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Annual and seasonal CO_2 fluxes from Russian southern taiga soils

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ABSTRACT

Annual and seasonal characteristics of CO_2 emission from five different ecosystems were studied *in situ* (Russia, Moscow Region) from November 1997 through October 2000. The annual behaviour of the soil respiration rate is influenced by weather conditions during a particular year. Annual CO_2 fluxes from the soils depend on land use of the soils and averaged 684 and 906 g C m^{-2} from sandy Albeluvisols (sod-podzolic soils) under forest and grassland, respectively. Annual emission from clay Phaeozems (grey forest soils) was lower and ranged from 422 to 660 g C m^{-2}; the order of precedence was arable < grassland < forest. The coefficients of variation for annual CO_2 fluxes caused by weather conditions ranged from 18% (forest ecosystem on Phaeozems) to 31% (agroecosystem). The contribution from the cold period (with snow, November–April) to the annual CO_2 flux was substantial and averaged 21% and 14% for natural and agricultural ecosystems, respectively. The CO_2 fluxes comprised approximately 48–51% in summer, 23–24% in autumn, 18–20% in spring and 7–10% in winter of the total annual carbon dioxide flux.

1. Introduction

CO_2 emissions from the soil surface and respiration of plant communities form the Gross Ecosystem Respiration. Estimates of the global annual carbon dioxide flux from soils of terrestrial ecosystems range from 68 ± 4 Pg C yr^{-1} (Raich and Schlesinger, 1992) to 100 Pg C yr^{-1} (Musselman and Fox, 1991). Soil CO_2 emission is one of the major fluxes in the global carbon cycle, equal to or smaller than the estimated gross primary productivity of 100–120 Pg C yr^{-1} (Houghton and Woodwell, 1989). Even a small change in soil respiration can influence the annual CO_2 input into the atmosphere considerably. Critical factors which have been reported to effect soil respiration rates include temperature and moisture of soil, vegetation, substrate quality and net ecosystem productivity (Rustad et al., 2000). The destruction of plant communities as a result of human activity (deforestation and reforestation, ploughing, drainage, etc.) can also essentially influence the carbon dioxide flux from soils (Schlesinger and Andrews, 2000). Global warming, as a result of the greenhouse effect, leads to intensification of biogenic CO_2 emissions. Comparatively few direct comparisons of soil respiration rates have been made among natural and disturbed ecosystems. Reliable estimates of seasonal and annual CO_2 fluxes from different ecosystems allow us to forecast the response of their soils in the case of land use change and to amend previous regional and global estimates of annual carbon dioxide fluxes.

The objective of the present study is to quantify annual and seasonal carbon dioxide emissions by different ecosystems of the southern taiga zone on the basis of long-term *in situ* measurements of CO_2 fluxes.

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Table 1. *Brief description of plant cover and some properties of investigated soils (layer 0–10 cm)*

	Albeluvisols		Phaeozem		
Characteristic	Forest	Grassland	Forest	Grassland	Arable
Plant cover	Pine, lime, aspen, oak, birch; rich in herb	Rich mixed grass; mown, unfertilized	Lime, aspen, birch; rich in herb	Poor motley grass; unmown, unfertilized	Unfertilized five-field crop rotation (cereals–fallow)
Age, yr	80–100	47–50	45–55	17–19	250
Total C, %	1.9	2.2	2.4	1.6	1.1
pH_{H_2O}	5.6	5.4	6.8	6.5	6.0

2. Materials and methods

2.1. Site description

Experimental sites were located on sandy sod-podzolic soils (Albeluvisols Umbric)[1] in the territory of the Prioksko-Terrasny State Reserve (Moscow Region, Russia, 54°50′N, 37°35′E), and on clay grey forest soils (Phaeozems Albic) 4 km west of Pushchino. This region belongs to the southern taiga zone (coniferous forests). The mean annual air temperature is ca. 5.4 °C and the mean monthly temperatures of July and January are 18 and −6 °C, respectively (Lopes de Gerenyu et al., 2001). The annual precipitation amounts to 670 mm. Snow cover usually appears during November and stays until the end of April. Measurements were carried out *in situ* during 3 yr under mature mixed forest and grassland on Albeluvisol, and under secondary mixed forest, grassland and cultivation (winter wheat) on Phaeozems. Weather conditions during the measurements were described in detail by Lopes de Gerenyu et al. (2001). Basic soil properties and plant cover descriptions are reported in Table 1.

