ARCTIC
VOL. 46, NO. 3 (SEPTEMBER 1993) P. 197-204

Wintertime CO_2 Emission from Soils of Northeastern Siberia

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(Received 11 October 1991; accepted in revised form 10 February 1992)

ABSTRACT. The emission of CO_2 from northeastern Siberian soil was estimated for the period December 1989 to February 1990. Concentrations of air CO_2 near the ground and 1 m above the snow cover were measured by an infrared gas analyzer. Fluxes of CO_2 across the snow cover were calculated from the differences of these two values and the predetermined CO_2 transfer coefficients at various flux rates through a layer of snow. Temperature and moisture content of the soil profiles were also observed simultaneously. The average transfer coefficient of CO_2 for packed snow measured in the winter of 1989/90 was about 0.28 $cm^2 \cdot s^{-1}$. This value was used to estimate the average CO_2 flux from soil: 0.26 g $C \cdot m^{-2} \cdot day^{-1}$ in December 1989, 0.13 g $C \cdot m^{-2} \cdot day^{-1}$ in January 1990 and 0.07 g $C \cdot m^{-2} \cdot day^{-1}$ in February 1990. Thus a minimal total of about 13.8 g $C \cdot m^{-2}$ had been released from the tundra soil during the 90 days from December 1989 to February 1990. Using the study by Kelley *et al.* (1968) and assuming that the minimal CO_2 transfer coefficient is also applicable for the entire tundra and Northern Taiga zones between September and June, the total emission from this region would amount to 0.23×10^{15} g of carbon. The main source of this CO_2 probably originated from microbial oxidation of soil organic matter. This assertion is supported by the existence of a relatively warm layer in the frozen soil at 40-120 cm depth. This warm layer was about 10-40°C higher than the ambient air, or about 5-10°C higher than the soil surface, and its moisture content was also higher than the surrounding layers.

Key words: CO_2 flux, Siberian tundra, soil temperature, moisture content

RÉSUMÉ. On a évalué l'émission de CO_2 provenant du sol dans le nord-est sibérien, durant la période allant de décembre 1989 à février 1990. On a mesuré les concentrations du CO_2 ambiant près du sol et à 1 m de la couverture de neige, à l'aide d'un analyseur de gaz infrarouge. On a calculé les flux du CO_2 à travers le couvert nival à partir des différences de ces deux valeurs et des coefficients de transfert du CO_2 prédéterminés pour divers taux de flux à travers une couche de neige. On a aussi observé simultanément la température et la teneur en humidité des profils pédologiques. Le coefficient de transfert moyen du CO_2 pour la neige tassée mesuré durant l'hiver de 1989-90 était d'environ 0,28 $cm^2 \cdot s^{-1}$. Cette valeur a servi à estimer le flux moyen du CO_2 provenant du sol : 0,26 g $C \cdot m^{-2} \cdot jour^{-1}$ en décembre 1989, 0,13 g $C \cdot m^{-2} \cdot jour^{-1}$ en janvier 1990 et 0,07 g $C \cdot m^{-2} \cdot jour^{-1}$ en février 1990. Par conséquent, un total minimal d'environ 13,8 g $C \cdot m^{-2}$ a été libéré du sol de la toundra au cours des 90 jours allant de décembre 1989 à février 1990. En nous servant de l'étude menée précédemment par Kelley *et al.* (1968) et en supposant que le coefficient minimal de transfert du CO_2 s'applique aussi à l'ensemble des zones de toundra et de taïga septentrionale entre septembre et juin, l'émission totale provenant de cette région se monterait à $0{,}23 \times 10^{15}$ g de carbone. La source principale de ce CO_2 venait probablement de l'oxydation microbienne de la matière organique contenue dans le sol. Cette assertion est soutenue par l'existence d'une couche de température relativement élevée dans le sol gelé, qui se trouve de 40 à 120 cm de profondeur. La température de cette couche était de 10 à 40 °C plus élevée que l'air ambiant, ou environ de 5 à 10 °C plus élevée que la surface du sol, et sa teneur en eau était aussi plus élevée que les couches adjacentes.

Mots clés : flux de CO_2, toundra sibérienne, température du sol, teneur en eau

Traduit pour le journal par Nésida Loyer.

РЕФЕРАТ. Исследована эмиссия CO_2 из почвы Северо-Восточной Сибири в период с декабря 1989г. по февраль 1991г. Концентрации воздушного CO_2 определялись в пробах отобранных из подснежного слоя и на высоте 1м с помощью ИК-спектрометра в режиме анализа дискретных проб. Отдельные пробы измерялись также с помощью газохроматографического метода. Потоки CO_2 рассчитывались на основе известных значений градиента CO_2 и величин коэффициентов переноса через снежный покров, которые определялись экспериментально в различные месяцы. Так же измерялись величины температуры и влажности в толще активного слоя. Среднее значение коэффициента переноса для уплотненного снега за зимний период 1989/1990 составило 0.28 $см^2$ $с^{-1}$. Минимальное значение эмиссии CO_2 за период декабрь-февраль составило 13.8г С $м^{-2}$. Принимая эту величину потока за базовую с учетом данных полученных ранее на Аляске, можно в первом приближении считать, что общий поток углерода в атмосферу в зимний период (сентябрь-начало июнь) составил из биомов арктические тундры и северные тайги (со сходными режимами температуры и влажности, и потенциалу органического вещества) как минимум 0.23 Гт С. Основной источник CO_2, по всей видимости, связано с деятельностью биоты в толще активного слоя. Это предположение подтверждается наличием относительного теплого слоя, глубина залегания которого согласуется с наличием биологического оптимума. Температура этого слоя на 5-10 С выше температуры окружающих горизонтов почвы.

