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Soil respiration in a high arctic glacier foreland in Ny-Ålesund, Svalbard

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Abstract: Soil respiration rates were measured in a successional glacier foreland in Ny-Ålesund, Svalbard, and the amount of CO_2 efflux during the plant-growing season was estimated using a simple regression model. Three study sites (Site 1, Site 2 and Site 3) were set up along with the primary succession in the deglaciated area of East Brøgger Glacier in Ny-Ålesund, Svalbard, Norway (79°N 12°E). Another study site, Site RB, was set up on a riverbed in the Bay River between Site 2 and Site 3. Soil respiration (SR), air temperature at 10 cm height (AT), soil surface temperature (SST) and soil temperature at 1 cm depth (ST) were measured at the four study sites with an open-airflow system using an infra-red gas analyzer from July to August, 1995. The mean soil respiration rate varied among the four sites: 6.2, 44, 63 and 3.7 mg CO_2 $m^{-2}h^{-1}$ at Site 1, Site 2, Site 3 and Site RB, respectively. These differences in the soil respiration rate among the four sites corresponded with the soil organic amount, microbial biomass, and root biomass. The soil respiration rate showed the best correlation with AT at Site 1, Site 2 and Site RB, and with ST at Site 3. The cumulative amount of CO_2 efflux calculated using correlation equations obtained from the above relationships between SR and AT or ST was 5.8, 46, 69 and 3.3 g CO_2 m^{-2} at Site 1, Site 2, Site 3 and Site RB, respectively, for two months (from July to August, 1995). These values were extremely low compared to those of warmer ecosystems, such as low-arctic tundra, temperate mixed forests, and tropical moist forests.

key words: high arctic, primary succession, soil respiration rate

Introduction

It is generally anticipated that global warming will stimulate soil microbial activity and the decomposition rate of soil organic matter. As arctic ecosystems have large carbon pools in permafrost (Oechel and Vourlitis, 1994) and the arctic is predicted to receive greater-than-average climate warming, the increase in the decomposition rates in these areas may result in a large release of CO_2 to the atmosphere as soil respiration. The increase in soil respiration could affect the regional and possibly global carbon cycle and climate (Oechel and Vourlitis, 1994). Thus, an understanding of the controls of the soil respiration rate is important to estimate the effect of warming on the carbon cycle in arctic ecosystems. There have been numerous reports on the soil respiration rate in sub- or low-arctic ecosystems (Grogan and Capin III, 1999; Sommerkorn *et al.*, 1999; Rustad *et al.*, 2001; Sjögersten and Wookey, 2002), but there are relatively few about the high-arctic (Rustad *et al.*, 2001; Elgerling, 2003); in particular, there are none at all on the primary successional series on the high-arctic glacier foreland. Under the current increase in deglaciated area in polar and high altitude areas, evaluating soil respiration rate and carbon cycle in the high-arctic glacier foreland has been increasing in importance for predicting the future global carbon cycle. In order to examine the soil respiration and carbon cycle in the deglaciated area, comparison between different successional stages is effective because the deglaciated area is extremely spatially heterogeneous. The objectives of this study were (1) to determine the environmental factors controlling the soil respiration rate and (2) to estimate the amount of CO_2 emitted as soil respiration from different stages in a primary succession at a high-arctic glacier foreland in Ny-Ålesund, Svalbard. This study is part of a larger study examining the process and function of carbon cycling in the arctic primary succession (Nakatsubo *et al.*, 1998; Bekku *et al.*, 1999; Uchida *et al.*, 2002; Muraoka *et al.*, 2002).

