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Net ecosystem productivity and peat accumulation in a Siberian Aapa mire

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ABSTRACT

Net ecosystem productivity (NEP) was studied in a bog located in the middle taiga of Siberia using two approaches, the accumulation of peat above the hypocotyl of pine trees, and the eddy covariance flux methodology. NEP was 0.84 tC ha^{-1} yr^{-1} using the peat accumulation method; it was 0.43–0.62 tC ha^{-1} yr^{-1} using eddy covariance over three growing seasons. These data were compared with NEP of the surrounding forest, which was 0.6 tC $\pm$ 1.1 ha^{-1} yr^{-1}. The trees growing on the bog reached a total height of about 3 m and an age of 80–120 yr when peat accumulation reached 0.5–0.6 m. At that stage the growth rate of the oldest trees declined. This indicates that there is a maximum age that can be reached by trees growing on hummocks (< 150 yr), depending on conditions. The data show that the determination of NEP in bogs by using the peat accumulation above the hypocotyl is a useful method which can be applied on a wide range of bog types, but it may systematically overestimate NEP. The total sink capacity for carbon assimilation of bogs is comparable to that of forest, although methane emissions and losses of dissolved organic carbon must be taken into account when assessing the regional carbon cycle.

1. Introduction

More than half of the wetland phytomass of Russia (55% of a total of 5556 Tg) is located in the main forest zone. More than a quarter (28%) is located in the northern taiga and the forest transition to the tundra, and only 17% is located in the tundra (Shvidenko et al., 2001a) where wetlands and bogs are the dominant vegetation. The Siberian distribution of peat is similar to Finland, where the largest deposits of peat are also found in the southern forest region which had been uncovered from ice earlier than the north (Kauppi et al., 1997). In the boreal region, however, forests have received more attention in the study of the carbon cycle. Bogs in the forest region were widely neglected, even though they contain more carbon than the peat layers in the arctic region. While estimates of total carbon storage in peat exist, we have very little information on the accumulation of carbon in these ecosystems, especially in the Siberian forest belt. According to Shvidenko et al. (2001b), the net primary production of Russian bogs was 0.22 tC ha^{-2} yr^{-1}, which would be about twice as high as the recent carbon accumulation in ombrotrophic mires in Finland (0.10 tC ha^{-2} yr^{-1}; Tolonen and Turunen, 1996).

In the following we will try to quantify the accumulation of *Sphagnum* peat by approaching this problem with two independent methods to be used on the same bog, namely an inventory method using the pine trees as markers for peat accumulation and eddy correlation technology. It will be shown that the inventory approach shows

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an annual accumulation of $0.84\,tC\,ha^{-1}\,yr^{-1}$, which is higher that the average growing season uptake measured by eddy correlation ($0.52\,tC\,ha^{-1}\,yr^{-1}$), and both rates are very similar to the measured carbon sink activity of the surrounding forest ($0.6\,tC\,ha^{-1}\,yr^{-1}$). Thus bogs in the forest belt should receive more attention in view of the global C-budget.

2. Methods

The accumulation of *Sphagnum* peat was measured using the age of pine trees as a marker. (Borggreve, 1889). *Pinus sylvestris* trees growing on hummocks of Aapa bogs germinate in the uppermost layer of *Sphagnum* moss. By developing a root system in deeper moss layers, the position of the hypocotyl remains constant in relation to the deeper layers while *Sphagnum* continues to grow in height, and this growth rate will cover the hypocotyl and the lower stem over time. Thus, the pine tree 'appears' to sink into the peat relative to the bog surface, but it is the growth of *Sphagnum* which causes the burial of the lower stem. Thus, the depth of *Sphagnum* above the hypocotyl and its C-content can be used as a measure of net ecosystem productivity (NEP), because the net accumulation occurs in the oxic zone of the peat, where decomposition might take place. The C-accumulation thus accounts for heterotrophic respiration. Since the hypocotyl rests in fresh growing moss, some compaction will take place in the root horizon of the tree below the hypocotyl, but it is assumed that the tree will follow this compaction and remain in a constant position relative to its surroundings. A typical bending of the lower stem occurs, and it is unclear if this bending results from the compaction process or from snow cover of young trees.

With increasing depth of the moss layer the growing conditions of the tree will deteriorate, because the deeper soil layers will thaw later in spring; also the roots will be located close to the anoxic zone of the upper bog layer and the root system will be flooded periodically with rising water table in spring and autumn. It is expected that the trees will eventually die from shortening of the growing season and periodic anoxic conditions. This is the reason why this method can only quantify the recent accumulation of peat, if living trees are inspected.

