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An estimate of the terrestrial carbon budget of Russia using inventory based, eddy covariance and inversion methods

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Abstract

We determine the carbon balance of Russia, including Ukraine, Belarus and Kazakhstan using inventory based, eddy covariance, Dynamic Global Vegetation Models (DGVM), and inversion methods. Our current best estimate of the net biosphere to atmosphere flux is $-0.66\,\mathrm{Pg\,C\,yr^{-1}}$. This sink is primarily caused by forests that using two independent methods are estimated to take up $-0.69\,\mathrm{Pg\,C\,yr^{-1}}$. Using inverse models yields an average net biopshere to atmosphere flux of the same value with a interannual variability of 35 % (1σ). The total estimated biosphere to atmosphere flux from eddy covariance observations over a limited number of sites amounts to $-1\,\mathrm{Pg\,C\,yr^{-1}}$. Fires emit 137 to 121 $\mathrm{Tg\,C\,yr^{-1}}$ using two different methods. The interannual variability of fire emissions is large, up to a factor 0.5 to 3. Smaller fluxes to the ocean and inland lakes, trade are also accounted for. Our best estimate for the Russian net biosphere to atmosphere flux then amounts to $-659\,\mathrm{Tg\,C\,yr^{-1}}$ as the average of the inverse models of $-653\,\mathrm{Tg\,C\,yr^{-1}}$, bottom up $-563\,\mathrm{Tg\,C\,yr^{-1}}$ and the independent landscape approach of $-761\,\mathrm{Tg\,C\,yr^{-1}}$. These three methods agree well within their error bounds, so there is good consistency between bottom up and top down methods. The best estimate of the net land to atmosphere flux, including the fossil fuel emissions is -145 to $-73\,\mathrm{Tg\,C\,yr^{-1}}$.

Estimated methane emissions vary considerably with one inventory-based estimate providing a net land to atmosphere flux of $12.6\,\mathrm{Tg\,C\text{-}CH_4\,yr^{-1}}$ and an independent model estimate for the boreal and Arctic zones of Eurasia of $27.6\,\mathrm{Tg\,C\text{-}CH_4\,yr^{-1}}$.

1 Introduction

The carbon balance of Russia plays an important role in the global carbon budget, primarily due to its large areas of forest and peat and wetlands and its enormous soil carbon reservoirs. Tundra and wetland make up about 25 % of the total area, 49 % of Russia is forested while agriculture and grassland make up the remaining 16 % (Fig. 1).

Because only a small area of Russia exists south of 50° N and more than half of the country lies north of 60° N, large regions of Russia experience six months of snow cover and soils that are permanently frozen. For instance, the Lena basin is almost covered completely by permafrost, at places up to several hundred meters depth. In these areas, over thousands of years, large stores of carbon in lake sediments, in wetland, forest and tundra soils were created. This could happen because the low temperatures at northern latitudes inhibit microbial decomposition, while carbon input through photosynthesis could remain at high levels during the boreal spring and summers. Consequently, there are now large stores of carbon (C) in northern high latitude regions, particularly in permafrost regions (International Arctic Science Committee, 2010).

IASC (2010), McGuire et al. (2009) and Tarnocai (2009) in what are probably the most up to date and comprehensive reviews of the Arctic carbon balance, estimate soil carbon storage of northern high latitude terrestrial ecosystems to be between 1400 and 1850 Pg in the upper one metre of soil. The precise magnitude and spatial variability remain largely unknown. Schepaschenko et al. (2011b, 2012b) estimated the stock of organic carbon in Russian Federation (RF) at 323 Pg in the first 1 m of the soil, including 16 Pg C in the on-ground organic layer. Zimov et al. (2006) argue that there exists approximately 400 Pg of carbon in currently frozen soils of that was accumulated in non-glaciated regions during the Pleistocene, in what was then steppe-tundra vegetation. These carbon-rich loess soils are called Yedoma sediments. Another 250 Pg C may be stored in deep alluvial sediments below 3 m in river deltas of the seven major Arctic rivers (Schuur et al., 2008), with half of this alluvial carbon being in the Lena delta (Tarnocai, 2009).

Not only soil carbon stocks make the boreal zone of Russia an important player in the global carbon balance. NOAA-AVHRR NDVI trend studies indicated greening trends in the area (Myneni et al., 1997; Zhou et al., 1999). Increasing temperature and the lengthening of the growing season (Serreze et al., 2000; Chapin et al., 2005) would cause enhanced biospheric activity (Lucht et al., 2002; Beer et al., 2006; Chen et al., 2006). A recent study of NOAA-AVHRR NDVI trends indicates a decrease in photosynthetic activity (browning) during 1997–2006, following the greening signal observed during 1982–1997 (Piao et al., 2011; Serreze and Barry, 2011). Piao et al. (2008) and Parmentier et al. (2011) indicate that at the end of the growing season enhanced respiration may reduce the gains in uptake at the spring. Atmospheric inverse models (Bousquet et al., 1999; Gurney et al., 2002; Rödenbeck et al., 2003) and forest inventory studies (Nilsson et al., 2000; Shvidenko and Nilsson, 2003) confirm that there is a carbon dioxide sink in the RF, but the precise magnitude of the sink is still a matter of considerable debate. More recently Quegan et al. (2011), present a multiple constrained analysis of the carbon budget of a large region (~ 300 Mha) in Central Siberia, using forest inventory, remotely sensed data and modeling. Ciais et al. (2010) in an analysis of the northern hemispheric C budget suggest the existence of a net biosphere to land flux of CO_2 of the order of -0.6 to $-1\,\mathrm{Pg\,C\,yr^{-1}}$ for Russia during the period 2000–2004. They also found consistency between the bottom up and top down estimates, within the reported uncertainties of each approach.