Ключевые слова: потоки CO_2, сибирская тундра, почвенная температура, почвенная влажность

INTRODUCTION

According to Milankovich's astronomical theory, the temperature optimum of the Holocene peaked about 9400 years ago (Lorius *et al.*, 1988; Langway and Oeschger, 1989). However, the emissions of anthropogenic CO_2 and other greenhouse gases to the atmosphere could significantly alter the Earth's climate in the near future. The arctic ecosystems, which contain vast quantities of carbon as soil

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organic matter, are most sensitive to climate change. Depending on future climatic conditions, arctic tundra has the potential to act either as a major source or a sink for atmospheric CO_2. The arctic ecosystems could serve as carbon sinks in the summer, when plant photosynthesis is almost a continuous process under the long period of continuous summer light and wet soil conditions. Moreover, the existence of a layer of moisture-saturated soil on ground surface prevents the decay of organic matter and the diffusion of air through the active layer of the permafrost. On the other hand, increases in the depth of the active layer and/or decreases in soil moisture could result in increased rates of decomposition of soil organic matter and net CO_2 emission from the tundra (Oechel, 1990). Loomis (1978) postulates that the contents of soil nitrogen and organic matter could be estimated as a function of the mean annual temperature and a "moisture" factor. He suggests that 300 to 400×10^{15} g C might be released to the atmosphere with each 1°C increase in global temperature. This increase represents possibly the maximal rate of carbon release from soils (Schlesinger, 1989). However, the reliable estimate of future CO_2 emission from tundra soil requires detailed investigations of the background CO_2 flux between atmosphere and permafrost through the active layer.

The latitudinal distribution of atmospheric CO_2 suggests that the maximum of annual average concentration is located within 60-80°N (Tucker *et al.*, 1986), outside the 30-60°N band, where the main sources of industrial CO_2 are located (Rotty, 1983). Annually about 0.1×10^{15} g $C{\cdot}yr^{-1}$ of anthropogenic CO_2 is emitted within the 60-70°N latitudinal band. There exist now many long-term time series of background CO_2 levels in the atmosphere from various monitoring stations (Wong *et al.*, 1984; Komhyr *et al.*, 1985). These records show that the seasonal amplitude of atmospheric CO_2 is greatest within 50-70°N, with a value of about 14-16 ppmv (Komhyr *et al.*, 1985; Chan and Wong, 1990). The large seasonal amplitude provides a good signal-to-noise ratio to study the fertilization effect of CO_2 on northern ecosystems (Shaver *et al.*, 1992), as well as the air-sea gas exchange of CO_2 from the arctic surface seawater (Tans *et al.*, 1990; Wong and Chan, 1991). Thus, the long-term study of carbon dynamics within arctic and subarctic ecosystems would provide additional information to assess the effects of climate warming on the biosphere. Results from these studies may also be used to partition the contribution from the ocean and the terrestrial biosphere as CO_2 source/sink of the natural carbon cycle (Pearman and Hyson, 1980; Tans *et al.*, 1990; IPCC, 1992; Quay *et al.*, 1992).

Previous studies of CO_2 fluxes between arctic tundra or the active layer of permafrost and the atmosphere were sampled mainly near Barrow, Alaska (Kelley *et al.*, 1968; Kelley and Weaver, 1969; Johnson and Kelley, 1970; Coyne and Kelley, 1971, 1974; Peterson and Billings, 1975) and in Scandinavia (Svensson *et al.*, 1975). In this paper, we present data on CO_2 concentration gradients across the snowpack of the northeastern Siberian ecosystems in the winter of 1989/90, together with values of temperature and moisture content across the active soil layer.

METHODOLOGY

Our study was based at the Northeastern Science Station, Pacific Institute of Geography, located in Chersky, northeastern Siberia, at the lower Kolyma River (68.5°N, 161.4°E), about 80-100 km from the East Siberian Sea of the Arctic Ocean (Fig. 1). The study area is phytogeographically a transition of various northern landscapes: shrub tundra, open woodland-tundra, and forest tundra. The vegetation in this area is similar to that between the High Arctic Tundra and the Low Arctic Tundra as recognized by the North American classification scheme (Bliss and Matveyva, 1992).

