Present and Future Carbon Balance of Russia's Northern Ecosystems
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Carbon exchange

Summary: Recent increases in the seasonal amplitude of atmospheric CO₂ at high latitudes suggest a widespread biospheric response to high-latitude warming. We have shown that the seasonal amplitude of net ecosystem carbon exchange by northern Siberian ecosystems is greater in disturbed than undisturbed sites, due to increased summer influx and increased winter efflux. Net carbon gain in summer and respiration in winter were greater in a cool than in a warm year, especially in disturbed sites and did not differ between high-arctic and treeline sites, suggesting that high-latitude warming, if it occurred, would have little effect or would reduce seasonal amplitude of carbon exchange. We suggest that increased disturbance contributes significantly to the amplified seasonal cycle of atmospheric CO₂ at high latitudes.

Most undisturbed ecosystems at high latitudes have abundant mosses, lichens, and evergreen trees or shrubs, which photosynthesize at low rates throughout the snow-free season (Oechel and Sveinbjörnsson 1978, Fan et al. 1995, Goulden and Crill In press). Mosses and the associated organic mat reduce soil thaw during summer because of their low thermal conductance, so soils freeze quickly in autumn, minimizing winter respiration (Zimov et al. 1993, Chapin et al. 1996). Even in Siberian larch forests the understory is primarily mosses and evergreen shrubs. Following disturbance at high-latitudes, there is a shift in dominance from evergreen plants to herbs, grasses, and deciduous woody species that produce leaves 2-4 weeks after snowmelt and shed leaves 2-4 weeks prior to autumn snow cover, thus shortening the season of photosynthetic activity. These deciduous species have higher maximum rates of photosynthesis (Oberbauer and Oechel 1989) and productivity (Shaver and Chapin 1991) than mosses and evergreens. The decline in moss cover increases summer soil heat flux and delays winter freezing of soils (Zimov et al. 1993).

In recent decades disturbance has increased at high latitudes. The area burned has doubled in western and central Canada (Flannigan and Van Wagner 1991), and 50-80% of Siberian forests have burned in the last 40 yr (Zimov et al. 1993), causing a shift from mosses to grasses and deciduous shrubs (Viereck 1973). Other disturbances include insect outbreaks, overgrazing by reindeer, and nitrogen deposition.

From June 1995 to the present we examined the relative impact of temperature and disturbance on the seasonal amplitude of carbon exchange in five undisturbed and five disturbed ecosystems in the forest tundra zone of northeast Siberia (69°N, 161°E) and in four disturbed and four undisturbed sites on

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the arctic coast 130 km to the north (70°N, 161°E). Daytime carbon gain in undisturbed ecosystems in the forest tundra zone (forest tundra, bog, wetland, and shrub tundra) was compensated by a similar seasonal pattern of nighttime CO₂ efflux. Consequently, average net daily flux was relatively small throughout the year. Disturbed sites differed from undisturbed sites during summer in having greater daytime CO₂ influx (2.1-2.5 fold), greater nighttime CO₂ efflux (1.8-2.6 fold), greater average daily CO₂ influx (1.6-3.0 fold), and a 6-wk shorter season of positive daytime carbon gain; winter respiration was also 4.3-fold greater in disturbed than in undisturbed sites. Thus, the seasonal amplitude of CO₂ exchange (integrated summer uptake minus integrated winter efflux) was 2.3-3.3 fold greater in disturbed than in undisturbed sites (Fig. 1, Table 1).