Since the early 1990s, Russia has seen some important political developments that bear on our current analysis. After the collapse of the Soviet collective farming system, a significant decrease in area of agricultural lands in Russian Federation occurred. According to the official Russian statistics (Kurganova et al., 2010a), 43 million ha of agricultural lands (including 30.2 million ha of arable) were abandoned after 1990 and the ratio between croplands and grasslands was significantly changed. An estimate for 2009 accounted for 30 million ha of arable lands, which have not been converted to forest (Shvidenko et al., 2010a). This was by far the largest land use change (LUC) of the 20th century in the Northern Hemisphere (Lyuri et al., 2010), of which the implications for shifts in C budgets and pools of the territory of Russian Federation still need to be confirmed. Current estimates of C accumulation in grassland soils after abandonment are uncertain, with estimates of the biosphere to atmosphere flux of from $-8\,\mathrm{Tg\,C\,yr^{-1}}$ (Vuichard, et al., 2008) to $-45\,\mathrm{Tg\,C\,yr^{-1}}$ (Kurganova et al., 2010a,b), mostly in European Russia. In Kazakhstan where cropland area decreased by 40 % between 1990

and 1996, due to abandonment, a C sink could exist as well but has not been estimated.

We provide here an integrated analysis of the full terrestrial carbon budget of Russia based on multiple constraints (e.g., Schulze et al., 2009). This analysis includes all terrestrial and inner aquatic ecosystems (lakes, rivers and other water reservoirs). It should ideally also include fluxes of all important carbon contained gases Pg (carbon-dioxide, CO_2, carbon-monoxide, CO, methane, CH_4 and non-methane hydrocarbons, NMHC), particles and aerosols to the atmosphere, hydrosphere and lithosphere in a spatially and temporally explicit way. While we currently cannot achieve this complete picture, we do present an estimate of the CH_4 balance that is of critical importance in establishing the vulnerability of the permafrost system to climate change. Finally, we consider the processes that impact major components of the ecosystem carbon cycle, such as biological productivity, processes of organic destruction, natural and human-induced disturbances and human consumption of plant products. If useful in guiding both policy implications and further research, our methodology requires assessing uncertainties in a comprehensive way (Shvidenko et al., 2010b). We present as much as possible such an analysis.

To achieve this task, we use four different approaches to couple the different existing time and spatial scales. Bottom up Dynamic Vegetation Models (DGVM) are used to provide insight into the mean and interannual variability in fluxes. DGVM models ignore, however, the effects of other important drivers, in particular forest regrowth, and demography changes, nitrogen deposition and changes in fire disturbance regime. Therefore, we use a comprehensive landscape based inventory method (Landscape Ecosystem Approach, LEA), developed at IIASA (Shvidenko et al., 2010a; Schepaschenko et al., 2011a) to give estimates of C stocks and fluxes. Further observational constraints come in the form of eddy-covariance data from a network of ecological observatories (van de Molen, personal communication) and an analysis of inverse model estimates that provide a top down constraint on the budgets.

2 Methodology and data sources

2.1 Landscape ecosystem approach (LEA)

Within the LEA, the accounting schemes for carbon budgets are a combination of flux-based and pool-based approaches. The flux-based method is applied as a recurrent chain:

$$\mathrm{NEP} = \mathrm{NPP} - H_{\mathrm{SR}} - \mathrm{DEC} - F_{\mathrm{LIT}} - F_{\mathrm{HYD}} \tag{1a}$$

$$\mathrm{NBP} = \mathrm{NEP} - \mathrm{DC} \tag{1b}$$

where NBP, NEP, NPP, are, respectively, Net Biome Production, Net Ecosystem Production, and Net Primary Production, H_{SR} is heterotrophic soil respiration, DEC is the flux due to the decomposition of dead wood, F_{LIT} is the flux to the lithosphere, F_{HYD} is the flux to the hydrosphere, and DC are fluxes caused by natural and human- induced disturbances, including consumption of plant products. The need for including or not-including the lateral fluxes (F_{LIT} and F_{HYD} in Eq. 1 as well as the trade as part of DC in Eq. 2) is defined by the systems boundaries of the account. For the pool-based approach:

$$\Delta(\mathrm{C}) = \mathrm{C}_{\mathrm{syst},t+\Delta t} - \mathrm{C}_{\mathrm{syst},t} \tag{2}$$

where $\Delta(\mathrm{C})$ is the change of carbon pools and $\mathrm{C}_{\mathrm{syst},t+\Delta t}$ and $\mathrm{C}_{\mathrm{syst},t}$ are carbon pools considered in the accounting system at the end and at the beginning of the period Δt, respectively. Poor knowledge of, for instance, carbon pools in soils poses severe restrictions on the use of the pool based method, but for some applications like forest biomass estimated from forest inventories, it provides useful results (Pan et al., 2011).

The empirical basis for the LEA is the Integrated Land Information System (ILIS) for Russia developed by IIASA. The ILIS includes a hybrid land cover (HLC, Fig. 1) and numerous attributive datasets of available measurements. The HLC for the Russian territory was developed based on the system integration and harmonization of

multi-sensor remote sensing products (GLC-2000; MODIS VCF, AVHRR, LANDSAT TM, ENVISAT ASAR, others) and available on-ground data (e.g., State Land Account, State Forest Account, data on natural and human-induced disturbances). The downscaling and parametrization of the HLC is performed at each 1 km pixel using a special optimization algorithm. Details of the approach are described in (Schepaschenko et al., 2011a). Probably, this product represents one of the most accurate descriptions and classifications of terrestrial ecosystems of Russia. Major components of the LEA were defined by sets of different empirical models applied by land classes and bioclimatic zones. Net Primary Production (NPP) was assessed based on numerous in situ measurements (beside those of forests). Forest NPP was estimated by an original, arguably unbiased approach (Shvidenko et al., 2007). Estimates of NPP do not include $\mathrm{CO_2}$ fertilization effect and nitrogen deposition. Heterotrophic Soil Respiration (H_{SR}) was assessed through a special accounting system by identifying type of soil, vegetation class and bioclimatic zone with corrections applied for climatic characteristics of individual growth seasons.