Materials and methods

The study area is located at the front of East Brøgger Glacier in Ny-Ålesund, Svalbard, Norway (79°N 12°E). The growing season is from early July, when the snow cover disappears, to late August, when the first snow falls. The annual mean air temperature and annual precipitation in this area are −5.7°C and 487 mm, respectively (source: Norsk Polarinstitutt). Three study sites were set up along a primary successional series on different aged moraines in the deglaciated area of the East Brøgger Glacier (Fig. 1). Site 1, situated just in front of the glacier toe, became ice-free only recently (within 30 years) and has little plant cover. Site 2 is on a moraine with a few scattered vegetation patches (mainly *Saxifraga oppositifolia* L., *Poa alpina* L., and *Draba* spp.). Site 3 is located on a small moraine that became ice free more than 2000 years ago. At Site 3, approximately 17% of the ground surface is bare, 30% is covered with algal crust, and 53% is covered with bryophytes (mainly *Sanionia uncinata* (Hedw.) Loeske, *Hylocomium splendens* (Hedw.) Schimp, and *Aulacommium turgidum* (Wahlenb.) Schwaegr) and vascular plants (mainly *Salix polaris* Wahlenb, *Luzula confusa* Lindeb. and *Poa alpina*, L.). Soils at these sites are regosolic cryosols. In addition, one study site was set on a Bay River riverbed located between Site 2 and Site 3. The riverbed occupied a relatively large area in the deglaciated area of the East Brøgger Glacier (Fig. 1). The riverbed site (Site RB) is covered with gravel and sand but not with organic soil and plants. A more detailed description has been given in former reports (Minami *et al.*, 1996; Nakatsubo *et al.*, 1998).

The soil respiration rate (SR) was continuously measured with an open-airflow system (OF-method) using an infra-red gas analyzer (Bekku *et al.*, 1997) for 24 to 36 hours for one measurement at the four study sites from July to August, 1995. The SR

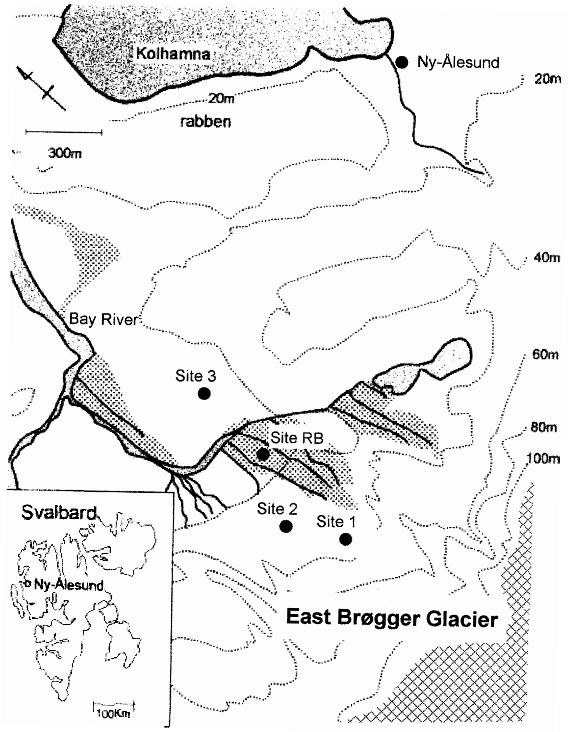

Fig. 1. Study area in Ny-Ålesund, Svalbard. The dotted area around the Bay River indicates the riverbed. The gray-meshed area indicates the approximate location of East Brøgger Glacier.

measurements with the OF-method replicated 2 to 3 times at each study site. In order to determine the spatial variations of SR, SR was measured by the dynamic closed chamber method (DC-method) with a portable soil respiration system (LI-6200 with 6000-09 soil chamber, LI-COR Inc., Lincoln, NE, USA) at six points randomly selected at the respective site. The air temperature at 10 cm height from the soil surface (AT), soil surface temperature (SST) and soil temperature at 1 cm depth (ST) were measured simultaneously with a copper-constantan thermocouple during the soil respiration measurements.

Results and discussion

Figure 2 shows diurnal changes in the soil respiration rate (SR) measured by the OF-method and SR measured by the DC-method at the four study sites. The SR measured by the DC-method was consistent with those measured by the OF-method at all sites (Fig. 2). This indicates that these SR values measured by both methods are reliable at all sites. The coefficients of variation of the SR measured by the DC-method were 33, 39, 27 and 58% at Site 1, Site 2, Site 3 and Site RB, respectively.