The sampling plots chosen for this study were located on different types of plant communities found in this area (Fig. 1): forest-tundra vegetation (site 1), tall-shrub community on floodplain (site 2), alpine tundra (site 3), southern Khalerchin tundra, which is a mosaic of typical tundra (sedge-dwarf-scrub polygonal mires) and southern tundra (low-shrub-sedge, tussock-dwarf-shrub mire) with patches of tall shrub vegetation (site 4), a mountain slope plant community down from site 3 (site 5), a marshy thermokarst depression (site 6), the edge of an area burned eight years ago (site 7), and a grass-shrub floodplain community (site 8). Since most of the northern landscapes were presented in the sample, we can consider the study area as a good representative site for the whole arctic ecosystem. The soil and vegetation found on these sites are described in the appendix.

For this study, the gross CO_2 gradients (ΔCO_2) across the snow layer, as well as temperature and moisture content of the soil profiles, were measured simultaneously. The gross CO_2 gradients were obtained as the differences of air CO_2 concentrations between the ground and 1 m above the snow surface. Most of the CO_2 measurements were taken on the east side of the Kolyma River along two aboveground transects across a typical gradual slope covered with loamy soil. The vegetation on this slope was a mosaic characterized by scattered Siberian larches 8-10 m tall, with shrubs, grass, moss, and lichen existing in various combinations. The transects crossed marshy and steppe areas, old rough country roads overrun with weeds, and also fields with bushes artificially cleared. Along the two transects, the active layer of the upper soil horizon varied from 25 to 140 cm in September. This active soil layer was frozen completely in December. Snow cover was close to 20 cm deep during the entire sampling period.

In the winter season of 1989/90, there were a total of 80 sample sites along the two transects. Usually the measurements were carried out twice daily, in the morning and evening, but sometimes only once in the daytime. In addition, about 1000 irregular samples were also taken from the other 55 sampling profiles among sites 2-8 (Fig. 1). Many soil profiles along the monitoring sites were used for thaw-layer study, including observations on soil temperature and moisture, the level of frozen subsoil water, and soil freezing-thawing dynamics. The total number of ΔCO_2 measurements from the two transects and the random samples exceeded 5000. We consider here mainly the monitoring data obtained along the two transects at site 1 (Fig. 1).

Initially, CO_2 fluxes from soil were determined by the chamber-dynamic method (de Jong *et al.*, 1979). Metal

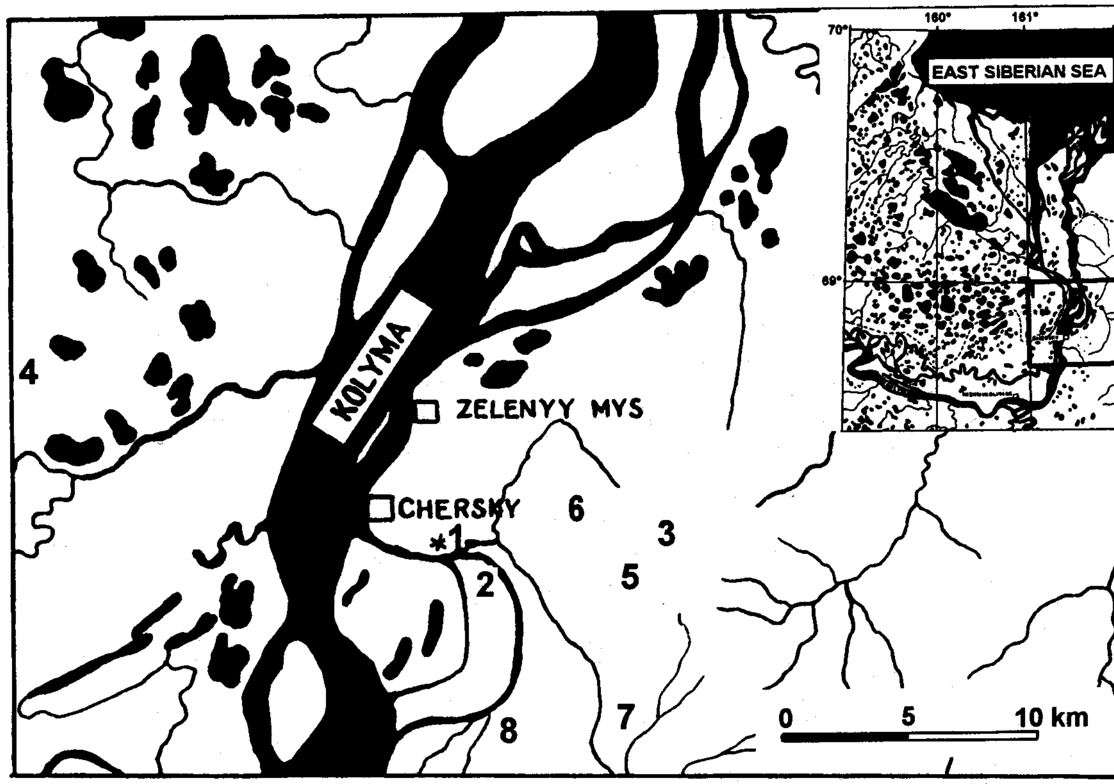

FIG. 1. Location of the Northeastern Science Station (*) and the sampling sites in northeastern Siberia: 1) forest tundra; 2) tall shrub floodplain; 3) alpine tundra; 4) Southern Khalerchin tundra; 5) mountain slope below site 3; 6) thermokarst depression; 7) burnt field; 8) grass-shrub floodplain.