About half of Russian forests have been inventoried more than 25 yr ago (Solontsov, 2010). Thus, data of forest inventories should be treated with considerable caution as their validity depends on the reliability of updating the obsolete forest inventory data. Very few studies have used a relevant combination of remote sensing, ground measurements and empirical models in order to reasonably update reported forest inventory data by regions that can be used in a pool-based methodology (Pan et al., 2011). Two periods were included in the latter analysis: 1990–1999 and 2000–2007. In order to estimate dynamics of soil and dead wood carbon, data of detailed snapshot inventories for 2007 have been used, and the dynamics of these indicators for the above periods were estimated based on empirical models of input organic matter into soil and impacts of disturbances on carbon pools. The analysis was done separately for European and Asian Russia.

The fluxes due to disturbances were defined as the product of the disturbed area and amount of transformed carbon, the calculation schemes accounted for the specifics of each individual type of disturbance (e.g., a modified approach of Seiler and Crutzen, 1980, was used for wild fires). The consumption of plant products (agriculture, forest) was calculated based on official statistical data including imports and exports.

Agricultural land includes currently cultivated and abandoned arable land (that has not been transferred into forest), fallows, cultivated pastures and hayfields. The carbon balance of agricultural land was estimated by accounting all the relevant fluxes of carbon. Thus it includes on the carbon gain side net primary production, the application of fertilizers and liming. Carbon losses include soil respiration, disturbances if relevant (i.e., fire), the lateral flux and consumption. The initial data used comes from Federal State Statistics service reports (FSSS, 2010) by administrative units (81 in total). The following indicators were used: land structure (crops, hayfield, pasture, fallow); seeded area by crop types (grains, industrial crops, vegetables, feed crops); harvest by crops; fertilising (Schepaschenko et al., 2012a).

Empirical equations (Rodin and Krylatov, 1998) were used to assess live biomass fraction and NPP based on the harvest. Crops residuals were estimated as the difference between net primary production and harvest (based on climatic indicators, soil and land use types). Crop residuals were accounted for as an input of organic matter to the soil carbon pool.

2.2 Land use change

Two processes defined land-use change in Russia after 1990s, the crucial period after the decline of the Soviet system where large changes in the economy took place. The first was the abandonment of agricultural land. Estimates of the total area of arable lands withdrawn form agricultural use, given for the period 1990–2005, diverge widely ranging from 10.1 (FAOSTAT) through 34.0 Mha (Larionova, et al., 2003) to 48.6 Mha (as the difference between the total area of arable land by the State Land Account and cultivated land – 76.4 Mha in 2007; FSSS, 2010). The second is the increase of forested area of 31.3 million ha in 1990–2007 (Pan et al., 2011) due to encroaching of

forests in abandoned agricultural land, decreasing harvest (FFS’RF, 2009) and zonal and altitudinal shift of forests likely due to climate change (e.g., Kharuk et al., 2010).

2.3 Eddy covariance estimates

Data were used from 14 sites representing the main ecosystem types in Siberia and European Russia, as listed in Annex I. From west to east they are: an oligotrophic bog, a wet and a dry Spruce forest near Tver on territory of the Central Forest Biosphere State Reserve, 350 km west of Moscow in European Russia; a natural grassland-steppe near Hakasia in Southern Central Siberia (HAK1), a regenerating grassland on agricultural fields abandoned in 1999 (HAK2) and one on fields abandoned in 1994 (HAK3); a bog, a Pine forest, a mixed forest and a Siberian Fir forest near Zotino in Central Siberia; a Larch and a Pine forest near Yakutsk in Eastern Siberia; a typical tundra site near Chokurdakh in North-Eastern Siberia; and a tussock sedge tundra site on a floodplain near the latitudinal tree line near Cherskii in the far Northeast of Siberia. Thus the major ecosystem types taiga, tundra, steppe and taiga-bog mosaic are represented.

Half hourly NEE were first integrated into daily NEE totals. Half hourly data was treated for nighttime corrections and gap-filled according to standard procedures (Reichstein et al., 2005; Papale et al., 2006). Daily totals were accepted only when more than 80 % of the hourly values of a day were present otherwise gap filled. For each site, the daily NEE data were grouped into 61 blocks of 6 days and averaged over all available years. This results in average annual cycles of NEE for all sites, except for Cherskii and Hakasia HAK1, which each required one unfilled block to be filled by linear interpolation. Considering the rather smooth course of NEE, this does probably not introduce a large error. As a first estimate, we assume that not-observed winter-time NEE fluxes are zero. This may be an assumption that causes an overestimation of the uptake. For instance the Spruce forest in Federovskaya shows an estimated loss during winter of around 100 $\mathrm{g\,C\,m^{-2}}$ (Wang et al., 2010), however for forest and tundra experiencing stronger winters this would be less. In the absence of measurements under those conditions, we cannot reliable estimate this quantity further. The annual Net Ecosystem Productivity (NEP) results from integrating the annual course of NEE (we use the term NEE for eddy covariance estimates at time scales shorter than 1 yr and NEP for the annual balance).

2.4 DGVMs

We use the results of 8 DGVMs (Sitch et al., 2008) whose data was collected for the purpose of the TRENDY inter-comparison (http://dgvm.ceh.ac.uk) and made available to the RECCAP participants. The models are run with a merged CRU-NCEP forcing dataset over 1901–2009 (http://dods.extra.cea.fr/data/p529viov/) and provide at their grid resolution, typically 1 degree, estimates of GPP, NPP, NEP and or NBP. Respiration can also be obtained from this data. The models used are CLM4, ORCHIDEE, HYLAND, LPJGuess, LPJ, OCN, SDGVM, TRIFFID (http://www-lscedods.cea.fr/invsat/RECCAP/). The models are run to equilibrium with a 286 ppm CO_2 concentration driven by 1901–1920 climatology. From there a changing climate and CO_2 are prescribed and the runs executed from 1901–2009. The data from the geographical area of Russia are obtained using the RECCAP mask. We included Kazakhstan, Ukraine and Belarus in our current estimates.