The SR measured by the OF-method increased from Site 1 to Site 3: the mean values of the SR were 6.2, 44 and 63 mg CO_2 $m^{-2}h^{-1}$ at Site 1, Site 2 and Site 3,

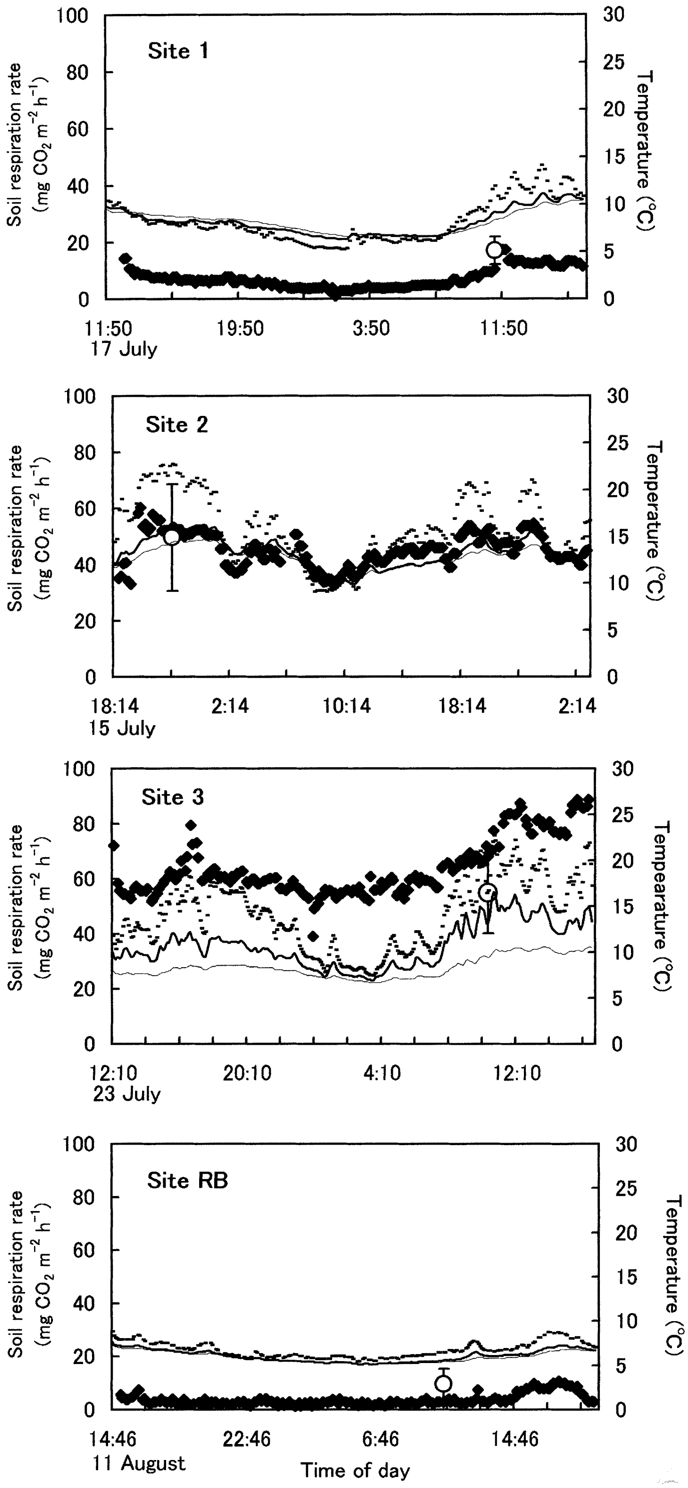

Fig. 2. Diurnal changes in the soil respiration rate at the four study sites. Solid diamonds indicate the rates measured by the OF-method. Open symbols show the rates measured by the DC-method. ----, air temperature at 10 cm height from the soil surface (AT); ——, soil surface temperature (SST); ——, soil temperature at 1 cm depth (ST).

