Invited Review

Environ. Control in Biol., **40**(3), 249-258, 2002

Carbon Fluxes of the Eurosiberian Region

E.-D. SCHULZE, C. WIRTH and M. HEIMANN

Max-Planck Institute for Biogeochemistry, PO Box 100164, 07701 Jena, Germany

(Received June 28, 2002)

The Kyoto protocol and the agreement reached at Bonn requires an assessment of the net carbon balance at different scales, ranging from projects and nations to continents. In the following we give an overview about the biological control of net carbon fluxes. Depending on the processes under consideration, these range from gross primary productivity, GPP (photosynthesis), and net primary productivity, NPP (plant growth), to net ecosystem productivity, NEP (CO_2 assimilation minus heterotrophic respiration), and net biome productivity, NBP, including non-respiratory losses, such as by harvest and fire. We give an overview about the quantification of these processes based on Europe and Siberia. The Kyoto commitment is focused on the woody component of NPP, which is in the order of 1 to 2 t C ha^{-1} $year^{-1}$. But, if all respiratory and non-respiratory losses are considered, the NBP decreases to less than 0.5 t C ha^{-1} $year^{-1}$. Given the uncertainty of the assessments, and the difference between NPP and NBP it appears questionable to include biological sinks into the carbon accounting of fossil fuel emissions.

Keywords : carbon cycle, Europe, Kyoto protocol, productivity, Siberia

THE CARBON CYCLE IN THE CONTEXT OF THE KYOTO PROTOCOL

The carbon cycle of the terrestrial biosphere has received increasing attention with the debate over and the agreement on the Kyoto protocol, which aims at balancing the fossil fuel reduction commitment against human induced increases in the sink activity of terrestrial ecosystems. This general aim puts new constraints on the carbon cycle research, because a regional assessment and verification is needed (Schimel et al., 2001 ; Schulze et al., 2002a). Also, a separate assessment of "human induced activities since 1990" will have to be measured against a high level of background carbon assimilation. Even though only a small fraction of the total sink activity is accountable, an assessment of the full carbon cycle and a C-balance remains an important issue in the verification process, because emissions from land-use may not be fully reported.

Given the political environment, in which the global C-cycle has become a key issue for management decisions, the EU project cluster CarboEurope has received major attention for quantifying the carbon sink of northern Eurasia. This project was established as a feasibility study to explore ways of quantifying sources and sinks on a continental scale (http ://www.bgc-jena.mpg.de/public/carboeur/). Thus, this paper presents comparative data of C-fluxes over Eurasia in order to point at inherent difficulties and limitations when extrapolating from research and inventory plots to regions and when downscaling inversion models to the land surfaces.

Corresponding author : E.-D. Schulze, fax : +49-3641-64-37-94,
e-mail : dschulze@bgc-jena.mpg.de

DEFINITIONAL ISSUES : WHO MEASURES WHAT ?

Terrestrial sinks or sources can be viewed on the basis of ecosystem processes (Schulze and Heimann, 1998 ; Schulze et al., 2000), and Fig. 1 illustrates the compartments that are integrated by Gross Primary Productivity (GPP), Net Primary Productivity (NPP), Net Ecosystem Productivity (NEP) and Net Biome Productivity (NBP). There are different approaches, by which these sink/source terms are being measured. Each approach contains some additional compartments or neglects some component which are part or not part of the original definition. This makes it very difficult to assess and compare data. In the following all data are converted to fluxes per hectare in order to avoid additional confusion about the assessment of total areas.

Following approaches are available. The inversion models (e.g. Gurney et al., 2002) assess fluxes at continental scale, and this includes fossil fuel emissions. The climatology of carbon dioxide (CO_2) in the troposphere will be the ultimate parameter for verification if the human induced changes of the carbon cycle were of success. The fluxes, which are derived from tropospheric CO_2 concentrations and isotope composition contain major uncertainties, but remain an ultimate check where on earth assimilation and emissions take place. The convective boundary layar (CBL)-budgeting method (Laubach and Fritsch, 2002) has similar scope as the inversion models, but can only be carried out during short campaigns. At present it is not an appropriate tool to derive long-term budgets, but the CBL methodology links process studies at canopy scale with fluxes derived from inversion models, and it thus becomes an important verification tool (see also Table 2).