2.5 Inverse estimates

We use the results of 11 inverse models, projected again on the RECCAP Russia mask. The data is available mostly from 1990–2008. Table 2 gives the details of the inversion schemes used (see also Gurney et al., 2012, personal communication). Inversions provide estimates of net atmosphere to land CO_2 fluxes, assuming known fossil fuel CO_2 emissions. The land-atmosphere residual CO_2 flux is calculated by removing these fossil fuel CO_2 emissions from the net flux and includes the sum of all-ecosystem NBP, CO_2 emissions from fires, CO_2 fluxes from freshwater systems, CO_2 emissions from peat burning, and CO_2 emissions from harvested wood (e.g. wood decay in landfills)

and food products, including those products imported into Russia by international trade and used in Russia.

Next to these relative large, continental scale fluxes, there area a number of smaller fluxes that need to be known.

2.6 Lateral fluxes to hydrosphere and trade

Lateral fluxes included fluxes to the hydrosphere, lithosphere and trade. Fluxes to the hydrosphere and lithosphere were assessed based on results of measurements in Russian territories (Shvidenko et al., 2010a). For comparison, river export of organic matter was taken from the COSCAT (Meybeck et al., 2006) dataset and provided in Table 3 where for all rivers flowing out of the Russian territory. These numbers are obtained by multiplying discharge with DOC and POC and DIC concentration to obtain the final export fluxes.

For trade, we use the approach and estimates based on Ciais et al. (2008). Wood export is taken from original Russian statistics and the FAOSAT (http://faostat.fao.org/site/628/default.aspx).

2.7 Fire and insect outbreaks

We use two estimates of vegetation fire emissions provided for 1998–2010. In the LEA we use (Shvidenko et al., 2011) burnt areas defined using NOAA AVHRR from the modified algorithm described in (Soja et al., 2004). Regional ground-based regressions were used to eliminate the bias in assessing areas. Carbon emissions were estimated based on Seiler and Crutzen (1980) using land cover characteristics and biophysical indicators from the hybrid land cover. The second estimate is based on the widely used GFED-3 data product (van der Werf et al., 2010). GFED-3 CO_2 emissions are calculated by a revised version of the Carnegie-Ames-Stanford-Approach (CASA) biogeochemical model and improved satellite-derived estimates of area burned, fire activity, and plant productivity to calculate fire emissions for the 1997–2009 period on a 0.5° spatial resolution with a monthly time step. For November 2000 onwards, the GFED-3 estimates are based on burned area, active fire detections, and plant productivity from the MODerate resolution Imaging Spectroradiometer (MODIS) sensor. We extracted the data for the Russian territory.

Emissions caused by biotic impacts in forests (mostly insect outbreaks) were estimated based on an algorithm described in Shvidenko et al. (2010a).

3 Results

3.1 Land ecosystem assessment

The results of the most recent assessment of carbon budget for Russian land by LEA are presented in Table 1 (Shvidenko et al., 2010a). The budget was adjusted to climatic conditions and disturbances of 2009. On average, this year is representative of the average climatic conditions since the 1970s, as 2009 does not show any of the observed extremes (Roshydromet, 2011).

In 2009, terrestrial ecosystems of Russia are estimated to be a net sink of atmospheric CO_2 of $-0.76\,\mathrm{Pg\,C\,yr^{-1}}$. Forests provide for about 90 % of this sink. The sink density of Russian forests is close to the long-term carbon sink density of the EU-25 forests at $-75 \pm 20\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Luyssaert et al., 2010). Overall, these results are close to the previous estimates of IIASA group for 2003–2008 (Shvidenko et al., 2010c) taken into account that that study only estimated NBP for terrestrial ecosystems and consumption of agricultural products was not included in the results. The two major biospheric gross fluxes – NPP and H_{SR} – are estimated at 4.76 and $-3.46\,\mathrm{Pg\,C\,yr^{-1}}$ respectively. Different authors have reported rather diverse results for NPP, ranging from $-2.75\,\mathrm{Pg\,C\,yr^{-1}}$ (Filipchuk and Moiseev, 2003) for ~ 2000, to averages of $-4.35\,\mathrm{Pg\,C\,yr^{-1}}$ for 1988–1992 (Nilsson et al., 2003) and $-4.73\,\mathrm{Pg\,C\,yr^{-1}}$ for 1996–2002 (Zavarzin, 2007) to $5.1 \pm 0.36\,\mathrm{Pg\,C\,yr^{-1}}$ (Shvidenko et al., 2010c). Several applications of the chlorophyll index method reported NPP in limits of ±10 % to the LEA

estimate (Zavarzin, 2007). Our DGVM estimate for NPP is within this range with 4.07–$4.7\,\mathrm{Pg\,C\,yr^{-1}}$ for the earlier part of the 20th century and the last 20 yr (Table 5).

The first spatially distributed estimate of soil respiration for Russia was published by Kurganova (2003) who, based on direct averaging of many year's measurements, estimated soil respiration to amount to 5.67; 2.78 and $2.89\,\mathrm{Pg\,C\,yr^{-1}}$ for the total soil respiration and its heterotrophic (H_{RS}) and autotrophic parts, respectively. Schepaschenko et al. (2011b, 2012b) using information on land-use and ecosystem type, bioclimatic zone, climatic conditions of individual years and NPP on soil respiration, estimated soil heterotrophic respiration of Russian lands at $3.47\,\mathrm{Pg\,C\,yr^{-1}}$, or ~ 25 % more than the estimate by Kurganova (2003). There are a very few (but rather consistent) estimates of CO_2 emissions to the atmosphere caused by the decomposition of dead wood (mostly in forests) – in the range of 0.23–$0.26\,\mathrm{Pg\,C\,yr^{-1}}$ (Zavarzin, 2007; Shvidenko et al., 2010c).

The spatial distribution of this carbon budget (for 2009) shows considerable variation, and substantial areas, particularly on permafrost and in disturbed forests, show both sink and source behavior (Fig. 2).