chambers 26 cm in diameter were installed on the ground before the soil was frozen. Early determinations showed very high spatial-temporal variations of the local CO_2 fluxes (Zimov *et al.*, 1991) and thus required a large number of observations at many sites to obtain reliable mean values of the CO_2 fluxes. Consequently in winter 1989/90, we abandoned the chamber-dynamic method and instead determined the ΔCO_2 across the snow layer by a modification of the soil profile method (de Jong and Schappert, 1972; Zimov *et al.*, 1991). This "snow profile" method was used to obtain all the data for Figure 2.

Before the completion of field measurements, it was necessary to estimate the transfer coefficients of CO_2 at various flux rates through a snow cover under stable weather conditions. These coefficients were determined by passing dispensed CO_2 gas at a constant flux rate through a layer of packed snow about 20 cm in thickness. The packed snow was transferred into metal barrels of 50 or 30 cm in diameter. Five different flux rates at 15, 30, 60, 90, and 120 $cm^3 \cdot m^{-2} \cdot h^{-1}$ were employed in the estimation. For each of the fluxes, the ΔCO_2 value was obtained as described below. The value of CO_2 transfer coefficient was then calculated by Fick's law as for the diffusion coefficient (de Jong and Schappert, 1972). The estimated transfer coefficients were 0.22 $cm^2 \cdot s^{-1}$ in January ($t = -40$ to -43°C), 0.33 $cm^2 \cdot s^{-1}$ in March ($t = -10$ to -12°C), and 0.30 $cm^2 \cdot s^{-1}$ in April ($t = -1$°C). Hence, an average winter CO_2 transfer coefficient of 0.28 $cm^2 \cdot s^{-1}$ was used in subsequent estimations. The CO_2 transfer coefficient thus reflected the non-isothermic conditions of the snow cover and is a function of the temperature gradient across the snow layer and its porosity. The winter average is about twice the CO_2 diffusion coefficient in air (Reid *et al.*, 1977). Presumably, the CO_2 transfer coefficient obtained in this study might be used for other sites and regions covered by wind-packed snow, e.g., alpine and coastal tundra, river floodplain. We could also use this value as the minimum estimate of the CO_2 flux in different northern landscapes. Note that a higher value of transfer coefficient averaging about 0.63 $cm^2 \cdot s^{-1}$ was obtained in the winter of 1990/91 by simultaneous measurement of CO_2 and CO_2 fluxes through a snow layer in a metal chamber inserted in the soil before snowfall (Zimov *et al.*, 1992).

During field sampling, the air for the analysis was withdrawn manually with a glass syringe fitted to a rubber bladder. The volume of the syringe was about 300 cm^3. After the air was sampled, the rubber bladder was closed tightly with a clamp. Several tests during the project confirmed the absence of any significant CO_2 contamination during sampling and storage before measurements. In practice, a thin pipe was inserted through the snow to reach the ground layer and the subnivean air was drawn in by means of the glass syringe. The rubber bladder was filled three times with the subnivean air before the clamp was closed. Usually the air sample was kept in the bladder for less than three hours before the analysis for CO_2 by an infrared gas analyzer (model GIAM-5). No diffusion through the bladder was observed. The results were also cross-checked periodically by another analytic technique using gas chromatography (model TSVET-530 with thermal conductivity detector, Porapac T, diameter 0.3 cm, length

250 cm). For undiluted samples, the analytical uncertainty did not exceed 2%. The influence of water vapor on IR absorption was investigated by comparing the CO_2 levels in wet (~100% saturation) and dry (~20% saturation) air at 20°C. The discrepancy did not exceed 7 ppm. Consequently, the water vapor effect was omitted from our study. The CO_2 flux of 120 $cm^3 \cdot m^{-2} \cdot day^{-1}$ (about 64 mg $C \cdot m^{-2} \cdot day^{-1}$) corresponded to a ΔCO_2 value of about 10 ppm. This value was used for all total estimates without correction.

The soil temperature was determined by buried thermistors with a precision of ~0.1°C. The thermistors were located at 20, 30, 40, 50, 60, 80, 100, 120, 140, and 180 cm below soil surface. The moisture content of the soil at 5 cm intervals was measured by means of a neutron moisture probe (Russian model VPGR-1) with a precision of ~5%.

RESULTS

The CO_2 fluxes from soil for the three coldest months in winter 1989/90 are presented in Figure 2. Curves (a) to (e) depict the variation of CO_2 fluxes from the different sampling plots along the base transects at site 1. Curve (f) shows the mean values for 19 monitored profiles: three from the field with bushes removed and four from each of the other sampling plots (see Figure 2 caption). Figure 3 shows the time variations in temperature and moisture content of the soil profile of the undisturbed control plot at site 1.