In order to quantify the growth of peat on hummocks, chronosequences of pine trees were harvested along hummocks of peat that separate the bog hollows in an Aapa mire where the hummocks are arranged as characteristic stripes perpendicular to the surface flow (Walter, 1968). For the purpose of this study five to six trees were taken along five stripes of *Sphagnum* (26 trees in total). At the stem of each tree the *Sphagnum* was cut out in $0.3\,m \times 0.3\,m$ columns to the depth of the hypocotyl using a saw. Thus any compaction of the material was avoided. The column was separated into visible layers of *Sphagnum* compaction. The total volume of peat was dried at $80\,^{\circ}C$ and weighed. A subsample was taken for C- and N-analysis using an elementary analyzer (Elementar Vario EL, Hanau, Germany).

The C-accumulation rates were compared with measurements taken at an eddy-covariance flux tower which operated between spring 1998 and November 2000. For details of the flux methodology see Kurbatova et al. (2002) and Arneth et al. (2002).

3. Experimental site

The study was undertaken in an ombrotrophic bog of the middle boreal zone, 30 km inland from the Yenisey river near the village of Zotino (60°45′N, 89°23′E). The bog occupies an area of about $5\,km^2$, but it is part of a much larger bog system. The bog is surrounded by Pleistocene fluviatile sand-dunes which are occupied by monotypic stands of *Pinus sylvestris* — lichen forest (Wirth et al., 1999). Mean annual temperature was $-3.8\,^{\circ}C$ between 1936 and 1989. Annual precipitation is 536 mm (45% in summer). Snow melt occurs in early May; first snow falls at the end of September (Schulze et al., 2002).

The microtopography of the bog is characterized by partially inundated hollows where *Sphagnum cuspidatum* and *Scheuchzeria palustris* dominate. In contrast, the hummocks are formed by *Sphagnum fuscum*, *Sphagnum angustifolium* and *Sphagnum magelanicum*, *Eriophorum vaginatum* and some Ericaceous shrubs (mainly *Vaccinium oxycoccus*). *Pinus sylvestris* is restricted to the hummocks. The bog is part of a larger bogdominated drainage system and shows some lateral flow, which results in an arrangement of the hummocks in stripes that are typical for Aapa-type bogs. About 50–60% of the bog surface is hollows.

4. Results

Peat density shows a large variability depending on the rate of active growth of *Sphagnum*. Average density increases from 12.43 ± 4.3 mg_{dw} cm^{-3} at the hummock surface to about 29.51 ± 11.0 mg_{dw} cm^{-3} below 0.3 m depth, which is close to the anoxic zone (Fig. 1A). Tree age increases with the depth of the peat column (Fig. 1B). The C-concentration of dry *Sphagnum* peat increases from 479.2 ± 7.9 mg g_{dw}^{-1} in living *Sphagnum* layers to 504.2 ± 4.8 mg g_{dw}^{-1} in 0.3–0.5 m depth, which is close to the anoxic zone of the peat. The N-concentration of the living *Sphagnum* layer was 6.3 ± 1 mg g_{dw}^{-1} (C/N-ratio of about 76) and it increased to 7.9 ± 2.5 mg g_{dw}^{-1} at depths below 30 cm, which decreased the C/N-ratio to about 60, but the difference between the layers was not significant, indicating surprisingly little decomposition in the upper peat layer (Kuhry and Vitt, 1996). The observed densities are lower than generally reported for peat (115 mg cm^{-3} average for the former Soviet Union; Boch et al., 1995) because our data refer to the aerobic zone of *Sphagnum* bogs, which is less compacted than the deeper layers of peat. In the more compacted lower bog layers C-concentrations increase to $>50\%$ (Yefremov and Yefremova, 2001) and the N-concentrations reach 1% (Yefremova et al., 2000).

Taking the measured changes in density and C-concentrations into account, the C-content of peat that accumulated above the hypocotyl was calculated (Fig. 1C). The C-content increased linearly with tree age at a rate of 0.84 tC ha^{-1} yr^{-1} ($r^2 = 0.76$).

The accumulation can be compared with the eddy correlation measurements carried out on the same bog, which yielded between 0.43 and 0.62 tC ha^{-1} yr^{-1} during the years 1998–2000 (Fig. 2). This is a high estimate because there may be some additional C-losses in late autumn and in winter (Arneth et al., 2002).