The forest area increased during the past 18 yr by 31.3 million ha (to 845.6 million ha in 2007). The average change in total organic carbon in forest ecosystems for this period was estimated at $+259\,\mathrm{Tg\,C\,yr^{-1}}$ for Asian Russia (the sink at $-39\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) and $+170\,\mathrm{Tg\,C\,yr^{-1}}$ in European Russia ($-105\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$), giving for the whole of Russia $-429\,\mathrm{Tg\,C\,yr^{-1}}$ ($52\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$). Major contributions to this change were the increase of live biomass (mostly in the European part) and dead wood and on-ground litter (mostly in Asian Russia). The uncertainty of these estimates was estimated to be about ±25 % (CI 0.95) (Pan et al., 2011). We emphasize that in that study the FAO definition of forest was used while all results from the LEA use the Russian definition. This causes a difference in the NBP for Russian land of about 15 %.

Changes in climate of the last two decades provoked substantial acceleration of vegetation fires in the Russian territory. Catastrophic (mega-) fires, enveloping large areas, can be of high severity and provide major impacts on ecosystems and landscapes. Piao et al. (2011) have observed a decline of spring and summer NDVI since 1997 after two decades of greening, and attributed this to climate trends. Over 1982–2005, Goetz et al. (2007) analyzed AVHRR vegetation indices and found increases in North-East Siberia and decreases in the Yakutsk region, attributed to recent fire emissions. Severe impacts appear now to have become a typical feature of the current fire regime. Note that most fires are ignited by humans (Mollicone et al., 2006).

Shvidenko et al. (2011) reported the total burnt area in Russian territories in 1998–2010 to be 106.9 million ha or on average 8.23 million $\mathrm{ha\,yr^{-1}}$ with a substantial interannual variability, from 4.2 (1999) to 17.3 (2003) million $\mathrm{ha\,yr^{-1}}$. Forestland comprises about two-third of this area. The estimated amount of vegetation carbon consumed by fires by the LEA model is on average 121.0 $\mathrm{Tg\,C\,yr^{-1}}$, going from 50 (2000) to 231 (2003) $\mathrm{Tg\,C\,yr^{-1}}$. The uncertainty of this estimate is around ±9 % for the area and ±23 % (CI 0.9) for the emissions. The emitted products of burning included C-$\mathrm{CO_2}$(84.6 %), CO (8.2 %), $\mathrm{CH_4}$ (1.1 %), NMHC (1.2 %). Particulate matter accounted for 3.5 %, of which $\mathrm{PM_{2.5}}$ is 1.2 %. The above estimate of the fire emission does not include decomposition of post fire dieback. This flux is part of DEC in Eq. (1) and on average is of the same magnitude as direct fire emissions.

These fire estimates are close to the results reported in GFED3 (van der Werf et al., 2010) – this study estimated the average burnt area in 1998–2010 at 9.17 million $\mathrm{ha\,yr^{-1}}$ (+11.5 %) and emissions of 137 $\mathrm{Tg\,C\,yr^{-1}}$ (+13.2 %). Figure 3 shows the monthly and annual pattern of carbon emissions due to fires for the two methods used. Noteworthy are the large emissions in 1997 and 2003. Overall, the average emission due to fires during 1998–2010 is estimated at 120–130 $\mathrm{Tg\,C\,yr^{-1}}$, with an estimated uncertainty of ~ 25 %. Note from Fig. 3 that a variability of a factor 0.5 to 3 is estimated around this average value. Note also that fires have a C sink legacy: in Central Russia, NDVI recovery after stand-replacing fires was calculated to occur in 13 yr (Cuevas-Gonzalez, et al., 2009). In absence of a regular forest biomass inventory, it is difficult to estimate the C sink of the area of re-growing forests on Russia. The latter is included as a part of the total sink of the forests.

Carbon emissions due to negative environmental impacts and biotic disturbances were also accounted for. These are for areas affected by insect and diseases, direct consumption of plant products biomass, decrease of NPP and post disturbance dieback of forest. For areas that were disturbed or lost stability, decreasing NPP and increasing post-disturbance dieback were accounted for. The flux of 50.8 $\mathrm{Tg\,C\,yr^{-1}}$ to the atmosphere for 2009 due to impacts of insect and diseases (Table 1) could be considered as a conservative estimate; for years with pandemic outbreaks of foliage-eating insects, such a flux could be substantially higher (e.g., for 2000–2001, when areas affected by Siberian silk worm in Siberia were estimated above 10 million ha)(FFS'RF, 2009).

Overall, agricultural land acts as a substantial sink in the LEA, including the response to abandonment since 1990. However, if consumption of the agricultural products is accounted for, substantial areas of arable land would become a net carbon source. In our budget we separately calculate the consumption at 170.4 $\mathrm{Tg\,C\,yr^{-1}}$ (Table 1).

Wetlands are estimated as a relatively high net sink in 2009 (−53.4 $\mathrm{Tg\,C\,yr^{-1}}$, Table 1). However we have to take into account low carbon emissions due to moderate fires, particularly on wetlands in 2009. On average, fire on wetlands provided ~ 16 % of all the fire emissions in 1998–2010. Note that in the $\mathrm{CH_4}$ budget the wetlands plays a very important role (e.g., Petrescu et al., 2010).

Several land classes were estimated as a net C source – open woodlands, burnt areas, grasses and shrubs (Table 1). Open woodlands are represented, to a significant extent, by forests disturbed by different agents, grass and shrubs are mostly situated in the northern bioclimatic zones on permafrost with a high heterotrophic respiration due to warming during recent decades.

The results from the LEA above are limited strictly to the Russian territory. Reliable information of carbon budgets of Ukraine, Belarus and Kazakhstan is scarce and not complete. These countries have presented their second national communications to the UN FCCC Secretariat (available at http://unfccc.int/national_reports/annex_i_natcom/submitted_natcom/items/4903.php). The common feature for all three countries, supported by some publications, e.g. Bun et al. (2004) is the estimate of forest as a net sink ($-3.6\,\mathrm{Tg\,C\,yr^{-1}}$ in Belarus, -15–$-18\,\mathrm{Tg\,C\,yr^{-1}}$ in Ukraine and $-1.3\,\mathrm{Tg\,C\,yr^{-1}}$ in Kazakhstan on average for the last 5 yr of the reporting period). However, emissions in agriculture and incompleteness, particularly of items of carbon disposal virtually compensate the forest sink and change the total estimate of NBP for the region to within 1–2 %. The default IPCC methodologies used and the incompleteness of the accounts does not allow assessing the uncertainties involved. We therefore exclude the latter results in the overall bottom-up inventory results, but note that this likely causes small errors.

