

Scientific paper

Arctic hot and CO₂ springs: Natural models of impact of climate change on terrestrial ecosystems

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Abstract: The main purpose of this research was to investigate the carbon cycle in tundra ecosystems in the vicinity of hot springs as natural models of Global Warming and elevated atmosphere CO₂. Empirical data on ecosystem CO₂ fluxes, plant photosynthesis and respiration, vegetation and soil composition were obtained during field expeditions on the Chukotskiy Peninsula (Russia) in 1997 (Chaplino hot springs, 64°26'N, 172°30'W) and 1998 (Ioni hot and CO₂ springs, 65°48'N, 173°22'W). It was found that the influence of naturally increased temperature on carbon exchange considerably depends on the ecosystem type. Under elevated soil temperatures wet sedge ecosystems tend to increase their production, plant biomass, and, to some extent, soil carbon storage. Both species composition and carbon cycle parameters in more drained shrub ecosystems are less sensitive to elevated temperature in the immediate vicinity of the hot springs. Natural CO₂ enrichment of canopy air near the hot springs promotes reduction of photosynthetic efficiency in the studied plant species.

1. Introduction

A growing set of problems connected with the increase of greenhouse gases in the atmosphere and global warming requires further acceleration of investigations of carbon cycling in the biosphere. Long-term decadal to age-long effects of global change are now in focus. How will primary production and respiration change, what are the anticipated trends in ecosystem carbon stocks, and could natural ecosystems effectively compensate for a climate change event? A wide range of scientific approaches is required to answer these questions. One possible way is to study hot and CO₂-springs as a natural model of global change. Since the early nineties this research field has grown rapidly. Studies were carried out in different biomes (Koch, 1993; Körner and Miglietta, 1994, and others), though with a lack of data on northern ecosystems (Cook *et al.*, 1998). Within the tundra biome area, the Chukotskiy Peninsula in the Far East of Russia is known to be the richest in geothermal springs. The goal of the present study is to compare the carbon stocks and fluxes in hot springs-affected tundra ecosystems with adjacent permafrost ecosystems as controls.

2. Methods

Areas with hot spring surface activity are located only in the eastern part of the Chukotskiy Peninsula. Two summer expeditions were conducted to study hot springs: in 1997 (Chaplino, 64°26'N, 172°30'W) and 1998 (Ioni lake, 65°48'N, 173°22'W). The recorded surface water temperatures in the springs was as great as +90°C. The permanent geothermal heating causes elevated temperature in soil horizons. The temperature was as much as +30°C in the upper 10 cm, higher deeper layers. Some of the Ioni springs have 24% carbon dioxide dissolved in surface water, which results in CO₂ concentration up to 600 ppm in the adjacent air.

Sampling plots were situated in typical tundra habitats on permafrost (control) and in the ecosystems affected by hot springs with no permafrost. In addition, we distinguished wet sedge and mesic shrub habitats. Four different sites were established in 1997 (temperature-affected sedge and shrub sites, and control sedge and shrub sites) and 5 in 1998 (the same sites and CO₂/temperature-affected sedge site in addition). The vegetation in the sedge sites located near hot springs was composed of *Carex cryptocarpa*, whereas *C. aquatilis* and *C. lugens* dominated at the control sites. The temperature-affected and control shrub sites were characterized by similar shrub species composition (*Betula exilis*, *Salix pulhra*, *S. chamissonis*, *S. reticulata*). The sedge species composition at these sites was different.

A portable infrared CO₂-analyzer "Li-Cor 6200" and the ecosystem closed chamber method (Vourlitis *et al.*, 1993) were applied to measure net ecosystem carbon flux (NF) and gross respiration (GR). CO₂ flux measured under natural illumination was taken to be an estimate of net ecosystem flux, whereas the rate of CO₂ flux in the darkened chamber served as a measure of gross respiration. Gross primary production (GPP) was calculated as a difference between these two fluxes. We used acrylic chambers 42 × 42 cm base and 30 cm height, transparent to photosynthetically active radiation. Seasonal carbon fluxes were calculated for 34-day periods, when the living phytomass reserves were maximal. A more detailed description of the measuring technique is given by Zamolodchikov *et al.* (2000).