The eddy-covariance flux method (Valentini et al., 2000b) is closest to the process definition of NEP, and it can be used to estimate NBP if harvest and non-respiratory losses are subtracted. However, also this method has its uncertainties when long-term budgets have to be quantified because the determination of the respiratory fluxes remains difficult. Also, in a

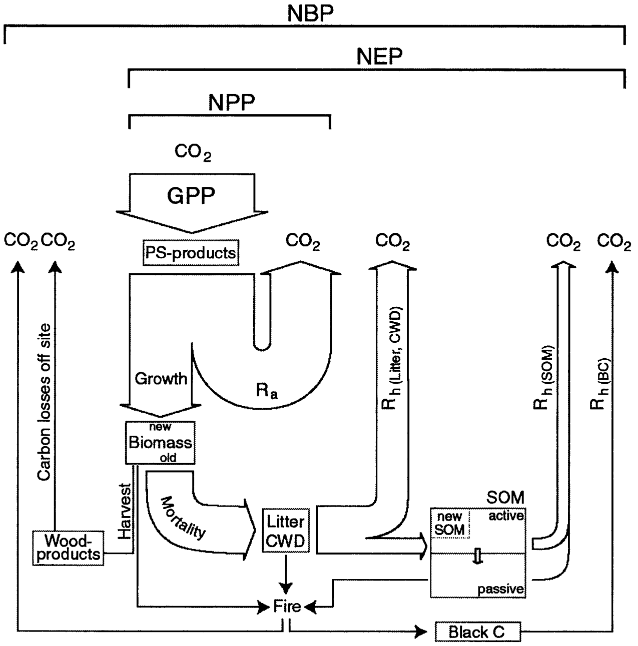

Fig. 1 Schematic presentation of the component fluxes being measured by different methodologies.

variegated landscape, the measuring point may be affected by advection from other ecsystems.

Ecosystem approaches (Schulze, 2000) give insight into the component fluxes, including soils, but processes are generally investigated on small plots which may not represent the landscape, and often do not include the full management cycle ranging from regeneration and thinning to harvest. However, multiple plots can be studied, which cover the variation of a landscape or of the ecosystem type under investigation. Present studies anticipate to cover the long-term development by the study of chronosequences. Nevertheless, research plots will always represent a selected range of conditions. The ecosystem approach derives the different productivity values from the study of plant growth, including fine root turnover, and carbon mineralization (decomposition). The errors involved in fine root and mineralization studies are large. Thus, also ecosystem studies carry a high degree of uncertainty.

Forest inventories (FAO, 2000; Shvidenko et al., 2001) are based on a large geographic scale, and respect national boundaries. They provide data on standing stem volume, increment of stem volume and harvested volume. Stem volume is expanded to whole tree volume of woody tissues, which is then converted into carbon stored by accounting for woody density and carbon concentration. There are two major ways of deriving carbon fluxes based on these data. (1) The difference in tree carbon stores at two points in time is given as a proxy for NBP. (2) The sum of stem volume increment and annual fellings expressed in carbon units is referred to as net annual increment, which may be equated with NPP of woody biomass compartments. Both approaches suffer from the inaccurracy inherent to expansion/conversion factors used. However, expanding from the measured data of stem wood volume to carbon in woody biomass includes a number of assumptions on wood density and on the ratio between woody biomass (stem, branches, twigs, stump and coarse roots) and stem volume, which depend on species, stand age and site conditions. This conversion can only be aggregated into a single number with major uncertainty. An additional difficulty arises in approach (2), since it employs biomass expansion factors to calculate allocation based on biomass distribution but do not reflect growth allocation patterns.

Net biome productivity determination based on soil data has also its intrinsic uncertainty based on the variability in soil carbon. In addition, if the estimate is based on black carbon, the methodology of the chemical analysis remains critical.

THE EURO-SIBERIAN CARBON FLUXES

The scaling problem

NPP decreases when plot studies are compared with large scale inventories (Fig. 2). Plot studies are designed to investigate specific processes, and they are not selected to represent a landscape average. Therefore it is not a surprise to see that landscape averaged NPP is different from NPP observed on plots. The large difference is explained by the fact, that plot studies include turnover of leaves and roots while inventories focus on stems. The data of inventories and plots are much more consistent, if only stem growth is being compared.

NEP is only available for plot studies, and there is no immediate equivalent value for inventories. The NEP flux is about 50% of NPP, which is consistent with earlier predictions, although the rates are higher than expected. It is interesting to see that also unmanaged forests of Siberia remain a significant C-sink at the ecosystem level. The data of Siberia and Europe were mainly taken in old stands, and there are only few campaigns on young forests. In Siberia, the highest rates of canopy flux were observed in 70 year old stands. Regenerations after logging were carbon neutral at least for 14 years (Valentini et al., 2000a). Thus, by focussing on old stands, the average NEP of the eddy flux network will most likely overestimate the regional flux.