respectively (Fig. 2 and Table 2). In a previous study, carbon and nitrogen contents in soils sampled from the same point as the SR measurements increased with the progress of succession: 1.6% and 0.02% at Site 1, 1.8% and 0.05% at Site 2, 7% and 0.37% at Site 3 (Bekku *et al*., 1999). Bekku *et al*. (1999) also reported that soil microbial biomass in this study area increased from 0.06 mg C g^{-1} soil d.w. at Site 1 to 0.33 mg C g^{-1} soil d.w. at Site 3 with successional age. Nakatsubo *et al*. (1998) reported that the contributions of root respiration to total soil respiration rate at Site 1, Site 2 and Site 3 were 0%, 0.1% and 29%, respectively. Thus, the increase in SR among the three sites reflects successional increases in the amount of soil organic matter, soil microbial biomass and root respiration.

On the other hand, the mean SR at Site RB was 3.7 mg CO_2 $m^{-2}h^{-1}$, which was lower than that at Site 1. This smallest SR value among the four sites can be attributed to the lack of vegetation and decreased deposition of organic soil resulting from frequent disturbance by flood. Actually, the soil carbon and nitrogen contents and microbial biomass at Site RB were smallest among the four study sites: 1.4%, 0.004%, and 0.06 mg C g^{-1} soil d.w., respectively. The root respiration at Site RB could have been negligible because there was no vegetation cover.

The SR measured by the OF-method showed an apparent diurnal change at the four sites, and corresponded with the change in air temperature 10 cm above the soil surface (AT), soil surface temperature (SST) and soil temperature at 1 cm depth (ST) (Fig. 2). Table 1 shows the results of regression analysis between soil respiration rate and temperature factors, AT, SST and ST. The soil respiration rates were better fitted with exponential regression equations than with linear equations at all sites. Among the three temperature factors, AT best explained the temporal variations in SR at Site 1 ($R^2=0.826$, $P<0.0001$), Site 2 ($R^2=0.728$, $P<0.0001$) and Site RB ($R^2=0.538$, $P<0.0001$) (Table 1 and Fig. 3). At Site 3, the SR was best fitted with ST ($R^2=0.792$, $P<0.0001$) (Table 1 and Fig. 3). These results show that the temporal variations in soil respiration rate at Site 1, Site 2 and Site RB where there was little or no vegetation could be predicted by AT, and SR at Site 3 where more than 80% of the soil surface was covered

Table 1. Regression equations between soil respiration rate (SR) and temperatures.

Site 1	SR = 1.42 exp (0.186 AT)	$R^2=0.826$	$P<0.0001$
	SR = 0.556 exp (0.304 SST)	$R^2=0.817$	$P<0.0001$
	SR = 0.438 exp (0.331 ST)	$R^2=0.697$	$P<0.0001$
Site 2	SR = 25.6 exp (0.0341 AT)	$R^2=0.728$	$P<0.0001$
	SR = 17.8 exp (0.068 SST)	$R^2=0.632$	$P<0.0001$
	SR = 13.2 exp (0.0947 ST)	$R^2=0.603$	$P<0.0001$
Site 3	SR = 40.7 exp (0.0314 AT)	$R^2=0.611$	$P<0.0001$
	SR = 35.2 exp (0.0545 SST)	$R^2=0.720$	$P<0.0001$
	SR = 23.3 exp (0.119 ST)	$R^2=0.792$	$P<0.0001$
Site RB	SR = 0.198 exp (0.416 AT)	$R^2=0.538$	$P<0.0001$
	SR = 0.194 exp (0.467 SST)	$R^2=0.389$	$P<0.0001$
	SR = 0.218 exp (0.456 ST)	$R^2=0.278$	$P<0.0001$

AT, SST, and ST mean air temperature at 10 cm height from soil surface, soil surface temperature, and soil temperature at 1 cm depth, respectively.