Photosynthesis and respiration of the dominant plant species were determined using standard leaf cuvettes. Gas exchange measurements of plant leaves were started under ambient CO₂ concentration and canopy temperature. During these measurements the average CO₂ concentration in the leaf cuvette was about 340 ppm in all studied species with exception for *Carex cryptocarpa* at the CO₂-enriched site (351 ppm).

The above-ground plant biomass was harvested on completion of the seasonal carbon flux measurements. Soil carbon reserves in the ecosystems were estimated using original data on thickness of soil horizons, bulk density and carbon content in soil samples.

Leaf photosynthesis response to photosynthetically active radiation (PAR) was approximated using the classical two parametrical hyperbolic formula by Monsi and Saeki (1953). Leaf respiration response to air temperature was described by two parametrical exponential equations (Lloyd and Taylor, 1994). The parameters of the equations were estimated using non-linear regression fitting.

3. Results and discussion

Before discussing the results of carbon flux measurements, it is important to characterize the principal ecological differences between the studied ecosystems. The mean seasonal air temperature in the canopy did not differ significantly in the control and hot springs ecosystems ($P=0.2$), averaging 10°C. Mean seasonal soil temperature at the depth of 10 cm was about 5°C at the control sites and 13°C at the temperature-affected sites ($P<0.01$). Both CO₂ and temperature-affected sites demonstrated maximum soil temperature at depth 10 cm (25°C). Thus, the geothermal influence resulted in increased soil temperature, but did not lead to noticeable changes in the canopy air temperature. The sedge sites had significantly greater ($P=0.03$) average volumetric soil moisture in the upper 10 cm (74%), compared to the shrub ecosystems (57%). The average seasonal water table was also higher in the sedge habitats. The carbon dioxide concentration above the plant canopy in the CO₂-enriched ecosystem fluctuated from 390 to 450 ppm, depending on wind speed and direction. The mean seasonal increase of canopy air CO₂ concentration in this ecosystem over the other habitats was 36 ppm.

Figure 1 summarizes seasonal GPP and GR rates in the sedge and shrub ecosystems averaged for both seasons (CO₂-enriched sedge site is not included). It can be seen that the wet sedge ecosystems increased their production ($R=0.91$) and respiration ($R=0.85$) rates under elevated temperature, whereas the drier shrub ecosystems did not show any clear trends ($R=0.07\div 0.35$). In other words, the response of plant carbon exchange to elevated soil temperature depends on the ecosystem type. These trends in carbon fluxes are similar