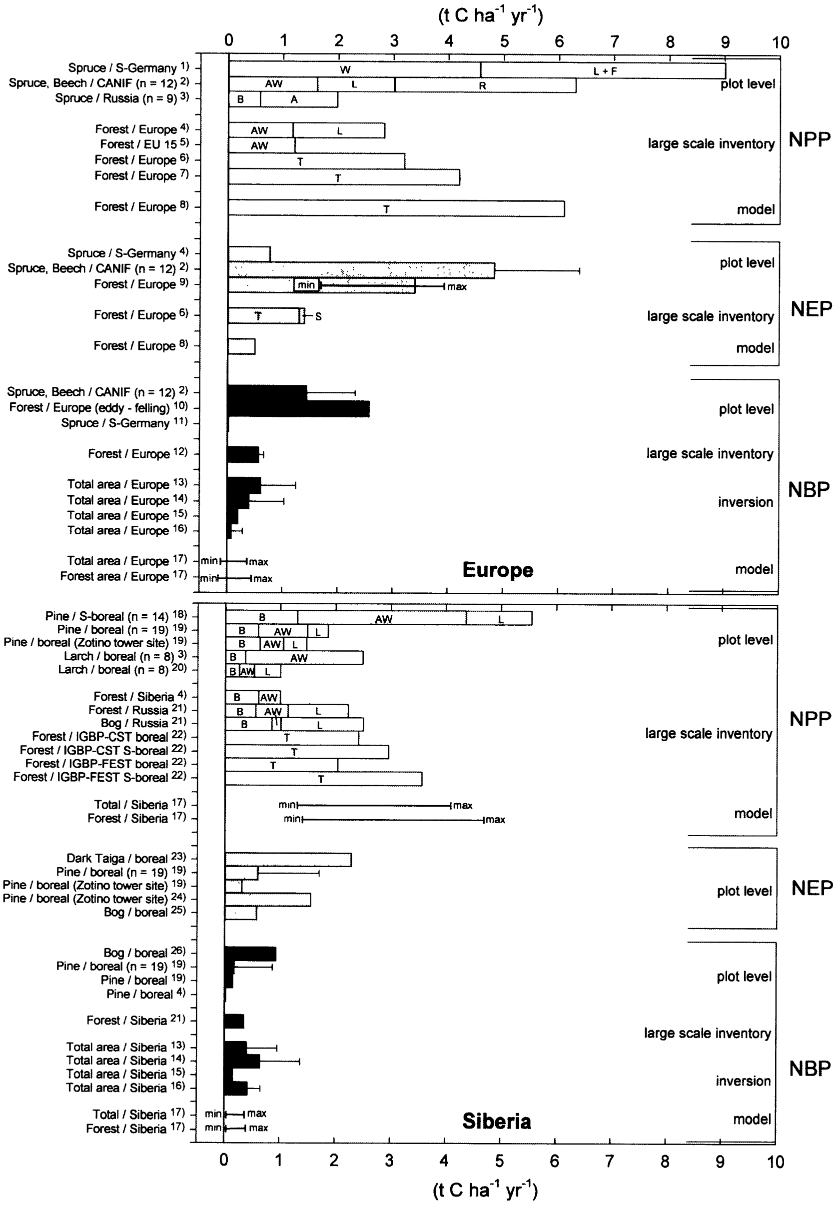

Fig. 2 Comparative presentation of NPP, NEP and NBP measured by different methods across Europe and Siberia.

B, below-ground ; A, above-ground ; AW, above-ground woody ; W, woody ; L, leaf or needle ; F, fine root ; R, compartments other than leaf and wood ; T, total. [1] Mund et al., 2002 ; [2] Schulze, 2000, sites along European CANIF Transect ; [3] Bazilevich, 1993 ; [4] Schulze et al., 1999 ; [5] FAO, 2000 ; [6] Nabuurs et al., 2001 ; [7] Nabuurs et al., 2002 ; [8] Milne et al., 2001 ; [9] Valentini et al., 2000b ; Martin et al., 1998 ; [10] Valentini et al., 2000b ; FAO, 2000 ; [11] Mund (pers. com.) ; [12] Nabuurs et al., 1997 ; Liski et al., 2000 ; FAO, 2000 ; Dolman et al., 2001 ; Nabuurs et al., 2001, 2002 ; Schelhaas and Nabuurs, 2001 ; [13] Gurney et al., 2002 ; [14] Bousquet et al., 1999 ; [15] Rayner et al., 1999 ; [16] Kaminski et al., 1999 ; [17] McGuire et al., 2001 ; [18] Buzykin, 1978 ; Gabeev, 1990 ; [19] Wirth et al., 2002 ; [20] Wang et al., 2001 ; [21] Shvidenko et al., 2001 ; [22] McGuire et al., 2002 ; [23] Röser et al., 2002 ; [24] Lloyd et al., 2002 ; [25] Arneth et al., 2002 ; [26] Schulze et al., 2002b.