3.2 Eddy covariance based estimates of net ecosystem exchange

Figure 4 shows the cumulative NEE for each of the 14 sites. Three clusters of sites may be distinguished, a wetland cluster where annual CO_2 biosphere to land fluxes occur between -50 and $-90\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, a grassland cluster between -125 and $-170\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, and a forest cluster with more different NEE rates. Among 7 forest sites, 4 sites (Zotino Pine and Fir, Yakutsk Pine and Larix) show an uptake between -200 and $-300\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, and the 3 other (Tver dry and wet Spruce and Zotino mixed forest) have an NEE between 0 and $-150\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$. Consequently, all sites appear as net sinks of CO_2, as expected for growing forests. The wet Spruce forest site near Tver in European Russia is the only site that is on average a source of CO_2 to the atmosphere, whereas it is CO_2 neutral is some years. This may be explained by the mature successional stage of the forest, the large respiration from the boggy soil and the contribution to the flux of an area of wind throw in the area. It must be noted that the Tver sites are more sensitive than other sites to treatment of low turbulence data, probably because of the larger amount of winter measurements and the frequency of calms. The slope of the lines in Fig. 4 is a measure of the daily uptake rate. It is striking to see that, except for the bog sites near Tver and Zotino, the slopes compare well for a large number of sites in the middle of the growing season (growing season is loosely defined here as the season when carbon dioxide uptake occurs). The

differences in annual CO_2 uptake between sites appear to correlate well with the length of the growing season. This suggests that the length of the growing season does not only determine to a large part the variability of NEE between years, but also between sites. The length of the growing season varies from about 2 months at the tundra sites to about 7 months in Tver. The assumption of zero NEE before and after the measurement season is not supported by the Fig. 4 for some sites, most notably the Fir and mixed forest near Zotino and the Pine and Larch forests near Yakutsk and the tundra site near Chokurdakh.

From the direct observations of NEE, NEP is calculated including corrections for neglect of winter fluxes (Wang et al., 2011) and the use of an open path sensor that is sensitive to significant errors in conditions of cold temperatures. For forest a low and high estimate that is based on the age class distribution of forest and the sampling bias that nearly all eddy covariance observations are taken in well-established well growing forests. Thus NEE from flux observations is somewhat being biased to a CO_2 sink (Wang et al., 2011). The lower NEP estimate (66 % of the NEE based value) is most likely to be closer to reality than the higher one. Table 2 presents these values and the total scaled value based on relative area. The final estimate of NEP of Russian ecosystems is a net sink of $-1.33\,\mathrm{Pg\,C\,yr^{-1}}$, which compares with that obtained by the LEA technique, when excluding the export of C from ecosystems to rivers headstreams and timber removal from forest, gives NEP of $0.94\,\mathrm{Pg\,C\,yr^{-1}}$. This is largely due to the fact that in both bottom up estimates forest is the main contributor and those estimates are close.

Table 2 presents the final results of NEP estimated from the limited available set of eddy covariance towers across Russia. We present also a scaled up estimate based on these observations. We note a number of uncertainties. First, the estimate is based on a limited number of sites that are considered representative of each biome. This is an assumption that needs to be made, but is hard to verify or quantify. The second issue relates to the estimate of land use change fluxes. To estimate the uncertainty associated with this, we present in Table 2 estimates from both the LEA system and the Gobal Land Cover estimates of land cover (GLC, 2000). For forests the estimates on NEP between LEA and flux towers up scaling are quite close, for tundra and wetland however, large differences exist. This sensitivity of emissions to land cover classification was noted earlier by (Petrescu et al., 2010) who identified the land cover estimates as one of the main uncertainties in estimating CH_4 emissions. Karelin and Zamolodchikov (2008) have provided an assessment of NEE in Russian tundra on 11 sites also from eddy covariance data and came to an average NEE of $-4.9 \pm 17.4\,\mathrm{g\,C\,m^{-2}}$. This close to neutral CO_2 balance of tundra is also rather different from our current estimate. Without further details on the precise methodologies followed remains hard to identify which of these estimates is more realistic. Our current estimate is however close to that of LEA.

3.3 River export

The river export from Russian rivers to the coastal seas is taken from the COSCAT catchments database (Meybeck et al., 2006) that contain rivers exporting into the ocean (Table 3). The total summed outflow is $16.1\,\mathrm{Tg\,C\,yr^{-1}}$ for dissolved (DOC) and $10.3\,\mathrm{Tg\,C\,yr^{-1}}$ for particulate (POC) organic material. Total dissolved inorganic (DIC) material is $29.9\,\mathrm{Tg\,C\,yr^{-1}}$, this brings the total outflow of carbon to $56.4\,\mathrm{Tg\,C\,yr^{-1}}$. The majority of carbon export takes place into the coastal Arctic seas with the main contributions coming from the Ob, Yenisey and Lena ($30.8\,\mathrm{Tg\,C\,yr^{-1}}$). A much smaller export takes place from the rivers flowing into the Japan and Ohkostk seas. It is important to note that the rivers draining into lakes and endhorheic basins also present a noticeable outflow of carbon. Other published estimates are similar from 23.5 to $28.4\,\mathrm{Tg\,C\,yr^{-1}}$ for DOC + POC and $33.8\,\mathrm{Tg\,C\,yr^{-1}}$ for DIC delivered to Arctic seas of Russia (Romankevich and Vetrov, 2001). The fate of this terrestrial carbon on the continental shelves is not examined in this study, but a significant fraction could be oxidized. Note also that recent results suggest that the outflow as measured at the mouth of the rivers, is not necessarily equal to the input from the terrestrial ecosystems, and that during transport biogeochemical transforms may take place (Battin et al., 2009) which make substantial re-assessment of our estimates probable.