Average daily air temperature was warmer (11.3°C) and exceeded 0°C for two weeks longer in summer 1995 than in 1996 (9.2°C). June and July, when growth and photosynthesis were most active, were drier in 1995 (41 mm) than in 1996 (74 mm). Daytime carbon gain and growing-season net daily carbon gain were greatest in the cool wet year (1996), whereas nighttime carbon efflux was greater in the warmer summer (1995), suggesting that respiration correlated positively with temperature, whereas photosynthesis correlated positively with precipitation, as expected in the dry Siberian climate and as we observed previously (Zimov et al. 1996). These interannual differences were larger in the disturbed than in undisturbed sites. Positive daytime carbon gain began and finished earlier in the warmer year (1995) despite warm September temperatures in that year, resulting in a similar season length of positive carbon gain in the two years. Integrated daytime carbon gain over the growing season was 10-30% greater in the cold than the warm year, whereas nighttime CO₂ efflux was 20-80% greater in the warm than the cold year, suggesting that respiration had a greater influence than did photosynthesis on interannual variation in growing-season net CO₂ flux.

Within each year, maximum nighttime CO₂ efflux coincided with maximum air temperature, and maximum net carbon gain coincided with minimum temperature, similar to the temperature responses observed between years.

Daytime CO₂ influx, nighttime CO₂ efflux, and average daily carbon gain during summer at the cold arctic coastal site were similar to values in forest tundra, despite an 8°C cooler summer temperature on the coast. As in forest tundra, daytime carbon gain, nighttime carbon loss, and net carbon gain in summer in the arctic site were greater in disturbed than in undisturbed sites.

Our results show that disturbance greatly increased the seasonal amplitude of net carbon exchange and had as great an effect on this seasonal amplitude as did either interannual or geographic differences in growing-season temperature. Moreover, there was little difference between years in length of the season of positive carbon gain, despite a 2-wk difference in length

of time above 0°C, suggesting that the 1-2-wk increase in time above 0°C and in NDVI at high latitudes (Myneni et al. 1997) might have modest effects on seasonal amplitude of net CO₂ exchange.

The pattern of greater net carbon uptake in cold than in warm years is consistent with earlier observations of high efflux in warm summers (Oechel et al. 1993, Zimov et al. 1996). These results are logical consequences of the broad temperature response curve of photosynthesis in arctic plants and the enhancement of respiration in warm years due to reduced water-logging and/or the greater temperature sensitivity of respiration compared to photosynthesis. Thus, in the north it is unlikely that increased warming would directly enhance summer net CO₂ uptake. The disturbed sites showed greater difference in annual carbon exchange between warm and cold years (160 g C m⁻² yr⁻¹) than did the undisturbed sites (25 g C m⁻² yr⁻¹), suggesting that disturbance could greatly amplify the sensitivity of high-latitude carbon exchange to any future warming.

In summary, changes in species composition associated with disturbance could contribute substantially to the increased seasonal amplitude of atmospheric CO₂ and of NDVI. The strong mid-summer increase in NDVI (Myneni et al. 1997) matches our pattern of carbon exchange in disturbed sites. The higher soil fertility of disturbed sites might increase their responsiveness to atmospheric CO₂. Based on our observed differences in seasonal amplitude of carbon exchange between undisturbed and disturbed sites, we calculate that an approximate 20-30% increase in area disturbed could account for the observed 40% increase in seasonal amplitude of atmospheric CO₂ at high latitudes. If our results are representative, changes in high-latitude disturbance regime and associated species shifts could have as great an effect on CO₂ feedbacks to climate as would direct temperature effects on carbon exchange.

Methane flux

Summary: The sizes of major sources and sinks of atmospheric methane (CH₄), an important greenhouse gas, are poorly known. CH₄ from north Siberian lakes contributes ~2 Tg CH₄ yr⁻¹ to observed winter increases in atmospheric CH₄ concentration at high northern latitudes. CH₄ emitted from these lakes in winter had a radiocarbon age of 27,200 years and was derived largely from Pleistocene-aged carbon.

The highest concentration and greatest seasonal amplitude of atmospheric CH₄ occurs at 65-70°N. Concentrations are highest in March-April and lowest in summer (Fung et al. 1991). Photochemical oxidation of CH₄ contributes to the low summer levels (Khalil and Rasmussen 1983) but does not explain why the seasonal amplitude of atmospheric CH₄ is twice as high in the Northern than in the Southern Hemisphere, given large summer effluxes from

North American bogs and tundra (Reeburgh and Whalen 1992) and modest CH₄ fluxes from Siberian wetlands (Christensen et al. 1995). Between August and April, 5.8 Tg of CH₄ accumulates in the atmosphere north of 60°N. High-latitude winter fluxes measured previously were only 10-12% of the annual total (Whalen and Reeburgh 1988, Whalen and Reeburgh 1992), an insufficient flux to explain a winter maximum in atmospheric CH₄. Our research provides evidence for a large winter CH₄ source from Siberian lakes.