2.2. CO_2 emission measurements

Soil CO_2 emission rates were measured by a closed chamber method over the period from November 1997 through October 2000 at 7–10 d intervals. In all 105 gas samples for arable soils and 145–147 samples for other sites were obtained. Measurements were carried out between 9 and 11 a.m., when the current value of the soil respiration rate was approximately equal to the mean daily value (Larionova et al., 1989). The number of replicates was three during the cold period (November–April) and five during the warm period (May–October). Chamber techniques for each of the seasons were also different.

During the warm period steel (lightproof) cylindrical chambers 10 cm in diameter by 10 cm in height were used. Chambers were inserted into the soil to a depth of 3–5 cm before the gas was sampled. In forest and arable sites the chambers were installed between growing plants. In grassland sites the plants were cut off before installation of the chamber. Thus the total soil respiration (root respiration + heterotrophic soil respiration) without above-ground plant respiration was determined. The characteristics of CO_2 concentrations in a chamber were determined during 45 min with 15-min intervals on Phaeozems and during 30 min with 10-min intervals on Albeluvisols. To reduce the temperature and gas pressure changes in a chamber during the sampling procedure, the chambers were painted with a light colour and the period of gas sample withdrawal was shortened as much as possible. During the cold snowy period (November–April), 32 × 32 cm steel bases (with a water seal) were dug permanently to a depth of 20 cm into the soil and steel boxes 32 × 32 × 15 cm were inserted. To exclude disturbances from the snow cover, the bases were built up by special sections as required. The increase of CO_2 concentrations in the chamber was measured during 135 min with 45-min intervals. Due to weak soil respiration and low air temperature during the cold season the pressure and temperature changes in the chambers were negligible.

The gas samples (20 cm^3) were collected by a syringe, transported to the laboratory in hermetically sealed vacuumed flasks and analysed by gas chromatography. Simultaneously, soil moisture and temperature in the upper soil layer (0–5 cm) were determined.

[1]We cite soil names according to the Russian Soil Classification, and the corresponding names according to the Soil Classification the FAO (Stolbovoi, 2000) are given in parentheses.

2.3. Analyses

The CO_2 flux can be calculated according to eq. (1) in order to account for the decreased net flux when the soil air to temperature gradient decreases (Panikov and Gorbenko, 1992):

$$dC/dt = F_{CO_2}\big/H - D_s/H(C - C_0)/Z_{CH}. \quad (1)$$

Equation (1) can be integrated to

$$C = C_0 + F_{CO_2} Z_{CH}\big/D_s\{1 - \exp[-D_s/(Z_{CH}Ht)]\}, \quad (2)$$

where F_{CO_2} is CO_2-C flux (in mg C m^{-2} h^{-1}), C_0 is the initial head-space concentrations of CO_2-C (in mg C m^{-3}), C is the head-space concentration of CO_2-C (in mg C m^{-3}), at a time t (in h), H is the height of the head-space layer in the chamber (in m), D_s is the CO_2 diffusion coefficient[2] in the soil (in m^2 h^{-1}), and Z_{CH} is the depth (in m) of the lower chamber edge below the soil surface.

For the warm period we assumed a linear increase of head space CO_2 concentration in the chamber with time during the first 20 min. During the cold season the net flux of CO_2 was negligible within the measurement interval (1.5–2 h). Thus, eqs. (1) and (2) can be simplified to:

$$dC/dt = F_{CO_2}\big/H \quad (3)$$

and

$$C = C_0 + F_{CO_2}t\big/H, \quad (4)$$

respectively.