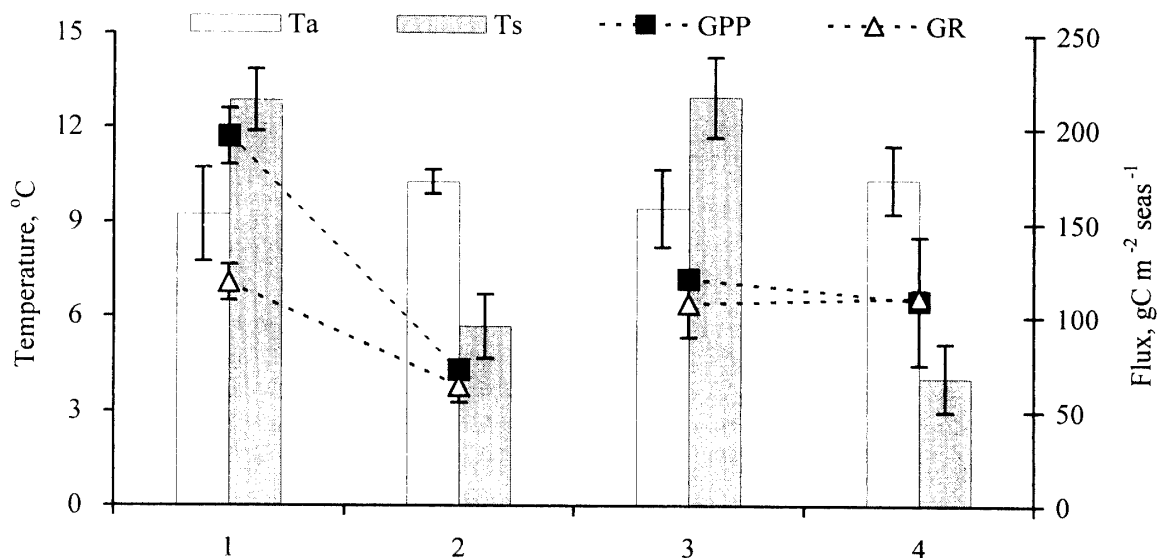


Fig. 1. Mean seasonal values of gross primary production (GPP), gross ecosystem respiration (GR), air temperature in a canopy (Ta) and soil temperature at the depth of 10 cm (Ts) in the studied ecosystems. The ecosystems are (1) wet geothermal with sedge dominance, (2) wet control with sedge dominance, (3) mesic geothermal with shrub dominance, and (4) mesic control with shrub dominance. Data are means \pm standard errors.