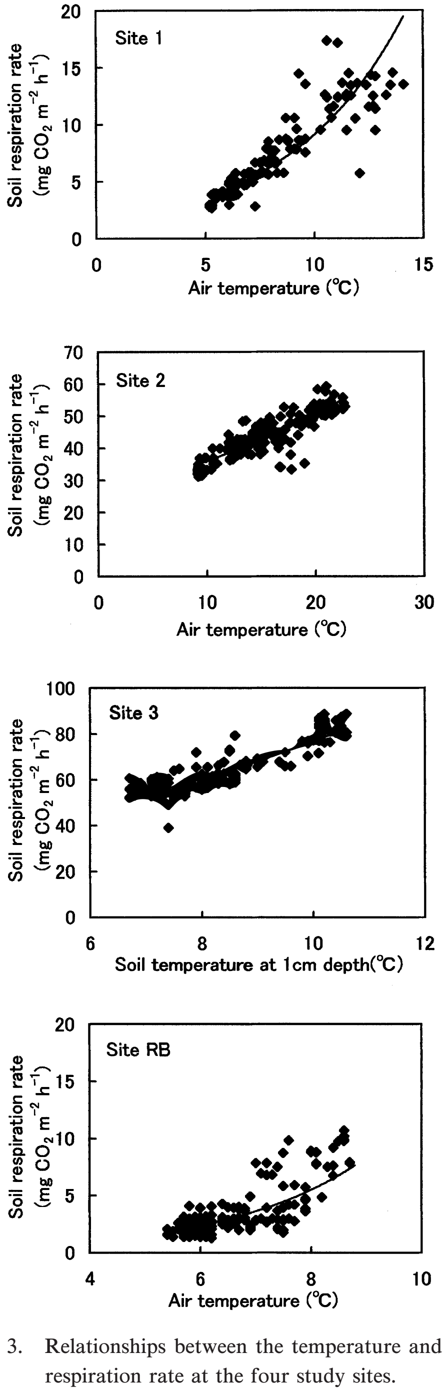

Fig. 3. Relationships between the temperature and soil respiration rate at the four study sites.