Estimates of NBP are surprisingly close, if ecosystem level studies, inversion models and forest inventories are compared for West Europe. Similar to NEP, also NBP does not contain the information where the carbon is being stored. It could be in stems of old trees, in the organic layer above mineral soil or in charcoal after fire. It is to be expected that part of this carbon is sensitive to changes in management and climate. The mean residence time of this carbon that is associated with NBP remains uncertain. If the NBP flux was calculated only on the bass of old soil C, the fluxes would be much lower (Schulze et al., 1999). Apparently, there is an NBP flux in the order of 0.5 t C ha^{-1} $year^{-1}$. It will be very difficult to identify and verify the human induced flux since 1990 for NBP.

To our surprise, in Siberia NBP as derived by inversion models appear to indicate a higher flux than NBP derived from experimental plots. One reason for this observation may be that the highest NBP flux was observed for Sphagnum bogs. This number cannot be extrapolated to the conditions of the northern tundra, and the fate of organic soils under forest remains an issue which needs further consideration. Forests on organic soil that have been studies appear to be a C-souce (Valentini et al., 2000a, b ; Milyukova et al., 2002). At this moment we do not even know the area of forests that grow on peat.

European versus Siberian fluxes

The quantification of continental fluxes is based on an assessment of the areas of different land use and the carbon pools that exist on these areas above- and below-ground. It is assumed that most other C-compartments of these ecosystems, such as soil C, correlate with the C-pool of the plant cover, which has its limitation for organic soils (peat) and for heavily managed systems. In the following we will focus on forests and wooded lands and to some extent bogs, because it is felt that managed grasslands may be close to carbon neutral. It is known that agricultural lands are a C-source (IPCC, 2000), but the magnitude of this flux remains to be studied in future.

The assessment of forest area remains uncertain (Table 1), and it depends on the definition of forest area. Based on the FAO definition, Europe and Russia (including CIS countries and Siberia) have a total area of forest and wooded land of 1.15×10^9 ha, of which 1.03×10^9 ha are proper forest. Thirty-six point eight percent of the total land area is wooded land. If one included orchards and other woody cultivations as a consequence of forest definitions inherent to the Kyoto protocol this number will increase in an yet unknown manner (see also Schulze et al., 1999, 2002a).

Only the above-ground biomass of proper forests has been determined fairly accurately. Above-ground biomass is on average 75 to 84% of total woody biomass. However this number does not include foliage of leaves and needles nor fine roots. It is promising, that the biomass estimates on an area basis are consistent (Table 1). It becomes also apparent, that some of the plot scale studies (e.g. the CANIF study : Schulze, 2000) are based mainly on old stands which have a much higher biomass than the average ensemble of age-classes in Europe. The average biomass of the Euroflux sites is still under assessment. In these cases, it will be necessary to consider the change in biomass over time when interpreting the flux data.

A comparative analysis of the flux data (Fig. 2) indicates, that all fluxes (NPP, NEP and NBP) are higher in Europe than in Siberia, which compensates part of the Siberian advantage of being larger. The difference in fluxes is mainly due to the difference in length of the growing season (Schulze and Schimel, 2001), and not due to age structure. Siberia has larger areas of unmanaged forest than Europe, and young forests regenerating after logging or fire are not necessarily a C-sink at the NEP level (Schulze et al., 1999 ; Valentini et al., 2000a ; Wirth et al., 2002). Also, unmanaged forests of Siberia have an age structure, which is determined by a fire cycle. This age structure could be such that stands consist of a single even-aged

Table 1 Carbon stocks and fluxes in Europe, European Russia and Siberia.

Region	Area (×10³ ha)		Forest biomass (Tg C)		
	Total	Forest	Total	Above-ground	Total biomass per area (Tg/ha)
EU-15[1]	323 963	113 567	4 863	4 105	42.82
Russia[1]	1 709 761	886 538	29 649	22 741	36.30
—European Russia[2]	433 161	166 200	8 599	—	51.70
Siberia[2]	1 276 600	597 300	24 262	—	40.61
—West Siberia[2]	—	90 000	4 460	—	49.60
—East Siberia[2]	—	227 900	11 266	—	49.40
—Far East[2]	—	279 400	8 536	—	30.60