In the following, we briefly compare the data obtained from the other profiles (site 2-8, Fig. 1) with the average values of the base profile (site 1) for the same time. From September to December, fluxes from soil under highly productive shrubby and grassy associations in valleys, marshy meadows, and tundra were 2-4 times higher than those from soil of the base profile. Compared to data from the base profile, higher fluxes also were obtained initially at sites where moss and lichen were removed. However, the differences were gradually reduced and at the end of December, there was practically no difference between these fluxes. The fluxes on the top (site 3) and at the bottom (site 5) of a mountain slope, representing respectively the low and high productivity levels of the alpine tundra, were approximately equal to those of the base profile in the early months. However, by December the fluxes from the alpine tundra plots were 1.5 times lower than fluxes from the base profile. The CO_2 fluxes from soil on the previously burned field (site 7) differed very little from those obtained at the base profile, except from December to January, when their intensity was 1.5 times higher.

For discrete samples, the maximum ΔCO_2 value of 330 ppm, which corresponds to a carbon flux of 1.9 $g \cdot m^{-2} \cdot day^{-1}$, was observed at one site of the Khalerchin tundra in the second quarter of December. The average carbon flux for the seven sites from the Khalerchin tundra was 0.84 $g \cdot m^{-2} \cdot day^{-1}$.

Combining all the observations, the minimum average flux of CO_2 from soils of this region was about 0.26 g $C \cdot m^{-2} \cdot day^{-1}$ in December, 0.13 g $C \cdot m^{-2} \cdot day^{-1}$ in January and 0.07 g $C \cdot m^{-2} \cdot day^{-1}$ in February. Thus a total of 26 × 10^3 $cm^3 \cdot m^{-2}$ of CO_2, or about 13.8 g $C \cdot m^{-2}$, had been released from the regional soils during these three coldest months in 1989/90.

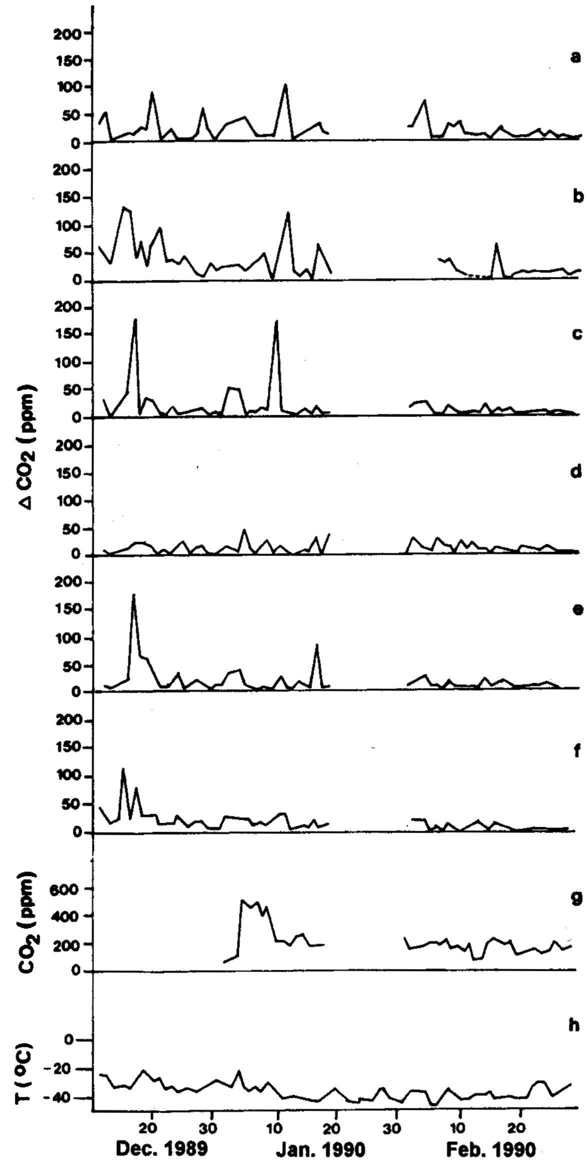

FIG. 2. CO_2 fluxes from frozen soils in a larch forest with birch and moss-lichen cover (site 1 of Fig. 1). ΔCO_2 is the difference in concentrations between CO_2 at the bottom of the thick snow and in the atmosphere. ΔCO_2 of 10 ppm corresponds to CO_2 flux of 120 $cm^3 \cdot m^{-2} \cdot day^{-1}$. a) undisturbed surface; b) bushes removed; c) moss-lichen cover; d) 30 cm upper layer of soil replaced by sod of grassy meadow; e) old country road with grass-shrub vegetation; f) mean ΔCO_2 values of 19 observation points (three profiles from plot b, four profiles each from plots a, c, d, and e above; g) time course of CO_2 concentration in drying soil layer at sample plot d; h) time course of mean daily air temperature.