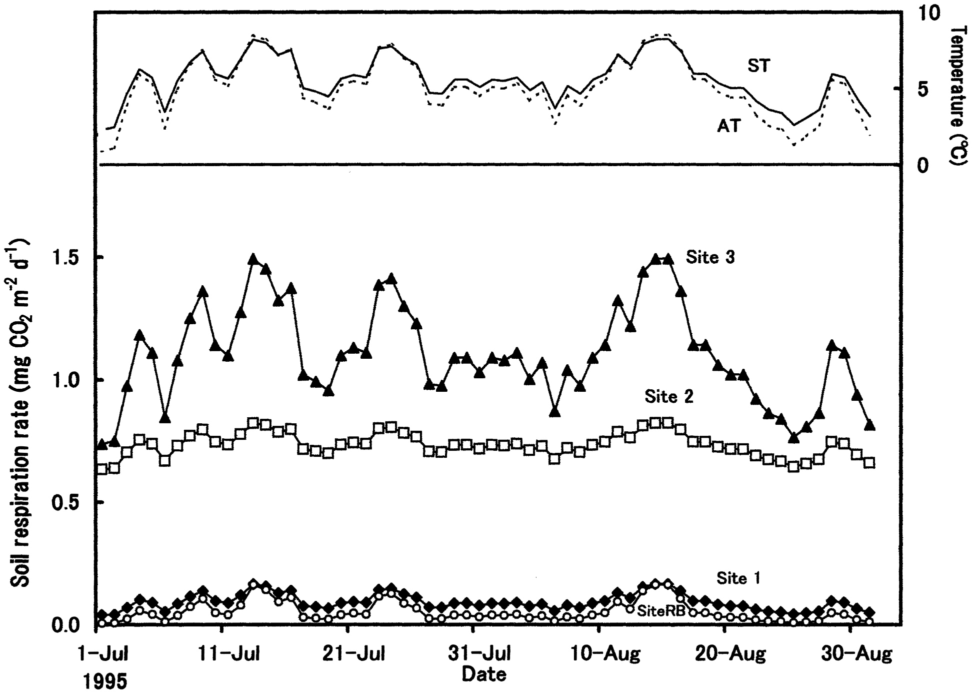

Fig. 4. Seasonal change in the soil respiration rate estimated by the best regression equations in Table 1 and temperature data from early July to the end of August, 1995. ○, SR at Site RB; ◆, SR at Site 1; □, SR at Site 2; ▲, SR at Site 3; ----, Air temperature at 10 cm height (AT); ——, Soil temperature at 1 cm depth (ST).

with vegetation could be predicted by ST.

Figure 4 shows a seasonal change in the daily soil respiration rate calculated using the best fitted equations in Table 1 and the data of AT and ST at the four study sites from early July to the end of August, 1995. The estimated SR corresponded well with the change in the temperatures (AT and ST) at the four study sites. This is to be expected because the models for estimation were a simple regression equation considering only temperature. The estimated SR at Site 3, however, fluctuated more than those at other sites. The estimated SR at Site 2 was much higher than that at Site 1, whereas the soil properties and vegetation at Site 1 and Site 2 are more similar than those at Site 2 and Site 3 (Nakatsubo *et al.*, 1998; Bekku *et al.*, 1999). These trends in the estimated SR are related to the larger values of the y-intercept and/or the temperature coefficient in the regression equations at Site 2 and Site 3 (Table 1). The values of the y-intercept and the temperature coefficient indicate respiration rate at 0°C and temperature sensitivity, respectively. Thus, the larger y-intercepts at Site 2 and Site 3 might indicate larger microbial biomass or larger biomass-specific respiration rate. Whereas the y-intercepts were similar at Site 2 and Site 3, the temperature coefficient was much different between the two sites. This might indicate a difference in respiratory properties of microbial communities between Site 2 and Site 3. Though the causes of the difference in the

Table 2. Mean soil respiration rate in the growing season and the amount of CO_2 evolved from soil from July to August in different ecosystems in the world.

Ecosystem	Place	Mean SR ($mg\ CO_2\ m^{-2}\ h^{-1}$)	CO_2 evolved ($g\ CO_2\ m^{-2}$ 2moths^{-1})	Exp. Period	Method	Reference
Tropical moist forest	Panama	na	1361	1983–1986	OF&DC	Kursar (1989)
Temperate deciduous forest	Ottawa	na	920	1992	DC	Lessard et al. (1994)
Temperate mixed forest	Massachusetts	na	640	1991	AB	Bowden et al. (1993)
Tall-grass prairie	Kansas, USA	na	982	1991	AB	Grahammer et al. (1991)
Low-arctic tundra	Alaska	na	555–686	1992	DC	Oberbauer et al. (1992)
Low-arctic shrub tundra	Fairbanks, Alaska	nd	935	1996–1997	SD	Grogan and Capin III (1999)
Low-arctic tussock tundra	Toolik, Alaska	nd	623	1996–1997	SD	Grogan and Capin III (1999)
Low-arctic tussock tundra	Sagwon, Alaska	nd	807	1996–1997	SD	Grogan and Capin III (1999)
Low-arctic wet-sedge tundra	Toolik, Alaska	132	nd	na	na	Rustad et al. (2001)
Low-arctic dry-heath tundra	Toolik, Alaska	202	nd	na	na	Rustad et al. (2001)
Low-arctic moist tussock tundra	Toolik, Alaska	378	nd	na	na	Rustad et al. (2001)
Low-arctic shrub hearth tundra	Abisco, Sweden	818	nd	na	na	Rustad et al. (2001)
High-Arctic dry tundra	Ny-Ålesund	1.5	nd	1991–1993	na	Rustad et al. (2001)
High-Arctic glacier foreland						
Site 1	Ny-Ålesund	6.2	5.8	1995	OF&DC	Present study
Site 2	Ny-Ålesund	44	46	1995	OF&DC	Present study
Site 3	Ny-Ålesund	63	69	1995	OF&DC	Present study
Site RB	Ny-Ålesund	3.7	3.3	1995	OF&DC	Present study

OF; open air-flow method. DC; dynamic closed chamber method. AB; alkali absorption method. SD; closed chamber method with soda lime.
na and nd denote not available and not determined, respectively.

parameters between the sites in the regression equations is not elucidated in the present study, these results show that even in a glacier foreland, the soil respiratory properties were much different, reflecting different successional ages.