Monthly CO_2 fluxes from the soils (g C m^{-2} month^{-1}) were calculated by using mean monthly values of CO_2 emissions (g C m^{-2} d^{-1}). Seasonal and annual fluxes were obtained by summarising monthly fluxes.

3. Results and discussion

3.1. Monthly, seasonal and annual CO_2 fluxes

Results from three years of measurements of CO_2 emission from soils of different southern taiga ecosystems, soil and air temperatures, soil moisture and height of snow cover are shown in Figs. 1 and 2. Emissions of CO_2 from the soils were characterised by considerable spatial and temporal variability, especially during spring and autumn. The annual behaviour of the soil respiration rate is governed by weather conditions during the year, and may have either a single peak in summer or several peaks. We observed that the CO_2 emission rate during the cold season (snow, November–April) was always above zero and less than 100 mg C m^{-2} h^{-1}. During the warm period (snow free season, May–October) the soil respiration rate was 3.5–4.5 times higher and reached 300–330 mg C m^{-2} h^{-1}. As a rule, sandy Albeluvisols were characterised by higher soil respiration rates than clay Phaeozems because of a better airing of these soils, and a greater mass of roots in grassland soil and fresh organic material (litter) on the forest soil surface.

Mean monthly, mean seasonal, and mean annual CO_2 fluxes from the studied soils were calculated (Table 2). The average annual carbon dioxide fluxes (ACDF) from Albeluvisols amounted to 684 and 906 g C m^{-2} yr^{-1} in the forest and grassland, respectively. The annual emission from grey forest soils ranged from 422 to 660 g C m^{-2} yr^{-1}, and the order of precedence was arable < grassland < forest. It was found that the grassland ecosystems on Albeluvisols during the whole year were characterised by higher CO_2 emissions than the grassland ecosystems on Phaeozems, because of a richer grass composition and higher root respiration. The annual CO_2 fluxes from the soils under forest were similar.

The CO_2 flux from soils can be estimated to be approximately 10% greater because the closed chamber technique was reported to give a general underestimation of ca. 10% as compared to results obtained with an open system (Rayment, 2000). Nevertheless, our estimations of ACDF correspond to estimates of annual soil respiration obtained for other ecosystems of the boreal zone: 760 ± 340 g C m^{-2} yr^{-1} (Raich and Schlesinger, 1992; Pajary, 1995; Janssens et al., 2001).

The coefficient of temporal variation (CV) for individual monthly CO_2 flux measurements ranged from 0.7 to 110%. The highest temporal variation of the CO_2 flux (CV = 78–110%) was observed in March for the majority of the ecosystems studied. The temporal CV for individual monthly CO_2 fluxes during the period from April to November rarely exceeded the 50% level. Seasonal fluxes varied less than monthly ones. The CV for the calendar seasons were 64% for winter, 37% for spring, 24% for summer and 28% for autumn. The variability of CO_2 fluxes for cold (November–March) and warm (April–October)

[2]The diffusion coefficient ranged from 3.6×10^{-4} to 3.6×10^{-3} m^2 h^{-1} and averaged 6.3×10^{-4} m^2 h^{-1}.