DISCUSSION

Kelley *et al.* (1968) observed that the concentration of CO_2 under snow cover in the Arctic remained relatively stable during winter but then increased in early May until the snow left the tundra. The release of CO_2 trapped in gas pockets in early spring (Kelley *et al.*, 1968; Coyne and Kelley, 1974) is probably not caused by physical processes, because the high variability of CO_2 fluxes are uncorrelated with the

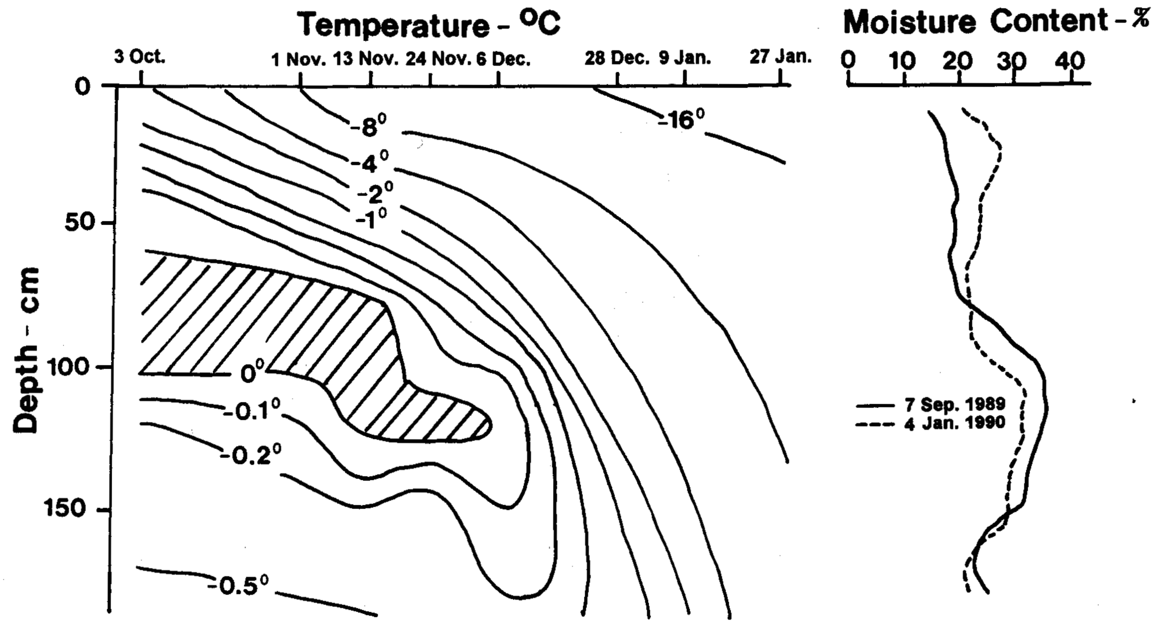

FIG. 3. Variations of soil temperature and moisture content from base transect at site 1. Thermistors were located at 20, 30, 40, 50, 60, 80, 100, 120, 140, and 180 cm below surface. Dates when temperatures were determined are also shown at the top. Soil moisture content was measured in the same pits by VPGP-1 neutron moisture probe at 5 cm intervals.

relatively stable physical parameters. It is more likely that the winter CO_2 fluxes from soil are caused by biological activity. This activity is only possible in the presence of liquid water and the existence of soil microbial decomposers that are adapted to the severe winter environment.

In sandy loam, all the free water becomes frozen only at −3°C. The loosely linked water in sandy loam is present at a temperature as low as −10°C. In loam, the temperature at which free water can be present is even lower than −10°C. The non-frozen moisture content in loam is about 5% at −5°C.

In autumn, the upper soil layer is frozen and moisture from the deep horizon migrates to the frozen front. As a result of this redistribution of water in the soil, the moisture content increases considerably within the upper layer, while it is reduced in the lower levels (Fig. 3). Hence the porosity of the drying layer is increased. This aids in the aeration of the deep layers, especially when fissures are formed in the upper soil layer as a result of the compression and drying processes during freeze-up.

In winter, the frozen active layer has a relatively "warm" layer at 40-120 cm depth (Fig. 3). The temperature regime in this layer is about 10-40°C warmer than the ambient condition, or about 5-10°C warmer than the temperature in the upper soil layer. Figure 3 also shows the evolution and disappearance of the "warm" layer from October to January. For example, in December the temperature at ground level was −12 to −15°C, it was −8 to −12°C near 20 cm depth, and −1 to −5°C at the 40-120 cm layer. This "warm" layer coincides with the second deep maximum of many species of soil invertebrates (Chernov, 1978). In this and similar regions, aerobic microorganisms also show the same distribution (Chernov, 1978). In arctic regions, the soil microorganisms are generally adapted to the frigid environment (Flanagan and Bunnell, 1980). Some species of microorganisms are known to reproduce at temperatures below −8°C (D. Gilichinsky, pers. comm. 1992). Our growth-chamber experiments show that the soil biota continue to produce CO_2 even when the soil temperature drops to −7°C. In different soil types, microbial activities are characterized by synchronous processes with a periodicity of about two to eight days (Gorbenko and Panicov, 1989). The same periodicity is also evident in Figure 2 (a–f).