Region	NPP			NEP			NBP		Remark
	Scale	Average	S.D.	Component	Average	S.D.	Average min–max	S.D.	
EU-15	Plot	9.0	2.3	(B+AW+L)	0.8		0.03		Waldstein[3]
	Plot	6.3	1.7	(B+AW+L)	4.8	1.5	1.4	0.9	CANIF[4]
	Plot				3.4[3]	1.9–3.9	2.57[3)4]		Euroflux[5], FAO[1]
Europ. Russia	Plot	1.5					0.8		Shvidenko et al., 2001
	Plot	2.8			−0.16				Schulze et al., 1999
	Plot	2.0							Bazilevich, 1993
Europe	Inventory	2.8		(B+AW+L)					Schulze et al., 1999
	Inventory	3.2		(B+AW+L)					Nabuurs et al., 2001
	Inventory	4.2		(B+AW+L)	1.4[6]		0.6[7]	0.1	see footnote
	Inventory	1.2		(AW)			0.6	0.1	FAO, 2000
	Model	6.1		(B+AW+L)					Milne et al., 2001
	Model						0.04–0.2		McGuire et al., 2001
	Inversion						0.6	0.6	Gurney et al., 2002
	Inversion						0.4	0.6	Bousquet et al., 1999
	Inversion						0.2		Rayner et al., 1999
	Inversion						0.1	0.2	Kaminski et al., 1999
Siberia									
S-Taiga	Plot	5.6[8]		(B+AW+L)					see footnote

Table 1 (continued)

Region	NPP			NEP			NBP		Remark
	Scale	Average	S.D.	Component	Average	S.D.	Average min–max	S.D.	
Boreal-pine	Plot	1.5		(B+AW+L)	0.3	1.4	0.15		Wirth et al., 2002 Zotino
Boreal-pine	Plot	1.9		(B+AW+L)	0.6	1.1	0.2	0.1	Wirth et al., 2002
Boreal-abies	Plot				2.3				Röser et al., 2002
Boreal-bog	Plot				0.6		0.93		Arneth et al., 2002
									Schulze et al., 2002
Boreal-Larix	Plot	1.0[9]		(B+AW+L)			0.3[10]		see footnote
Boreal-Larix	Plot	2.5		(B+AW)					Bazilevich, 1993
Sib-Total	Inventory	2.2		(B+AW+L forest)			0.4		Shvidenko et al., 2001
	Inventory	2.5		(B+AW+L bog)					Shvidenko et al., 2001
	Inventory	1.0		(B+AW)			0.02		Schulze et al., 1999
West	Inventory	0.8		(B+AW)			0.4		Shvidenko et al., 2001
East	Inventory	0.7		(B+AW)			0.3		Shvidenko et al., 2001
Far East	Inventory	0.4		(B+AW)			0.2		Shvidenko et al., 2001
Central	Inventory	2.4–2.9		(B+AW)					McGuire et al., 2001
Far East	Inventory	2.0–3.6		(B+AW)					McGuire et al., 2001
Total	Model	1.3–4.1		(B+AW)			0.04–0.2		McGuire et al., 2002
Forest	Model	1.4–4.7		(B+AW)			0.04–0.2		McGuire et al., 2002
Boreal	Inversion						0.4	0.6	Gurney et al., 2002
Boreal	Inversion						0.6	0.7	Bousquet et al., 1999
Boreal	Inversion						0.2		Rayner et al., 1999
Boreal	Inversion						0.4	0.2	Kaminski et al., 1999

Positive sign denotes an increase in carbon stock, i.e. a C-sink. Negative sign denotes a loss of carbon stock, i.e., a C-source. B, below-ground; AW, above-ground woody; L, leaf or needle. [1]FAO, 2000; [2]Shvidenko et al., 2000, 2001; [3]Waldstein: Mund et al., 2002; Schulze et al., 1999; [4]CANIF: Schulze, 2000; [5]Euroflux: Valentini et al., 2001a, b; [6]Nabuurs et al., 2002; [7]NBP-European inventories: Nabuurs et al., 1997, 2001, 2002; Liski et al., 2000; FAO, 2000; Dolman et al., 2001; Schelhaas and Nabuurs, 2001; Martin et al., 1998; [8]Buzykin, 1978; Gabeev, 1990; [9]Wang et al., 2001; [10]Schulze et al., 1995.

Table 2 Verification of fluxes across scales.

Region	Ecosystem	Canopy-flux	CBL-flux	
Siberia (Zotino)	—	−0.05[1] forest ; −0.03 bog	−0.049[1]	(mg m^{-2} s^{-1})
Germany (Hainich)	—	−0.93[2] forest	−0.72[2]	(mg m^{-2} s^{-1}) forest+ag
Siberia (Zotino)	−0.93[3]	−0.58[4]		(t C ha^{-1} $year^{-1}$)
Italy (Collelongo)	−5.40[5]	−5.65[5]		(t C ha^{-1} $year^{-1}$)

[1] Styles et al., 2002 ; [2] Laubach and Fritsch, 2002 ; [3] Wirth et al., 2002 ; [4] Arneth et al., 2002 ; [5] Schulze, 2000.

cohort, as it is frequently the case in pine and larch, or that uneven-aged stands emerge, which are similar to forests that are managed by selection cutting, in which young and old trees form a mixed canopy. Obviously, the unmanaged forest of Siberia is a carbon sink irrespective of the method used to estimate the carbon balance. This contradicts the view, that "overmature" forests may be carbon neutral. The forest terminology based on "maturity" of the forest is oriented towards harvest and not meant to make inferences on sink/source dynamics.