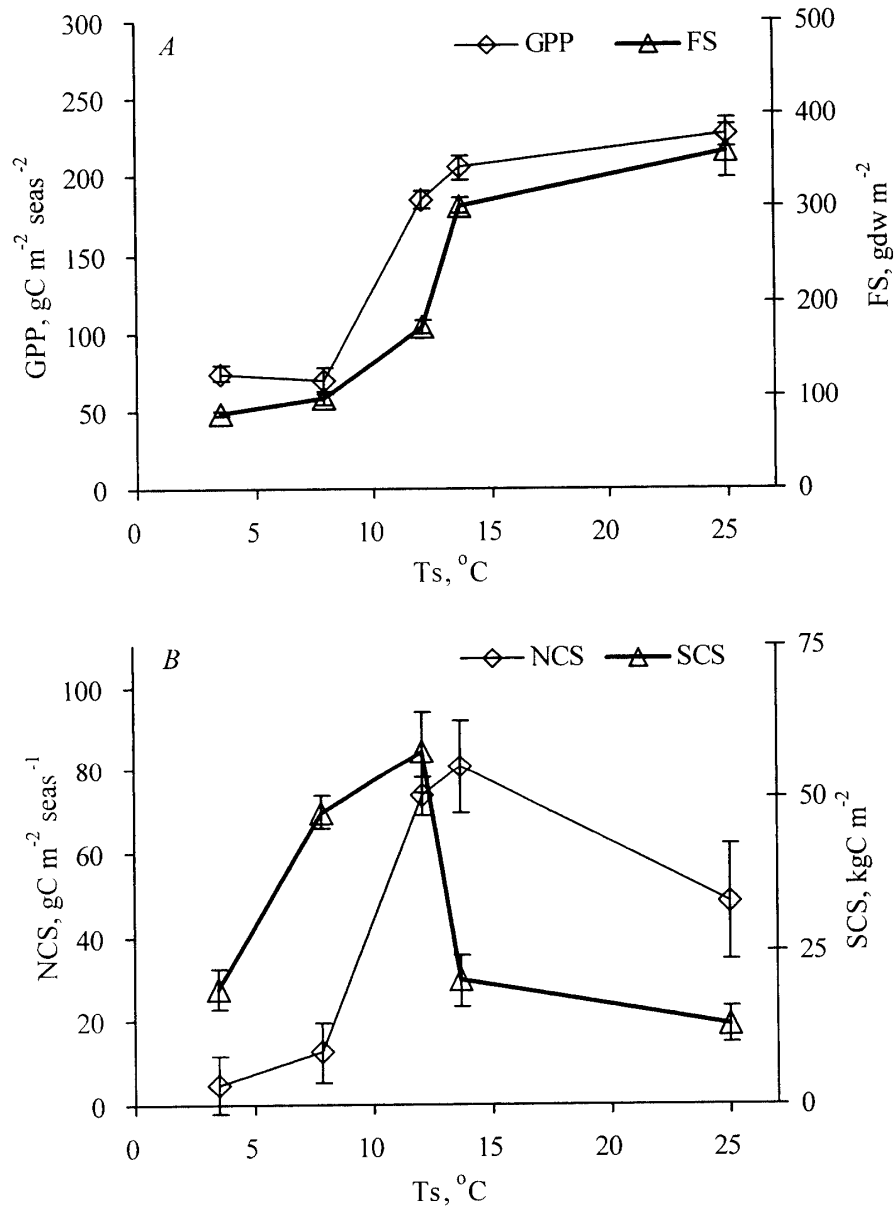


Fig. 2. The relationship between mean seasonal soil temperature at the depth of 10 cm (T_s) and carbon/phytomass parameters in different sedge ecosystems. The parameters are gross primary production rate (GPP, left axis, A), storage of foliage of vascular plants (FS, right axis, A), net carbon sink (NCS, left axis, B), and soil carbon storage (SCS, right axis, B). Each of the data points represents individual site. Data are means \pm standard errors.

to the dependencies shown in manipulation experiments (Johnson *et al.*, 1996; Oechel *et al.*, 1998). The rates of GR and GPP CO_2 fluxes in the shrub permafrost habitats are significantly higher compared to the sedge control sites, whereas the reverse takes place in the geothermal ecosystems.

Figure 2 shows the responses of GPP, net carbon flux, foliage biomass of vascular plants, and soil carbon storage to soil temperature in the sedge ecosystems, including the