Based on aggregation of available measurements on Russian territories, Shvidenko et al. (2010c) reported the total lateral export of organic carbon from the catchments to the hydrosphere and lithosphere at $81 \pm 36\,\mathrm{Tg\,C\,yr^{-1}}$ of which the export to the hydrosphere comprises $61 \pm 31\,\mathrm{Tg\,C\,yr^{-1}}$, comparable to our numbers and the carbon accumulation on geochemical barriers of the lithosphere at $20 \pm 18\,\mathrm{Tg\,C\,yr^{-1}}$. The export to the hydrosphere includes C fluxes to all rivers and numerous interim lakes. These estimates are in line with a recent global analysis (Alvarez-Cobelas et al., 2012).

3.4 Land use change and land abandonment since 1990

Land use change is often estimated by a bookkeeping method based on Houghton et al. (2012). Unfortunately after 1990 this database is not updated while considerable changes occurred after the fall of the economic Soviet system and this present a problem. Particularly, the area of arable lands in Russia has drastically decreased since the early 1990s when the Soviet economy collapsed. This land use change (LUC) is considered the largest of the 20th century in the Northern Hemisphere and is responsible for a substantial CO_2 sink determined by the recovery of soil organic carbon that was previously depleted during intense cultivation (Guo et al., 2002). Formerly ploughed lands were indeed found to increase the carbon content in the soil profile already after 4 yr since the LUC, as a consequence of the encroachment of recovering grassland vegetation (Kurganova et al., 2008). Vuichard, et al. (2008), using a model prescribed with FAO data for rates of cropland abandonment estimated a mean sink of $-8\,\mathrm{Tg\,C\,yr^{-1}}$ between 1991 and 2000 ($-47\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$). This is likely to represent an underestimate because regrowth of forest and shrubs over abandoned farmland was not modeled, and the study was restricted to Southern European Russia, whereas significant abandonment took place after 2000 in Belarus, and after 1990 in Central Asian former SU territory (e.g., Kazakhstan), see for instance Henebry (2009).

According to field measurements of soil carbon content after LUC, carbon accumulation rates decline over time and are well described by a negative logarithmic model with the soil carbon pool tending asymptotically to a new equilibrium level (Kurganova et al., 2010a). Observed average changes in soil carbon are $132 \pm 21\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (mean ± SE) within 15 years after land abandonment, $67 \pm 9\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ between 15 and 30 yr and drop to $43 \pm 4\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ when arable fields remain uncultivated for > 30 yr.

The magnitude of the sink varies also across different soil types of the Russian agricultural regions: mean carbon accumulation rates within the 0–20 cm soil layer during the first 15 yr after abandonment range from $-66 \pm 24\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in Kastanozems to $-175 \pm 52\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in Chernozems, with Albeluvisols and Phaeozems having similar intermediate rates (-131 ± 13 and $-134 \pm 36\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, respectively). However as a result of the high variability in the rates of accumulation for each soil type, there are no significant differences among different geographical regions. Interestingly, estimates of the carbon balance of abandoned croplands on chernozem soil in Hakassia at 5 and 10 years after LUC, made by eddy covariance measurements of ecosystem CO_2 fluxes show NEE rates of −216.2 and $-143.3\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Belleli, 2007) which agree with the above results from soil inventories.

Estimates of total carbon sequestration in abandoned agricultural soils in Russia after 1990 differ widely by one order of magnitude (−64 to −694 Tg C) because of differences in methodological approaches, limited amount of experimental data, time periods addressed, but mostly due to inconsistencies in the area of abandoned arable land among different statistical sources. On the assumption that the most realistic area abandoned arable lands since 1990 in Russia is 30.2 Mha (FSSS, 2009; the remote sensing estimate consistent with the area of cultivated land is 34.9 Mio ha in 2009; Shvidenko et al., 2010a), the results of study so far based on the largest number of experimental data (Kurganova et al., 2010) indicate the total carbon accumulation in the first 20-cm depth of soil of former arable soils to be $-548 \pm 35\,\mathrm{Tg\,C}$ over the period 1990–2006. This yields an average rate of C accumulation of $-34 \pm 2.2\,\mathrm{Tg\,C\,yr^{-1}}$ in the 1990–2006 time window.

3.5 Forest products and wood export-import

Official data of removal of wood from Russian forests is low-biased due to substantial illegal harvest and only partial accounting of the rural consumption. The total removal due to all types of harvest is estimated at $51\,\mathrm{Tg\,C\,yr^{-1}}$ for 2003–2010. Of the total removal, wood products export minus import was accounted at $-21.1 + 1.1 = -20\,\mathrm{Tg\,C\,yr^{-1}}$, with export substantially exceeding import (Shvidenko et al., 2010a). The carbon balance of wood product pools, that eventually release CO_2 back to atmosphere, includes increases in the long-term wood product pool ($12\,\mathrm{Tg\,C\,yr^{-1}}$) short-term pool emissions including fuel wood, unused waste and residuals of wood processing ($-19\,\mathrm{Tg\,C\,yr^{-1}}$), and the flux from previously accumulated wood products. In Russia, the total amount of C stored in wood product pools decreases with time because the new inputs are less than the output reflecting former decades of higher harvest. Harvest as a component of NEE, corresponds to a sink of $-51\,\mathrm{Tg\,C\,yr^{-1}}$. In the total harvest component of NEE, trade (export) accounts for a sink of atmospheric CO_2 of $-20\,\mathrm{Tg\,C\,yr^{-1}}$. Finally, the wood products (including trade) present a net land-to-atmosphere CO_2 flux over Russian territory of 51 (harvest) – 21 (net trade) – (−5) (decrease in wood product pools), that is a net CO_2 source to the atmosphere of $25\,\mathrm{Tg\,C\,yr^{-1}}$ (Ciais et al. unpublished data). Based on official data from FAOSTAT, the flux due to the wood export is estimated to be 12.5 (±3) $\mathrm{Tg\,C\,yr^{-1}}$. Import of food and other carbon products amount to $-18\,\mathrm{Tg\,C\,yr^{-1}}$.