Tree height increased linearly with age until about age 50 (Fig. 3). Then the variability in tree height increases depending on growth conditions. The oldest harvested tree was 121 yr, which was not the maximum age that can be reached under these conditions, but mainly determined by the practicality of harvest. The growth rate of the trees, as measured by the width of tree rings at

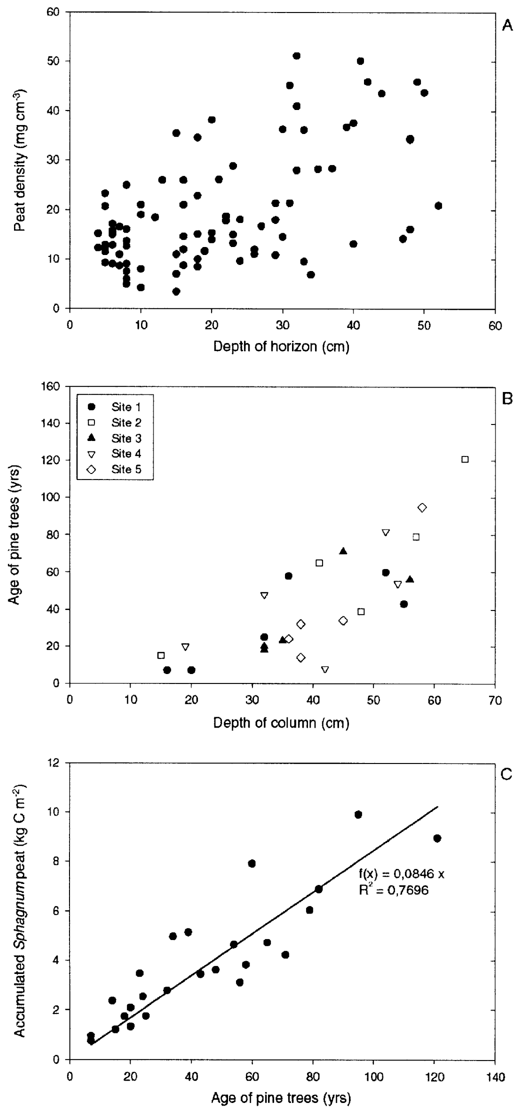

Fig. 1. (A) Peat density as related to depth in the profile. (B) Tree age as related to depth of the peat column above the hypocotyl. (C) Carbon content in the *Sphagnum* peat column above the hypocotyl.

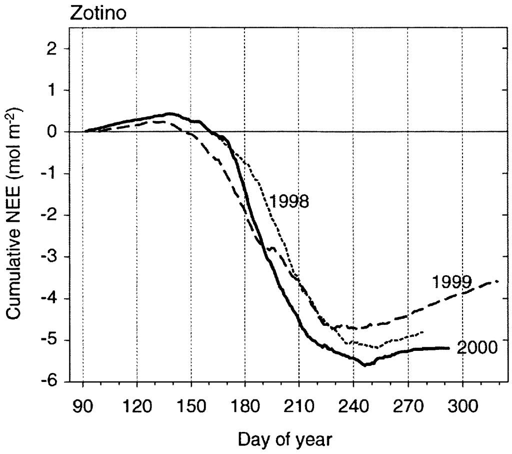

Fig. 2. Cumulative daily eddy fluxes above the bog during summer 1998, 1999 and 2000. The *y*-axis shows the cumulative flux balance of net ecosystem exchange (NEE). The endpoints of the traces represent the annual net ecosystem production, NEP.