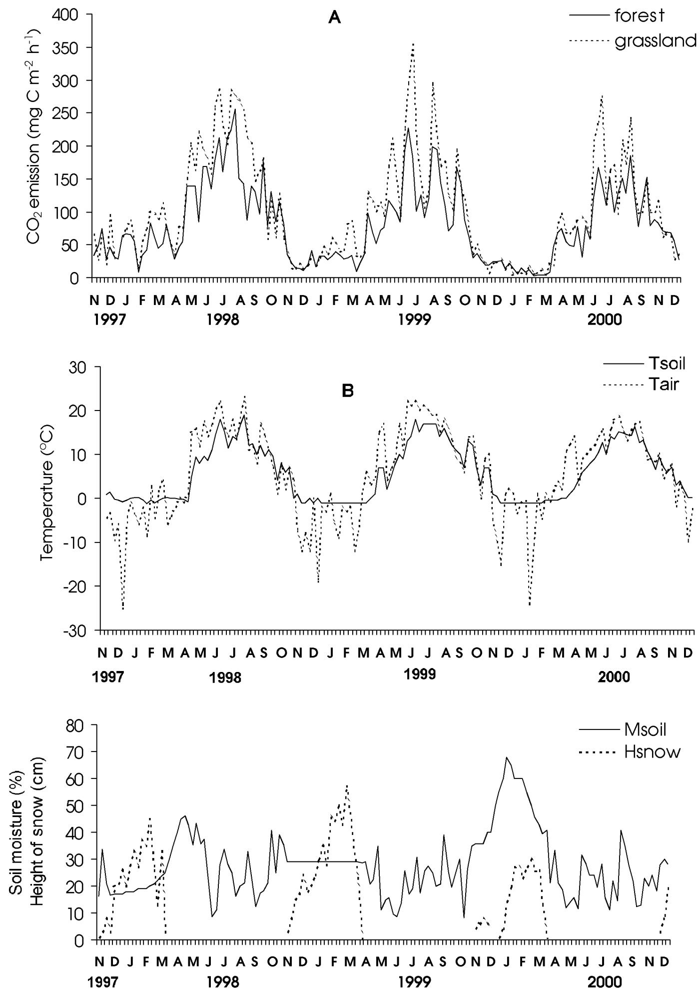

Fig. 1. Emission of CO_2 from Albeluvisols under forest and grassland (A), soil and air temperature (B) and soil moisture and height of snow cover (C).

periods between different observed years was 52% and 21%, respectively. The coefficient of variation for the annual CO_2 fluxes ranged from 18% (forest ecosystem on Phaeozem) to 31% (agroecosystem). As a rule, the variability of monthly, seasonal and annual fluxes was caused by the difference in climatic conditions during the periods studied.

3.2. *Contributions from different periods to the annual carbon dioxide flux (ACDF)*

We calculated the contribution of the individual months, the calendar seasons (winter, spring, summer, autumn) and warm and cold periods to ACDF. The contribution from individual months to ACDF varied from 1.5 to 20.6% and depended on the type of ecosystem. The CO_2 fluxes comprised approximately 49% in summer, 24% in autumn, 19% in spring and 8% in winter of the total ACDF. The contribution of the cold period (November–April) to the annual CO_2 flux was considerable and averaged 21% and 14% for natural and agricultural ecosystems, respectively. Emission of CO_2 during the cold period was an essential part of the annual emission, which should be taken into account while calculating the carbon budget for the whole year. According to other studies (Sommerfeld et al.,