In the Pleistocene, most of the northern Siberian plains were unglaciated and accumulated ~400,000 Tg of organic carbon in sediments (mainly derived from plant roots), similar to the total carbon in the terrestrial biosphere. These sediments contained abundant ice (40 to 70% of soil volume), which began melting during the Holocene to form thermokarst (thaw) lakes that now make up ~30% of the landscape. These lakes migrated across the north Siberian plains during the Holocene, releasing to the atmosphere an average of 170-220 g C m⁻² yr⁻¹, including ~16 g CH₄ m⁻² yr⁻¹; we estimate that half of this CH₄ was derived from Pleistocene carbon. Siberian lake sediments produce CH₄ bubbles in lakes throughout the year (Zimov and Govorushko 1979), particularly near shores with active erosion. During winter, the bubbles form koshtas, which are flat bubbles of CH₄ in lake ice separated by ice films that periodically sublime and release CH₄ to the atmosphere. In areas where CH₄ ebullition (bubbling) is most active, channels through the ice remain open all winter.

To evaluate the significance of this source, we incubated Pleistocene sediments from an eroding lakeshore with lake water. The yield was 65±3 mg CH₄ g⁻¹ sediment at 15°C (mean ± SE, n=3) over 12 months, equivalent to 5% of the carbon originally present in the soil; 26±2 mg CH₄ g⁻¹ were emitted at 3.5°C, and 19±2 mg CH₄ g⁻¹ were emitted at 0°C. These data indicate that the carbon in Pleistocene sediments is sufficiently labile to support methanogenesis and that, although methanogenesis is temperature-sensitive, it occurs at substantial rates at 0 to 3.5°C.

To test whether methanogenesis in lake sediments is currently fueled by Pleistocene-aged organic matter, we measured stable and radiocarbon isotopes of CH₄ emitted by ebullition from two representative thaw lakes near Cherskii, Republic of Sakha (Yakutia), Russia (69°N, 161°E). CH₄ collected from these lakes in winter (April) had an average ¹⁴C age of 27,200 yr. This age indicates that Pleistocene sediments deposited 20,000-40,000 ¹⁴C years ago contributed 68-100% of CH₄ flux from these lakes. In contrast, CH₄ emitted in the summer (July) had an average ¹⁴C age of 9,200 yr, indicating that Pleistocene carbon fueled 23-46% of summer methanogenesis and thus that more CH₄ was produced in the younger surface sediments, which are warmer in summer than winter. Thus about half of current annual methanogenesis is

fueled by Pleistocene carbon. In contrast, CH₄ from Alaskan lakes was only 200 yr old because Alaska lacks extensive Pleistocene sediments.

The $\delta^{13}\text{C}$ value of CH₄ collected from Siberian lakes was -71 to -73. This value is less than that produced in summer by Alaskan tundra lakes or North American wet tundra. These values imply that the Siberian winter-collected CH₄ was not as oxidized as in these other environments, or that there was an isotopic difference in substrate or a different pathway of methanogenesis. The hydrogen isotopic composition of the CH₄ was variable, but most samples from the Siberian lakes were low ($\delta\text{D} = -370$), indicative of a biotic source for CH₄, low oxidation rates in the water column, and CH₄ production by fermentation.