The variation of the different investigations is not only due to the components being measured by different approaches, but also due to the fact that some uncertainty exists if the same region is being measured by different methodologies. Only few direct comparisons show agreement (Table 2). When a variegated landscape of forest and bogs was measured in Siberia, the 24-h fluxes were very close between CBL-budgets and forest eddy flux, but the CBL-budget for forest alone was about 20% higher than the surface flux if it is considered that bogs cover about 50% of the landscape. In Germany the CBL budget was lower than the eddy-flux by about 20%, but this was due to harvested fields surrounding the forest. Comparing ecosystem and eddy flux budgets, both estimates are very close, if the measurements take place in the same stand. The difference was larger for bogs in Siberia, but in this case the inventory measured the raised hummocks but not the wet depressions of the same bog.

CONCLUSION

We conclude from the EuroSiberian Carbonflux data that

— pristine forests of Siberia are a carbon sink. Human induced changes in land-use (cutting and regeneration of these forests) may result in a decrease of this flux.

— the study of NPP is not sufficient to characterize a plot or a landscape as C-sink.

— the approaches to quantify NBP converge to rather consistent numbers, which range for Europe at about 0.5 t C ha^{-1} $year^{-1}$. The larger flux as observed by eddy covariance (2.5 t C ha^{-1} $year^{-1}$) needs to be corrected for differences in C-stocks. NBP for Siberia ranges between 0.1 and 1 t C ha^{-1} $year^{-1}$, with Sphagnum bogs being the largest sink.

— the uncertainties which are inherent to any regional flux estimate can only be reduced by using a range of methodologies for prediction and verification of the same entity.

REFERENCES

Arneth, A., Kurbatova, J., Kolle, O., Shibistova, O.B., Lloyd, J., Vygodskaya, N.N., Schulze, E.-D. 2002. Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and central Siberian bog. II. Interseasonal and interannual variability of CO_2 fluxes. Tellus **5B** : (in press).

Bazilevich, N.I. 1993. Biological Productivity of Ecosystems of Northern Eurasia. NAUK Publisher, Moscow, Russia (in Russian) ; taken from : http : //www-eosdis.ornl.gov/NPP/npp_home.html

Bousquet, P., Ciais, P., Peylin, P., Ramonet, M., Monfrey, P. 1999. Inverse modelling of annual atmospheric CO_2 sorces and sinks. Part 1 : Methods and control inversion. J. Geophys. Res. **104** : 26161-29193.

Buzykin, A.I. 1978. Productivity of Pine Forests. Nauka Publishers, Moscow, pp 230; taken from: http: //www-eosdis.ornl.gov/NPP/npp_home.html

Dolman, A.J., Hutjes, R.W.A., Nabuurs, G.-J., Schelhaas, M.-J., ter Maat, H. W., Moors, E., Huygen, J., Haarsma, R., Ronda, R., Schaeffer, M., Leemans, R., Bouwman, L., Busch, G., Eickhout, B., Kreileman, E., Strenger, B., de Vries, B., Willemsen, F., Dorland, C., Tol, R., Verhagen, A., Vleeshouwers, L., Kruseman, G., van Ierland, E. C., Holtslag, A. A. M., Ronda, R. 2001. Land Use, Climate and Biogeochemical Cycles: Feedbacks and Options for Emission Reduction. Publication No 410 200 107. Alterra, Wageningen, The Netherlands.

FAO 2000. Forest resources of Europe, CIS, North America, Australia, Japan and New Zealand. United Nations, New York, Geneva, pp 443.

Gabeev, V.N. 1990. Ecology and Productivity of Pine Forests. Nauka Publishers, Novosibirsk, pp 228; taken from: http: //www-eosdis.ornl.gov/NPP/npp_home.html

Gurney, K.R., Law, R.M., Denning, A.S., Rayner, P.J., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y. H. Ciais, P., Fan, S., Fung, I.Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Maki, T., Maksytov, S., Masarie, K., Peylin, P., Prather, M., Pak, B.C., Randerson, J., Sarmiento, J., Taguchi, S., Takahashi, T., Yuen, C.W. 2002. Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. Nature **415**: 626–630.

IPCC 2000. Land Use, Land-Use Change, and Forestry. Cambridge University Press, Cambridge, pp 377.

Kaminski, T., Heimann, M., Giering, R. 1999. A coarse grid three-dimensional global inverse model of the atmospheric transport. 2. Inversion of the transport of CO_2 in the 1980s. J. Geophys. Res. **104**: 18555–18581.