The cumulative amounts of CO_2 emission were 3.3, 5.8, 46 and 69 g CO_2 m^{-2} at Site RB, Site 1, Site 2 and Site 3, respectively from July to August, 1995 (Table 2). These values were extremely low compared to those of warmer ecosystems, such as the low-arctic tundra ecosystems, which range from 555 to 935 g CO_2 m^{-2} (Oberbauer *et al.*, 1992; Grogan and Capin III, 1999), the temperate mixed forest (640 g CO_2 m^{-2}, Bowden *et al.*, 1993), and the tropical moist forest (1360 g CO_2 m^{-2}, Kursar, 1989). Even when the mean SR rates in the growing season were compared, the soil respiration rates in the present study, which ranged from 3.7 to 63 mg CO_2 $m^{-2}h^{-1}$, were lower than those in the low-arctic tundra (Rustad *et al.*, 2001). However, the rates in the present study were much higher than the value previously reported (1.5 mg CO_2 $m^{-2}h^{-1}$) in Ny-Ålesund (Rustad *et al.*, 2001). The SR value reported by Rustad *et al.* (2001) is lower than those in Site RB in the present study. The lower value in Rustad *et al.* (2001) can be attributed to the measuring method and vegetation. The SR value in Rustad *et al.* (2001) was measured with a static closed chamber method that isolated the inside of the chamber from ambient air for 24 hours. It is likely that the CO_2 efflux was depressed because of the higher CO_2 concentration in the static chamber as compared with that under the ambient CO_2 concentration. In addition, the SR value in Rustad *et al.* (2001) was measured at a polar semi-desert site, about 2 km from Site 3, where approximately 70% of the ground surface is unvegetated, and 30% is covered mainly by *Dryas octopetala* L. (Robinson *et al.*, 1995). Soil carbon content at the polar semi-desert site was 3% based only on the upper organic layer beneath vegetation (Rustad *et al.*, 2001). Thus, the soil carbon content on a whole plot basis (including bare mineral soil) is below 1.5%, which is comparable with that at Site RB (1.4%), but less than those at Site 1 (1.6 %), Site 2 (1.8%) and Site 3 (7%). Because of the low soil carbon content and difference in the measurement procedure, the SR value in Rustad *et al.* (2001) is lower than those in the present study.

At present, the amount of CO_2 emitted from the soil in this area to the atmosphere may have a relatively small effect on the global carbon cycle and climate system. However, the microbial biomass in this area is comparable to or even larger than those in warmer ecosystems (Bekku *et al.*, 1999). Moreover, the temperature coefficient (Q_{10}) of the microbial respiration rate and microbial respiration rate per unit gram soil that was sampled from the area adjacent to Site 3 were higher than those in temperate and tropical soils (Bekku *et al.*, 2003). Bekku *et al.* (2003) also suggested that the Q_{10} of the microbial respiration rate would not change, and the soil respiration rate would increase under future global warming in the area around Site 3. However, the present study shows that even in an area in a high arctic glacier foreland, soil respiration rates were extremely different among the study sites reflecting successional ages. In addition, respiratory properties and the response to global warming might differ among different successional stages and different microbial communities, and also depend on environmental factors such as resource availability and soil physical properties. Further studies are needed to clarify the differences in the responses of soil ecosystems to global warming at different successional stages. These studies are necessary to predict changes in the carbon cycle in a high-arctic deglaciated area, and changes in the global carbon cycle under the current increase in deglaciation and future global warming.

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