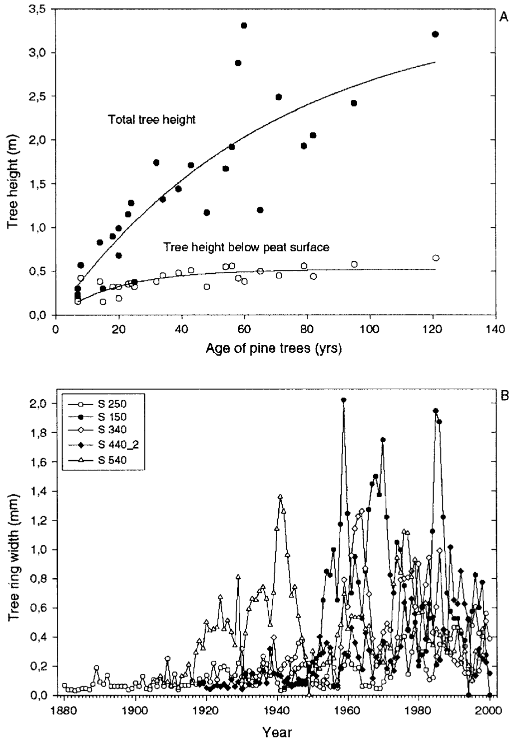

Fig. 3. (A) Total tree height and length of the buried tree base as related to tree age. (B) Tree ring width of the oldest tree at each sampling site as related to the year of growth.

the hypocotyl reached a maximum of 2 mm in one sample tree. In most other trees the maximum tree wing width was about 1 mm. The growth rate decreased with age in most of the oldest trees sampled on each hummock stripe. This would confirm the initial hypothesis that the trees drown in the peat. There were two trees that showed a recent increase in growth, which could indicate small-scale changes in the water relations on the top of a hummock, but this change occurred at very low rates of growth.

5. Discussion

The results of the two very independent estimates of NEP are quite close. It was to be expected that the eddy flux would yield a lower rate of NEP than hummock growth, because C-assimilation in hollows is expected to be much lower than that of hummocks (Ohlson and Dahlberg, 1991; Malmer and Wallèn, 1999). Actually, peat accumulation in the upper layer of hummocks is expected to undergo some decomposition. In the bog under investigation it was surprising to see that the C- and N-concentrations did not change significantly with depth in the oxic layer of the bog, which indicates that the rate of decomposition is very low, while compaction increased. This suggests that decomposition takes place mainly in the anoxic zone, which would yield methane (e.g. Waddington and Roulet, 1996). In the arctic wet tundra of Greenland the CO_2-equivqalent methane emissions reached 24% of the net ecosystem CO_2-exchange (Joabsson and Christensen, 2001).

The observed NEP rates of 0.84 tC ha^{-1} yr^{-1} using the 'Pine' method were lower than observations made by the same methodology in Finland, where recent carbon accumulation was estimated to reach 1.26 tC ha^{-2} yr^{-1} (Tolonen and Turunen, 1996). This difference could well be due to differences in climate, especially the length of the growing season. The rates at the Finish site, however, were also higher than eddy correlation measurements that were carried out in the same climatic region, namely the southern taiga of European Russia. In the central forest reserve near Nedlidovo, south of Finland, 0.6 tC ha^{-2} yr^{-1}

accumulated according to flux measurements. Very similar rates (0.6–0.7 tC ha^{-2} yr^{-1}) to those in this study were reported from long-term inventory studies, using ^{14}C, in continental Canadian *Sphagnum* bogs (Belyea and Warner, 1996). Generally, however, long-term inventory studies (> 1000 yr) result in lower accumulation rates than the 'Pine' method. For Siberia, Lapshina and Pologova (2001) reported peat accumulation rates of 0.145 tC ha^{-1} yr^{-1} in North Siberia and 0.412 tC ha^{-1} yr^{-1} in the southern taiga (range 0.07–0.56 tC ha^{-1} yr^{-1}). When comparing the different data, it becomes clear that the long-term accumulation rates as determined from C-pools and ^{14}C-age integrate millennia which include losses of methane (Joabsson and Christensen, 2001) and dissolved organic carbon, DOC, (Freeman et al., 2001) as well as rare events of fire, while the 'Pine' method observes the same quantity but integrates over a much shorter time-span, namely the last century. The variability of the regression line in Fig. 1C represents the small-scale variation in surface hydrology of a bog and not inter-annual variability. In contrast, the eddy correlation method is focussed on a few years, but it allows the detection of inter-annual variability, which is about 18% around the mean value in Fig. 2. The wet and cool year of 2000 resulted in a much lager net carbon fixation than the dry and warm year 1999. In Canada, a boreal wetland was even a carbon source in a warm year and a sink only in a cold year (Joiner et al., 1999; Lafleur et al., 2001). A similar observation was made in a bog in European Russia (Arneth et al., 2002). Thus the lower rates as measured by eddy covariance as compared to the 'Pine' method could also reflect higher respiration due to recent trends in global warming as compared to average temperatures of the past 100 yr.