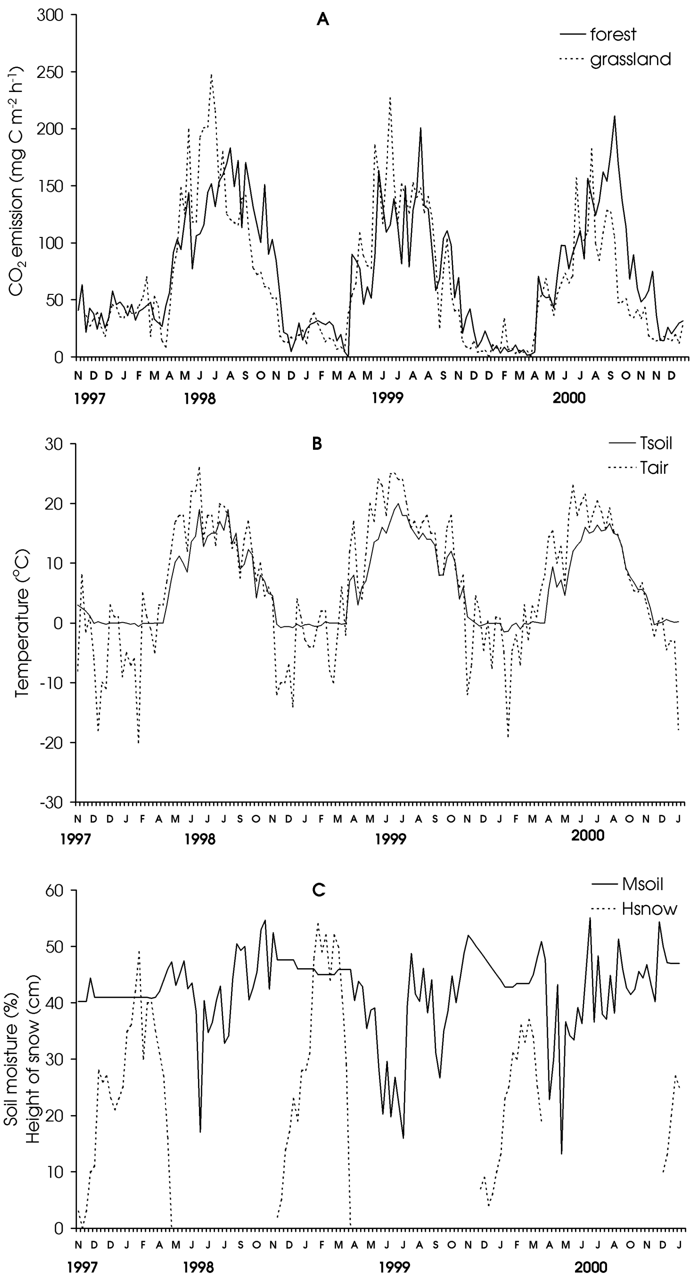

Fig. 2. Emission of CO_2 from Phaeozems under forest and grassland (A), soil and air temperature (B) and soil moisture and height of snow cover (C).

1993; Zimov et al., 1993; Pajary, 1995; Oechel *et al.*, 1997; Fyedorov-Davydov, 1998; Alm et al., 1999; Zamolodchikov and Karelin, 2001) the winter soil respiration has been estimated to contribute 10% or more to the annual CO_2 flux from tundra soil and 20% or more from boreal ecosystems.

Using the Soil Respiration Data Base (Kurganova and Kudeyarov, 1998) and the above estimations of

Table 2. *Mean seasonal and annual CO_2 fluxes from different southern taiga soils (mean ± s.d.)*

	CO_2 fluxes, (g C m^{-2} $period^{-1}$)				
	Albeluvisols		Phaeozem		
Period	Forest	Grassland	Forest	Grassland	Arable
December–February ***(winter)***	63 ± 38	77 ± 52	55 ± 34	43 ± 30	17 ± 0
March–May ***(spring)***	124 ± 45	196 ± 86	137 ± 55	158 ± 81	55 ± 10
June–August ***(summer)***	315 ± 101	439 ± 89	285 ± 64	301 ± 60	215 ± 60
September–November ***(autumn)***	191 ± 34	202 ± 43	185 ± 41	90 ± 28	136 ± 64
November–April ***(cold)***	150 ± 66	192 ± 103	143 ± 69	125 ± 71	50 ± 0.0
May–October ***(warm)***	534 ± 126	714 ± 112	518 ± 60	466 ± 87	366 ± 126
Annual	**684 ± 192**	**906 ± 229**	**660 ± 123**	**591 ± 157**	**422 ± 125**

the contribution from different seasons to ACDF, we calculated the annual carbon dioxide fluxes from other taiga soils (approximately 220 different ecosystems), where measurements of CO_2 emissions were carried out during summer season only, according to the following simple equation:

$$ACDF = F_s/C_s \times 100, \quad (5)$$

where ACDF is the annual carbon dioxide flux (in g C m^{-2} yr^{-1}), F_s is the summer CO_2 flux (in g C m^{-2}) (observed), and C_s is the contribution from summer season to ACDF (%) (estimated).

The calculated annual CO_2 fluxes ranged from 100 g C m^{-2} yr^{-1} (Albeluvisols Umbric, fallow) to 1650 g C m^{-2} yr^{-1} (Cambisols Eutric, spruce-fir forest) and depended on soil type and land use. Mean and median values of the ACDF for the boreal ecosystems were about 510 and 380 g C m^{-2} yr^{-1}, respectively.

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