to the Arctic Ocean. Over the past 70 years there has been a 7% increase in the delivery of freshwater from the major Russian rivers to the Arctic Ocean (Peterson et al. 2002; Serreze et al. 2003). The analysis of McClelland et al. (2004) evaluated three mechanisms for these changes: (1) the construction of dams on the major Siberian rivers, (2) the thawing of permafrost, and (3) an acceleration of the fire regime. Of these possible explanations, an increase in fire frequency during the 20th century has the greatest potential to influence trends in runoff. However, the changes in the fire regime cannot fully explain the magnitude of increase in the delivery of freshwater to the Arctic Ocean, and therefore it appears that a poorly detected increase in precipitation may be the primary cause of the increased discharge. Nevertheless, a major challenge is to better understand and quantify the role of disturbance regime dynamics in the discharge dynamics of freshwater into the Arctic Ocean.

24.6 Summary and Conclusions

While it is clear that changes in high latitude regions have consequences for the climate system via a number of possible pathways (Fig. 24.5), we do not completely understand whether the net effect of changes will enhance or mitigate warming. Responses of water, energy, and trace gas exchange may result in either positive or nega-

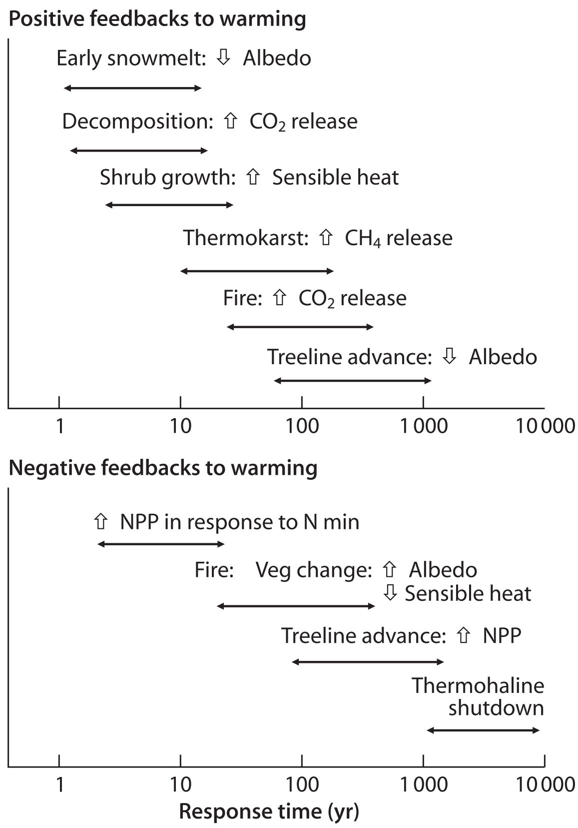

Fig. 24.5. The response times over which different positive and negative feedbacks to climate are most pronounced (reprinted with permission from Chapin et al. 2000a)

tive feedbacks to both regional and global warming. Of particular concern is whether the net response of high latitude ecosystems could lead to positive feedbacks that greatly enhance the rate of regional and global warming. While the responses of carbon storage in high latitude ecosystems have important implications for the rate of CO_2 accumulation in the atmosphere and international efforts to stabilize the atmospheric concentration of CO_2 (Smith and Shugart 1993; Betts 2000), it is important to understand how simultaneous changes in other trace gas exchanges and albedo of high latitude ecosystems also influence regional and global energy balance. For example, the reduction in radiative forcing associated with enhanced carbon storage from an expansion of the boreal forest may be exceeded by the warming effects of lower albedo (Betts 2000). Also, current responses of fire regimes to climate change suggest that fire is likely to increase in frequency and severity in the future, which has implications for both carbon storage and albedo of high latitude ecosystems. Increased delivery of freshwater from the high latitudes to the Arctic Ocean also has substantial implications for climate if it disrupts thermohaline circulation by weakening the formation of North Atlantic Deep Water, a response to warming that could ironically launch the Earth into another ice age (Manabe and Stouffer 1995). The exchange of water, energy, and trace gases among high latitude ecosystems, the atmosphere and the ocean are linked. Therefore, analyses of the response of high latitude ecosystems to global change will require an integrated understanding of how the response of these linkages will manifest themselves at a spectrum of spatial and temporal scales. The studies that have been conducted within and among the high latitude transects have laid the foundation for integration of ecological research with climate system research. Further development of this integrated understanding is relevant to identifying the implications for how the responses of high latitude ecosystems will influence the climate system. These insights are important for the development of mitigation and adaptation strategies in high latitude regions and in regions outside of the high latitudes.

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