It is promising to see that the C-accumulation as measured by the 'Pine' method is in general agreement with the other methodologies when considering the differences in time-frame. This is important, because the accumulation of peat above the hypocotyl of trees can be used fairly easily in a wide range of equally remote conditions. It could be a useful tool for further investigation of a wider range of bog conditions. The limitations of the methodology are just as clear. It can presently be applied only to bogs where the hydrology allows tree growth. However, in principle the 'Pine' method could to be extended to estimate the C-accumulation in hollows or on bogs without trees by using other vascular plants. While the 'Pine' method may overestimate C-accumulation due to neglecting the lower rates of hollows, the eddy covariance method also has intrinsic uncertainties which may underestimate NEP due to high-frequency turbulence above surfaces with low roughness. In addition, many bogs are located in depressions where lateral advective flux of CO_2 could occur from surrounding vegetation. Thus, we think that the actual NEP will be within the two boundaries measured by peat accumulation and by eddy flux.

It is interesting to note that NEP of the pine forest surrounding the investigated bog had a NEP of 0.6 ± 1.1 tC ha^{-2} yr^{-1} (Wirth et al., 2001) showing a large variation, with rates close to zero in young stands and reaching 1.7 tC ha^{-2} yr^{-1} in old stands. A comparison with the NEP of the surrounding forest shows that wetlands in the boreal zone are just as significant as forest in assimilating carbon (Valentini et al., 2000).

Considering the total greenhouse-gas budget, however, the losses of DOC and the emissions of methane must be considered, which will occur mainly from the hollows. Methane may reduce the C-equivalent sink significantly.

6. Conclusions

We conclude, that the 'Pine' method is a useful tool to study recent carbon accumulation in bogs. It may overestimate the carbon sink, but knowing the distribution of hummocks and hollows one could allow for a correction factor. However, it is also conceivable to use root systems of other vascular plants to study C-accumulation in hollows.

It is important to recognize that the C-sink of bogs is of similar magnitude to those of pine forests in Siberia. Thus with respect to the global C-balance wetlands and bogs need more attention and protection. Considering the intensity and frequency of fires and of harvest in forests and despite the measured inter-annual variability in C-assimilation, the net ecosystem productivity of bogs appears to be much more stable over time than of forests.

REFERENCES

Arneth, A., Kurbatova, J., Kolle, O., Shibistova, O. B., Lloyd, J., Vygodskaya, N. N. and Schulze, E.-D. 2002. Comparative ecosystem–atmosphere exchange of energy and mass in a European Russian and a central Siberian bog. II. Interseasonal and interannual variability of CO_2 fluxes. *Tellus* **54B**, this issue.

Belyea, L. R. and Warner, B. G. 1996. Temporal scale and the accumulation of peat in a *Sphagnum* bog. *Can. J. Bot.* **74**, 366–377.

Boch, M. S., Kobak, K. I., Vinson, T. S. and Kolchugina, T. P. 1995. Carbon pools and accumulation in peatlands of the former Soviet Union. *Global Biogeochemical Cycles* **9**, 37–46.

Borggreve, B. 1889. Über die Messung des Wachstums von Hochmooren. *Mittelungen des Vereins zur Förderung der Moorkultur im Deutschen Reich* **7**, 20–23.

Freeman, C., Evans, C. D. and Monteith, D. T. 2001. Export of organic carbon from peat soils. *Nature* **412**, 785.

Joiner, D. W., Lafleur, P. M., Caughey, H. M. and Barlett, P. A. 1999. Interannual variability in carbon dioxide exchanges in a boreal wetland in the BOREAS northern study area. *J. Geophys. Res.* **104**, D22, 27,663–27,672.

Joabsson, A. and Christensen, T. R. 2001. Methane emissions from wetlands and their relationship with vascular plants: an Arctic example. *Global Change Biol.* **7**, 919–932.

Kauppi, P. E., Posch, M., Hänninnen, P., Henttonen, H. M., Ihalainen, A., Lappapainen, E., Starr, M. and Tamminen, P. 1997. Carbon reservoirs in peatlands and forests in the boreal region of Finnland. *Silva Fennica* **31**, 13–25.

Kuhry, P. and Vitt, D. H. 1996. Fossil carbon/nitrogen ratios as a measure of peat decomposition. *Ecology* **77**, 271–275.