The presence of many aerobic organisms at deep horizons suggests the existence of an ecological optimum in the "warm" layer. Possibly the source of wintertime CO_2 emission from northern soil comes from the biological oxidation of available soil organic matter in this "warm" layer. In decomposing 100 g of soil organic carbon, about 800 kcal of heat may be released. This heating is quite sufficient to melt a frozen soil layer 20 cm thick and to increase its temperature by approximately 15°C, assuming no heat exchange between this layer and the adjacent soil. This mechanism of soil self-heating might provide sufficient warming to stimulate the continuous activity of soil biota during winter. The optimal conditions for aerobic activity occur during autumn. As the warm, dry aerated soil layer cools down during the coldest months, CO_2 flux also decreases from the late autumn maximum to a low value in March.

In the spring and summer seasons when soil temperature rises above 1°C, the active layer becomes saturated with moisture, which prevents the flux of air into deeper layers, resulting in anaerobic conditions. This reduces the summer aeration and decomposition of soil organic matter, thus causing a drop in CO_2 emission. As a result, a large accumulation of litter is observed in tundra and boreal ecosystems (Bolin *et al.*, 1979; Schlesinger, 1989). At present, the depth of the active layer might also be increasing from the effects of anthropogenic activities, such as fires and global warming

(Zimov *et al.*, 1991). As a result, the amount of organic matter available for microbial decomposition is also increasing. The increasing organic carbon, in turn, might provide additional substrate for biological oxidation and self-heating of the soil and, consequently, larger CO_2 emission. Thus the whole process behaves as a positive feedback system.

Using values from Kelley *et al.* (1968) for the average monthly concentration of CO_2 16 m above ground and at the ground level, together with the value of our experimental CO_2 transfer coefficients, 0.28 $cm^2 \cdot s^{-1}$, we can estimate the average CO_2 fluxes from the soil near Barrow, Alaska, for the period September 1965 to July 1966. The estimates show that CO_2 emission increased from 0.08 g $C \cdot m^{-2} \cdot day^{-1}$ in September to 0.16-0.18 g $C \cdot m^{-2} \cdot day^{-1}$ in the period from October to December, dropped to about 0.04-0.05 g $C \cdot m^{-2} \cdot day^{-1}$ during January and February, then reduced further to about 0.02-0.03 g $C \cdot m^{-2} \cdot day^{-1}$ during March and April. In early May, the CO_2 concentration under the snow increased until the snow disappeared in late June; the CO_2 fluxes increased from 0.11 g $C \cdot m^{-2} \cdot day^{-1}$ in May to 0.14 g $C \cdot m^{-2} \cdot day^{-1}$ in June. Hence the total CO_2 flux from soils at Barrow during September 1965 to July 1966 is estimated to be about 30 g $C \cdot m^{-2}$. Assuming this flux estimate represents the average value for the arctic tundra, we could compute the total flux of CO_2 from soil in the region during the winter months from September to June. Estimates of the total area of arctic and alpine tundras range from 7.34×10^{12} m^2 (Matthews, 1983) to 11×10^{12} m^2 (Olson *et al.*, 1983). For the arctic tundra only, the area is about 5.7×10^{12} m^2 (Shaver *et al.*, 1992). Thus, the winter emission of carbon from the arctic tundra zone alone amounts to 0.17×10^{15} g C.

At the northern fringes of the Boreal forest is a narrow Northern Taiga zone that covers a partly scrubby transition of about 2.1×10^{12} m^2 (Bolin *et al.*, 1979) where most of the same boreal trees occur but tend to be more weather beaten, smaller, or localized to sites with more available nutrients (Olson *et al.*, 1983). The winter CO_2 emission from soils of the same magnitude as in the tundra may also have occurred in this Northern Taiga zone. This assumption is supported by the large content of litter in the soils and by the very similar climatic conditions in these two zones, especially in terms of solar radiation, evaporation, precipitation, and temperature (Bolin, 1980; Bolin *et al.*, 1979). We also may assume that the minimal winter CO_2 emission from the Northern Taiga zone is similar to that from the arctic tundra. The calculation is based on a transfer coefficient of 0.28 $cm^2 \cdot s^{-1}$. Hence the Northern Taiga zone contributes 0.06×10^{15} g C to a total CO_2 emission of 0.23×10^{15} g C from soil of high northern latitudes between September and June. This CO_2 emission is more than double the 0.1×10^{15} g C annual emission of anthropogenic CO_2 (Rotty, 1983) within the 60-70°N latitudinal belt.

The method used in our study probably results in underestimating the CO_2 flux, since the subnivean air samples might be diluted by ambient air during sampling. If we assume that the CO_2 transfer coefficient of 0.63 $cm^2 \cdot s^{-1}$ obtained in the winter of 1990/91 (Zimov *et al.*, 1992; Semiletov *et al.*, 1992) represents the maximum value, then the total wintertime CO_2 flux from northern soils would increase to 0.52×10^{15} g C for the same two zones and the same 300 day time period.