Laubach, J., Fritsch, H. 2002. Convective boundary layer budgets derived from aircraft data. Ag. Forest. Met. **3029**: 1–27.

Liski, J., Karjalainen, T., Pussinen, A., Nabuurs, G.-J., Kauppi, P.E. 2000. Trees as carbon sinks and sources in the European Union. Environ. Sci. Policy **3**: 91–97.

Lloyd, J., Shibistova, O., Zolotoukhine, D., Kolle, O., Arneth, A., Wirth, C., Styles, J. M., Tchebakova, N. M., Schulze, E.-D. 2002. Seasonal and annual variations in the photosynthetic productivity and carbon balance of a central Siberian pine forest. Tellus **5B**: (in press).

Martin, P.H., Valentini, R., Jacques, M., Fabbri, K., Galati, D., Quaratino, R., Moncrieff, J. B., Jarvis, P., Jensen, N. O., Lindroth, A., Grelle, A., Aubinet, M., Ceulemans, R., Kowalski, A. S., Vesala, T., Keronen, P., Matteucci, G., Granier, A., Berbigier, P., Lousteau, D., Schulze, E.-D., Tenhunen, J., Rebmann, C., Dolman, A. J., Elbers, J. E., Bernhofer, C., Grünwald, T., Thorgeirsson, H. 1998. A new estimate of the carbon sink strength of EU forests integrating flux measurements, field surveys and space observations: 0.17–0.35 Gt(C). Ambio **27**: 582–584.

McGuire, A. D., Wirth, C., Apps, M., Beringer, J., Clein, J., Epstein, H., Kicklighter, D. W., Bhatti, J., Chapin III, F. S., de Groot, B., Efremov, D., Eugster, W., Fukuda, M., Gower, T., Hinzman, L., Huntley, B., Jia, G. J., Kasischke, E., Melillo, J., Romanovsky, V., Shvidenko, A., Vaganov, E., Walker, D. 2002. Environmental variation, vegetation distribution, carbon dynamics, and water/energy exchanges. J. Vegetation Sci. (in press).

McGuire, A. D., Sitch, S., Clein, J. S., Dargaville, R., Eser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D. W., Meier, R. A., Melillo, J. M., Moore, III B., Prentice, I. C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L. J., Wittenberg, U. 2001. Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO_2, climate and land use effects with four process-based ecosystem models. Global Biogeochem. Models **15**: 183–206.

Milne, R., Mobbs, D., Grace, J. 2001. The EuroBiota forest ecosystem model. In: "Long-Term Effects of Climate Change on Carbon Budgets of Forests in Europe" (ed. by Kramer, K., Mohren, G.M.J.). Alterra, Green World Research, Wageningen, p. 234–239.

Milyukova, I. M., Kolle, O. E., Varlagin, A. B., Vygodskaya, N. N., Schulze, E.-D., Lloyd, J. 2002. Carbon balance of a southern taiga spruce stand in European Russia. Tellus **5B**: (in press).

Mund, M., Kummetz, E., Hain, M., Bauer, G.A., Schulze, E.D. 2002. Growth and carbon stocks of a spruce forest chronosequence in central Europe. Forest Ecol. Management (in press).

Nabuurs, G.-J., Goodale, C., Pussinen, A., Schelhaas, M.-J., Mohren, G.M.J., Field, C.B. 2002 Temporal evolution of the European forest sector carbon sink since 1950. Global Change Biol. (in press).

Nabuurs, G.-J., Paivinen, R., Sikkema, R., Mohren, G.M.J. 1997 The role of European forests in the global carbon cycle—A review. Biomass Bioenerg. **13**: 345–358.

Nabuurs, G.-J., Pussinen, A., Liski, J., Karjalainen, T. 2001. Upscaling based on forest inventory data and EFISCEN. In "Long-Term Effects of Climate Change on Carbon Budgets of Forests in Europe" (ed. by Kramer, K., Mohren, G.M.J.). Alterra, Green World Research, Wageningen, p 220–234.

Rayner, P.J., Enting, I.G., Francey, R.J., Langenfels, R. 1999. Reconstruction of the recent carbon cycle from atmospheric CO_2, $\delta^{13}C$ and O_2/N_2 observations. Tellus **B51** : 213-232.

Röser, C., Nontagnani, L., Kolle, O., Meroni, M., Mollicone, D., Papale, D., Marchesini, L.B., Federici, S., Schulze, E.-D., Valentini, R. 2002. CO_2-exchange rates of three differently structured stands in central Siberia during one vegetation period. Tellus **5B** (in press).

Schelhaas, M.-J., Nabuurs, G.-J. 2001. Spatial Distribution of Regional Whole Tree Carbon Stocks and Fluxes of Forests in Europe. Alterra, Green World Research, Wageningen, p 300.