Kurbatova, J., Arneth, A., Vygodskaya, N. N., Kolle, O., Varlagin, A. B., Milukova, I. M., Tchebakova, N. M., Schulze, E.-D. and Lloyd, J. 2002. Comparative ecosystem–atmosphere exchange of energy and mass in a European Russian and a central Siberian bog. I. Interseasonal and interannual variability of energy and latent heat fluxes during the snow-free period. *Tellus* **54B**, this issue.

Lafleur, P. M., Roulet, N. T. and Admiral, S. W. 2001. Annual cycle of CO_2 at a bog peatland. *J. Geophys. Res.* **106**, D3, 3071–3081.

Lapshina, E. D. and Pologova, N. N. 2001. Carbon accumulation. In: *Atmospheric exchange by West Siberian peatlands* (eds. W. Bleuten and E. D. Lapshina). University of Utrecht, The Netherlands, 37–46.

Malmer, N. and Wallén, B. 1999. The dynamics of peat accumulation on bogs: mass balance of hummocks and hollows and its variation throughout a millenium. *Ecograph* **22**, 736–375.

Ohlson, M. and Dahlberg, B. 1991. Rate of peat increment in hummock and lawn communities on Swedish mires during the last 150 years. *Oikos* **61**, 369–378.

Schulze, E.-D., Vygodskaya, N. N., Tchebakova, N. Czimczik, C. I., Kozlov, D. N., Lloyd, J., Mollicone, D., Parfenova, E., Sidorov, K. N., Varlagin, A. V. and Wirth, Ch. 2002. The Eurosiberian Transect: an introduction to the experimental region. *Tellus* **54B**, this issue.

Shvidenko, A. Z., Nilsson, S., Stolbovoi, V. S., Gluck, M., Shchepashchenko, D. G. and Rozhkov, V. A. 2001a. Aggregated estimates of the basic parameters of biological production and the carbon budget of Russian Terrestrial Ecosystems: 1. Socks of plant organic mass. *Russ. J. Ecol.* **31**, 371–378.

Shvidenko, A. Z., Nilsson, S., Stolbovoi, V. S., Rozhkov, V. A. and Gluck, M. 2001b. Aggregated estimates of the basic parameters of biological production and the carbon budget of Russian Terrestrial Ecosystems: 2. Net primary production. *Russ. J. Ecol.* **32**, 71–77.

Tolonen, K. and Turunen, J. 1996. Carbon accumulation in mires in Finnland. In: *Northern peatlands in global climatic change. Proceedings of a workshop at Hyytiälä, Finland, Oct 1995* (eds. R. Leiho, J. Laine and H. Vasander). Publications of the Academy of Finland 1/96, 250–255.

Valentini, R., Dore, S., Marchi, G., Mollicone, D., Panfyorov, M., Rebmann, C., Kolle, O. and Schulze, E.-D. 2000. Carbon and water exchange of two contrasting central Siberian landscape types: regenerating forest and bog. *Functional Ecol.* **14**, 87–96.

Waddington, J. M. and Roulet, N. T. 1996. Atmosphere–wetland carbon exchanges: scale dependency of CO_2 and CH_4 exchange on the developmental topography of a peatland. *Global Biogeochemical Cycles* **10**, 233–245.

Walter, H. 1968. *Die Vegetation der Erde, Bd. II, Die gemäßigten und arktischen Zonen.* Gustav Fischer Verlag, Stuttgart, 497 pp.

Wirth, C., Schulze, E.-D., Schulze, W., von Stürzner-Karbe, D., Ziegler, W., Milukova, I., Sogachev, A., Varlagin, A., Panfyorov, M., Grigoriev, S., Kusnetzova, W., Siry, M., Hardes, G., Zimmermann, R. and Vygodskaya, N. N. 1999. Aboveground biomass and structure of pristine pine forests as controlled by competition and fire. *Oecologia* **121**, 66–80.

Wirth, C., Czimczik, C. I. and Schulze, E.-D. 2001. Beyond annual budgets: carbon flux at different temporal scales in fire-prone Siberian Scots pine forests. *Tellus* **54B**, this issue.

Yefremov, S. P. and Yefremova, T. T. 2001. Present stocks of peat and organic carbon in bog ecosystems of West Siberia. In: *Atmospheric exchange by West Siberian peatlands* (eds. W. Bleuten and E. D. Lapshina). University of Utrecht, The Netherlands, 73–87.

Yefemova, T. T., Yefremov, S. P. and Melentieva, N. V. 2001. Nitrogen in Russian bogs. *Soil Science* **9**, 1070–1082 (in Russian).