Johnson and Kelley (1970) estimated that nearly one-half of the tundra's gross primary production is respired or consumed by herbivores during the growing season. They presumed that the other half, i.e., the net primary production (NPP), is either accumulated or respired during the winter. Reviews of tundra productivity (Ajtay *et al.*, 1979; Bolin *et al.*, 1979; Heal *et al.*, 1981) suggest that the average NPP of the tundra ecosystem ranges from 63 to 130 g $C \cdot m^{-2} \cdot yr^{-1}$. Our estimate of the minimum flux of CO_2 from soil of the arctic region (30 g $C \cdot m^{-2}$) indicates that more than 23% of the tundra net primary production would be returning to the atmosphere during the winter season.

An estimate of the percentage of winter CO_2 emission from soils in terms of the atmospheric CO_2 concentration in high latitudes could be obtained by assuming that there is no air exchange in the atmosphere between the tundra area and other regions. The assumption is partially supported by the observation that the arctic region is a comparatively closed cyclonic center below the tropopause during the winter season (Vowinckel and Orvig, 1970). For an air column with a base area of 1 m^2 and with the CO_2 concentration of 350 ppm (1440 g $C \cdot m^{-2}$), the winter CO_2 emission would increase the average CO_2 concentration by approximately 7-16 ppm. Such a value is close to 50-100% of the CO_2 seasonal amplitude (Chan and Wong, 1990) observed in this area.

ACKNOWLEDGEMENTS

We thank G.M. Zimova, A.I. Daviodova, Z.V. Voropaeva, I.V. Semiletova, and O.V. Prosyannikova for their assistance.

APPENDIX. SOIL AND VEGETATION ON THE MAIN PERMANENT SITES IN THE STUDY AREA

Site 1 contains three sampling plots or profiles:

(1A). The base profile.

Soil — A combination of humic peat, humic gley and loamy soil. The depth of the seasonally thawed active layer is 0.4-1.3 m.

Vegetation — The overstory is mainly dominated by *Larix dahurica*. In the understory, it is occupied by *Betula middendorffii* with some invasion by *Salix* spp. In the herbaceous layer, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Ledum palustre*, *Empetrum nigrum*, *Arctous alpina*, *Pyrola incornata*, *Chamaenerium angustifolium*, *Carex* spp. are presented. The ground level is covered by *Sphagnum* moss and several species of lichen of the genus *Cladonia* and *Cetraria*.

(1B). The river terrace.

Soil — Recent organic-rich soil.

Vegetation — It is mainly a diverse grass-steppe, invaded by moss, shrubs, and herbs. *Betula middendorffii*, *Salix* spp., *Pinus pumila*, *Rosa acicularia* are widely spaced. *Empetrum nigrum* and *Vaccinium vitis-idaea* grow in the herbaceous layer. At the upper terrace, *Pulsatilla multifida*, *Artemisia dracunculus*, *Dianthus repens*, *Veronica incana*, *Dracocephalum palmatum*, *Sedum purpureum*, and *Thymus oxyodontus* are found. There are very few moss and lichen species.

(1C). The "meadow" area is an artificial plant community contained in (1A).

Soil — The upper 20-30 cm of the original soil profile (as in 1A) is replaced by a layer of typical meadow sod of loamy soil with slight peat formation.

Vegetation — The transplant community composes of *Calamagrostis purpurascens*, *Artemisia dracunculus*, *Tanacetum borealis*, *Chamaenerium angustifolium*, *Valeriana capitata*, *Sanguisorba officinalis*, *Rubus arcticus*, and a few mosses.

Site 2. The Kolyma floodplain.

Soil — different floodplain soils, from the alluvial sod of loamy soil near the river bank to the peaty gley soil at the inner floodplain.

Vegetation — The shrub layer is dominated by *Salix* spp., *Alnaster fruticosa*, and *Betula exilis*. In the grass-forb layer, *Arctophila fulva*, *Equisetum arvense*, *Calamagrostis purpurascens*, and *Carex* spp. can be found. *Carex wiluica*, *Carex* spp. *Eriophorum vaginatum*, *Comarum palustre*, and different moss species are present in the marshy area of the inner floodplain.

Site 3. The alpine tundra (the Rodinka mountain).

Soil — Recent organic-rich soil with loamy material.

Vegetation — *Betula nana*, *Pinus pumila*, *Salix* spp., *Vaccinium vitis-idaea*, *Empetrum nigrum*, *Carex* spp., and different herbaceous species predominate in the shrub-scrub layer. *Sphagnum*, *Cetraria* and *Cladonia* are the moss and lichens.

Site 4. "Ahmelo," the southern Khalerchin tundra.

Soil — Mainly tundra cryogenic soil from humic peat and humic gley soil to sandy soil. The depth of active layer ranges from 0.2 to 0.6 m.

Vegetation — Plant species distribution follows the micro-relief of the ground. *Salix* spp., *Betula exilis*, *Vaccinium vitis-idaea*, *Empetrum nigrum*, *Arctous alpina*, *Carex* spp., and different lichens predominate on polygon rim and the top of high-centered polygon, whereas *Ledum palustre* and the mosses *Polytrichum* and *Sphagnum* predominate on polygon trough and the basin of low-centered polygon.

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