We measured CH₄ ebullition fluxes from two thaw lakes using large funnels suspended beneath the ice. CH₄ fluxes were generally highest from October to January, when deep sediments had their annual thermal maximum. Fluxes were highly variable within a season; fluxes were highest at times of low atmospheric pressure, as in north temperate lakes. The average CH₄ ebullition flux in centers of lakes was $4.7 \pm 2.3 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$. Near eroding lakeshores, fluxes were so high that they frequently overturned the collection funnels; the flux emitted from open holes in the ice was $56 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$. In addition to open holes, there were koshkas containing 1-100 l of 50% CH₄ that vent CH₄ several times each winter and provide an additional unquantified CH₄ source. Sediments in these lakes released $22 \text{ g CH}_4 \text{ m}^{-2}$ in September, when we disturbed the sediments, but $<5 \text{ g CH}_4 \text{ m}^{-2}$ a month later. This large CH₄ release over one month provides independent evidence for a large CH₄ ebullition flux.

CH₄ can also move to the atmosphere in winter in overflow, when the weight of winter snow pushes the ice below the equilibrium water level of the lake. The CH₄ concentration in overflow water decreases from $1.7 \text{ mg CH}_4 \text{ l}^{-1}$ to $<0.01 \text{ mg CH}_4 \text{ l}^{-1}$. The 30 cm of overflow that typically accumulate on lakes of the forest zone would thus release 0.52 g of dissolved CH₄ $\text{m}^{-2} \text{ yr}^{-1}$.

The average summer diffusive flux measured in 19 lakes along a climate transect inland from the Arctic Ocean was $7.6 \pm 1.4 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$, a value similar to that in Alaskan lakes. The 19 lakes had $3.1 \pm 0.7 \text{ mg m}^{-2}$ of dissolved CH₄ in March, indicating that winter accumulation of CH₄ is typical of north Siberian lakes.

We estimate the total annual flux of CH₄ for the lakes in our study region to be at least $7 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$, ~50% of the potential flux we estimated ($16 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$) from regional carbon inputs to lakes. Approximately 75% of this flux occurs in winter. If these fluxes are typical of Siberian lakes, these lakes would emit ~1.5 Tg CH₄ in winter (2 Tg CH₄ annually). This is small relative to

global sources (Cicerone and Oremland 1988) but is 25% of the high-latitude winter accumulation of CH₄ in the atmosphere. If high-latitude warming trends (Chapman and Walsh 1993, Serreze et al. In press) continue, thawing of permafrost would increase, and methane flux from Siberian thaw lakes would act as a positive feedback to climate warming.

Structural accomplishments

In addition to the research findings of the past three years, there have been several tangible advances in the structural capabilities to do global-change research in Russia that have resulted from our DOE research. This research built on a pre-existing monitoring program of CO₂ exchange in forest tundra initiated by Zimov and colleagues in 1989. The DOE research enabled him to continue these measurements with improved instrumentation (Licor 6200 portable infrared gas analyzer) and to expand his monitoring of CO₂ exchange from a single forest-tundra site to 10 sites that include all the major ecosystem types of northern Siberia (see research results). Carbon exchange has been measured at weekly intervals throughout the annual cycle since June 1995 and will continue to be monitored in the future. The 9-yr data base for forest tundra is the longest record of regular carbon exchange measurements that we are aware of in any ecosystem. We have developed an AVHRR-based vegetation map of the Kolyma lowlands, from which we will estimate regional carbon exchange.

Our DOE research program contributed substantially to the role that Zimov and the Northeast Science Station can contribute to international research on global change. His station now has several computers and email and internet access. During the year that Zimov and his wife (also a researcher at the Northeast Science Station) spent in Berkeley, they substantially improved their English and became proficient in use of spreadsheet and graphics programs. Zimov presented his work at two meetings and established a new research collaboration with S. Tyler to monitor concentrations and isotopic composition of atmospheric CO₂ and CH₄ in Cherskii.

The DOE research also enabled Chapin to learn considerably more about the ecology of Siberia, its Pleistocene history, and the factors that might govern its future trace-gas feedbacks to climate. Discussions with Zimov and colleagues provided Chapin with a much broader intellectual framework from which to think about terrestrial feedbacks to climate.

Remaining funds

All funds awarded in this grant were spent.

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