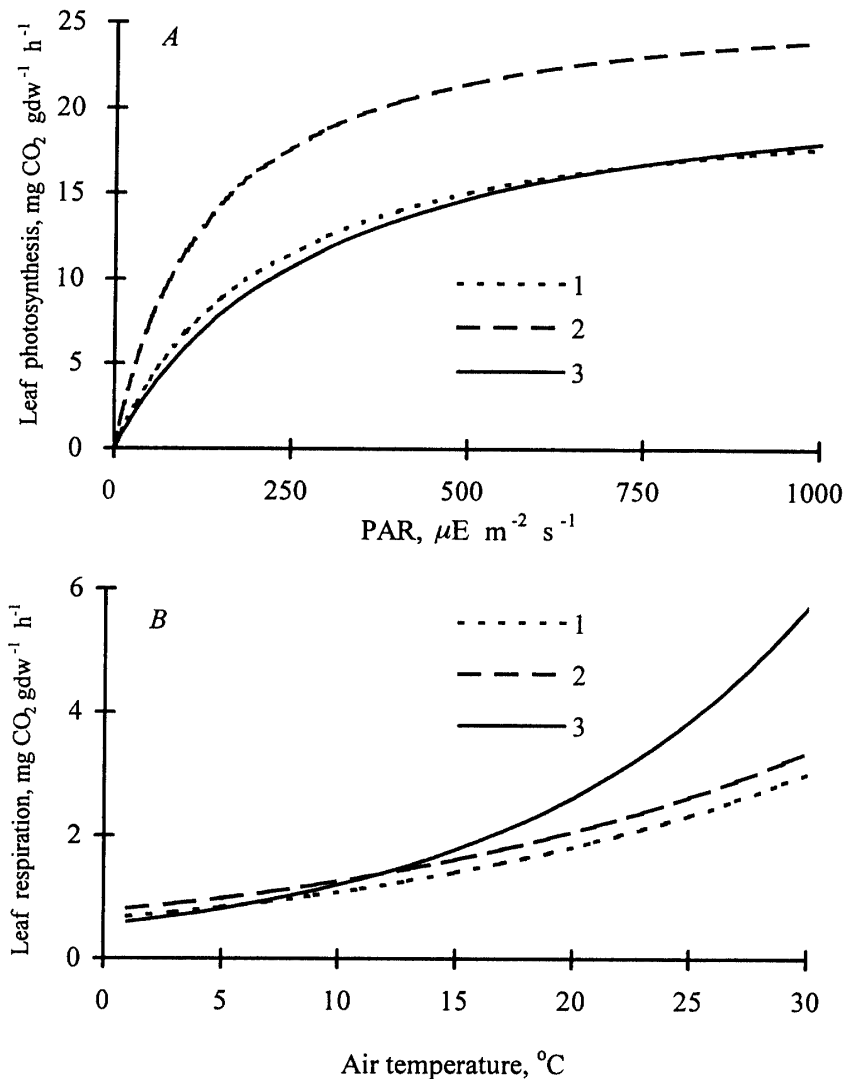


Fig. 3. Leaf photosynthetic response to ambient PAR (A) and leaf respiration response to air temperature (B) of *Carex cryptocarpa* (geothermal site with naturally elevated CO₂ and soil temperature, (1); geothermal site with naturally elevated soil temperature, (2)) and *C. lugens* (control site, (3)). Measurements of all plants were made in similar CO₂ conditions (340–350 ppm). Values of R^2 in non-linear approximations were estimated at 0.89–0.98 for leaf photosynthesis and 0.86–0.87 for leaf respiration ($n=54 \div 57$).

CO₂-enriched site. One can see that the increase in soil temperature stimulates the growth of foliage biomass ($R=0.92$). The rates of production ($R=0.93$) and respiration ($R=0.95$) are both well correlated with the biomass. However, foliage biomass in the shrub ecosystems does not depend on soil temperature ($R=0.27$).

Most of the carbon in the studied ecosystems is stored in the underground components. Within a 3–12°C range of average summer soil temperatures at depth 10 cm, the soil carbon storage is greater in the wet ecosystems under higher temperatures. However, it is smaller in ecosystems under temperatures higher than 12°C (Fig. 2B). Hence, we may consider this soil temperature as optimal for carbon storage in wet ecosystems. Differences in soil carbon

storage agree with measured seasonal net carbon fluxes, which also decrease under higher temperatures. The soil carbon storage at the control shrub site was 1.6 times less than in the temperature-affected shrub ecosystem (1997).

The respiration characteristics of *C. cryptocarpa* were not affected by long-term CO₂ enrichment in the canopy, whereas the efficiency of its photosynthesis decreased (Fig. 3). These findings are consistent with the results of other studies on long-term natural CO₂ enrichment both in the vicinity of hot springs and in experiments (Cook *et al.*, 1998; Hilbert *et al.*, 1987; Oberbauer *et al.*, 1986; Oechel *et al.*, 1994; Tissue and Oechel, 1987). The observed increase in GPP at the CO₂- and temperature-affected site (Fig. 2A) is due to the significant increment of green above-ground plant biomass, which, in turn, is mostly related to the elevated soil temperature.

The respiration response of the control sedge species (*C. lugens*) to temperature rise was steeper than that of geothermal species *C. cryptocarpa* (Fig. 3). The same was characteristic of other studied plant species: the originally arctic species were less economical under higher temperatures in comparison with *C. cryptocarpa*. Long-term adaptation of these species (*Betula exilis*, *Salix chamissonis*, *S. pulhra*, *Empetrum hermafroditum*) is not accompanied by considerable changes in respiration; instead, these species increase their photosynthetic efficiency.

4. Conclusions

- The influence of soil temperature on carbon exchange parameters of tundra ecosystems strongly depends on ecosystem type (species composition, hydrological pattern, etc.).
- There is a tendency in wet sedge ecosystem under elevated soil temperature for increase of gross primary production, above-ground plant biomass and, to some extent, soil carbon storage.
- Both species composition and carbon cycle parameters in more drained shrub ecosystems are less reactive to elevated temperature.
- CO₂ enrichment in a canopy reduces the photosynthetic efficiency of the studied plant species.

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