Schimel, D., House, J., Hibbard, K., Bousquet, P., Ciais, P., Peylin, P., Apps, M., Baker, D., Bondeau, A., Brasswell, R., Canadell, J., Churkina, G., Cramer, W., Denning, S., Field, C., Friedlingstein, P., Godale, C., Heimann, M., Houghton, R.A., Melillo, J., Mooré III, B., Murdiyarso, D., Noble, I., Pacala, S., Prentice, C., Raupach, M., Rayner, P., Scholes, B., Steffen, W., Wirth, C. 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature **414** : 169-172.

Schulze, E. 2000. Carbon- and Nitrogen Cycling in European Forest Ecosystems. Ecological Studies 142. Springer Verlag, Heidelberg, p 500.

Schulze, E.-D., Heimann, H. 1998. Carbon and water exchange of terrestrial systems. In "Asian Change in the Context of Global Change" (ed. by Galloway, J.N., Melillo, J.). Cambridge University Press, IGBP-Series Vol 3, p 145-161.

Schulze, E.-D., Lloyd, J., Kelliher, F.M., Wirth, C., Rebmann, C., Lühker, B., Mund, M., Knohl, A., Milykova, I., Schulze, W., Ziegler, W., Varlagin, A., Valentini, R., Sogachov, A., Valentini, R., Dore, S., Grigoriev, S., Kolle, O., Tchebakova, N., Vygodskaya, N.N. 1999 Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink — a synthesis. Global Change Biol. **5** : 703-722.

Schulze, E.-D., Prokuschkin, A., Arneth, A., Knorre, N., Vaganov, E.A. 2002b. Net ecosystem productivity and peat accumulation in a Siberian Aapa mire. Tellus **5B** : (in press).

Schulze, E.-D., Schimel, D. 2001. Uncertainties of global biogeochemical predictions. In "Global Biogeochemical Cycles in the Climate System" (ed. by Schulze, E.-D., Heimann, M., Harrison, S., Holland, E., Lloyd, J., Prentice, I.C., Schimel, D.). Academic Press, San Diego, p 3-15.

Schulze, E.-D., Schulze, W., Kelliher, F.M., Vygodskaya, N.N., Ziegler, W., Kobak, K.I., Koch, H., Arneth, A., Kusnetsova, W.A., Sogachev, A., Issajev, A., Bauer, G., Hollinger, D.Y. 1995. Above-ground biomass and nitrogen nutrition in a chronosequence of pristine Dahurian Larix stands in Eastern Siberia. Canad. J. Forest Res. **25** : 943-960.

Schulze, E.-D., Valentini, R., Sanz, M.-J. 2002a. The long way from Kyoto to Marrakesh : Implications of the Kyoto protocol negotiations for global ecology. Global Change Biol. **8** : 505-518.

Schulze, E.-D., Wirth, C., Heimann, M. 2000. Managing forests after Kyoto. Science **289** : 2058-2059.

Shvidenko, A.Z., Nilsson, S., Stolbovoi, S., Gluck, M., Shchepahchenko, D.G., Rozhkov, V.A. 2000. Aggregated estimation of basic parameters of biological production and the carbon budget of Russian terrestrial ecosystems : 1. Stocks of plant organic mass. Russ. J. Ecol. **31** : 371-378.

Shvidenko, A.Z., Nilsson, S., Stolbovoi, V.S., Rozhkov, V.A., Gluck, M. 2001. Aggregated estimation of basic parameters of biological production and the carbon budget of Russian terrestrial ecosystems : 2. Net primary production. Russ. J. Ecol. **32** : 71-77.

Styles, J.M., Lloyd, J., Zoltukhin, D., Lawton, K.A., Tchebakova, N., Francey, R.J., Arneth, A.A., Salamakho, D., Kolle, O., Schulze, E.-D. 2002. Estimates of regional surface carbon and oxygen isotope discrimination during photosynthesis from profles of CO_2 concentration and its isotopic composition in the convective boundry layer. Tellus **5B** : (in press).

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

Valentini, R., Matteucchi, G., Dolman, H., Schulze, E.-D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilgaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, Ü., Berbigier, P., Lousteau, D., Gudmundsson, J., Thorgairsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P.G. 2000b. Respiration as the main determinant of carbon balance in European forests. Nature **404** : 861-865.

Wang, C., Gower, S.T., Wang, Y., Zhao, H., Yan, P., Bond-Lamberty, B.P. 2001. The influence of fire on carbon distribution and net primary production of boreal Larix gmelinii forests in north-eastern China. Global Change Biol. **7** : 719-730.

Wirth, C., Czimczik, C.I., Schulze, E.-D. 2002. Beyond annual budgets : Carbon flux at different temporal scales in fire-prone Siberian Scots pine forests. Tellus **5B** : (in press).