3.6 Inverse model estimates

We use the results of 12 different inversion models and extract the values for the Russian territory. In Fig. 5 we show the mean and the range (min, max) of the inversion schemes. Note that towards the end of the period, the number of models, as well as the number of observational stations used in the inversions, increases. Most of the model estimated net-land-atmosphere CO_2 flux, with subtracted fossil CO_2 emissions, suggest a relative stable sink of atmospheric CO_2, while some others suggest a slowly increasing sink. For our analysis we use the mean atmosphere to land CO_2 flux of the last 10 yr at −653 Tg C yr^{-1} for the period of 1998–2008 for which most of the models yield results (Table 4). There is no uncertainty estimate attached to these numbers other than their range, which is expressed here by a standard deviation of 130 Tg C yr^{-1}. Chevalier et al. (2011) propagated the full error covariance matrix for a single inversion model and obtained over Russia an uncertainty of the order of 0.7 Pg C yr^{-1} (1σ Gaussian error). We also show the interannual variability as estimated by the standard deviation of the yearly estimates from each model. This is reasonably consistent at around 200–250 Tg C yr^{-1}). These results are furthermore in line with published model results which are available for NBP Boreal Asia of −630 Tg C yr^{-1} for 1280 million ha (Maksyutov et al., 2003), −580 Tg C yr^{-1} (from an average of 17 inverse models, Gurney et al., 2003), and −332 Tg C yr^{-1} (Baker et al., 2006). For the entire Russia 4 different inversions recently developed, and solving for fluxes over the transport model grid for 3 out of 4 inversions, for the period 2000–2004 Ciais et al. (2010), gives a net biosphere to atmosphere flux of CO_2 about −600 to −700 Tg C which agrees well with our mean value. While thus the exact magnitude of the Russian sink can vary, the balance of the evidence suggests a strong and consistent (i.e. small interannual variability) biospher to atmosphere flux of around −650 Tg C yr^{-1}.

3.7 DGVMs

The use of DGVMs at national level (even for such a large country as Russia) has both weaknesses and strengths. DGVMs allow us to study primarily interannual variability and trends as the long term balance between GPP and respiration is determined by a steady assumption. From other side, DGVMs tend to oversimplify the real land cover; generally consider only "potential" land cover and do not include some important land classes for Russia (e.g., bogs); underestimate (or ignore) disturbances and lack forest age classes and ignore harvest. As a rule, they also do not include crucial regional features such as permafrost, thermokarst processes and do not yet adequately include impacts of disturbances.

Virtually all DGVMs of the RECAPP database show an increase in GPP over the whole period from 1920 to 2008. This is balanced by an equally increasing amount of respiration. The average NBP, averaged over the Russian territory for the last 20 yr as estimated by these models is stable and points to a small source of 199 Tg C yr^{-1}, however the variability between the models, as expressed by one standard deviation in Table 5 is large and amounts to 100 % of this value. The average of the DGVM's NPP is very close to that of the LEA and the inverse model estimates, suggesting a likely overestimation of heterotrophic respiration by DGVMs at high latitude. The ratio GPP/NPP is for the total period 0.48 and increases to 0.51 for the last 20 yr, the corresponding ratio NPP/NBP doubles from 0.02 to 0.04. This suggests that the increase in GPP is not directly translated in NPP, but that from NPP the carbon is increasingly allocated into the more stable pools. However, it must again be noted that differences between models are large.

Our final bottom up estimate of the Russian net land to atmosphere flux is based on the sum of the eddy covariance estimate minus the smaller fluxes of fires, outflow, trade, crop abandonment, and amounts to −563 Tg C yr^{-1}, this is close to the independent bottom up estimate of the LEA system and to that of the inversions. With an estimated 418 to 490 Tg C of fossil fuel per year (UNFCCC, Shvidenko et al., 2011), this leaves a net atmosphere to land flux of −145 to −73 Tg C yr^{-1}.

3.8 CH_4 fluxes

The total emissions from Russia of CH_4 from 2001 to 2005 are 19.5 Tg C yr^{-1} (EDGAR), of these 15 Tg C yr^{-1} is due to the production of primary fuel, 1.5 Tg C yr^{-1} due to enteric fermentation of livestock, the rest made up of waste land production and biomass burning. Waste-water treatment also adds close to 1 Tg C yr^{-1}.

The net efflux of methane to the atmosphere caused by the biosphere within the Russian territory was estimated by a "semi-empirical" landscape-ecosystem approach at 16.2 ± 3.9 Tg C-CH_4 yr^{-1}. Model estimates of CH_4 fluxes for the Russian territory were derived by Petrescu et al. (2010) at 27.6 TgC-CH_4 yr^{-1}. This estimate refers only to boreal and arctic wetlands. A comparable estimate for boreal Asia, based on a combination of the biogenic MDM-TEM and the fire emissions, reported the annual release of around 41.5 TgC-CH_4 yr^{-1} between 1997–2006, with the most of emissions (38 TgC-CH_4 yr^{-1}) from the biogenic sources (McGuire et al., 2010).

Previous estimates of the biosphere's methane flux are very diverse – from 11 TgC-CH_4 yr^{-1} (Harris et al., 1993) to 20 TgC-CH_4 yr^{-1} (Nilsson et al., 2000) to 30 TgC-CH_4 yr^{-1} (Zelenev, 1996) and even 39 TgC-CH_4 yr^{-1} (Rozanov, 1995). More recent regional estimates demonstrate more consistency. If the estimates of methane flux for West Siberian wetlands during the last two decades differed at order of magnitude (from 1.6 to above 20 TgC-CH_4 yr^{-1}), estimates of the last several years vary around 3.2–3.5 TgC-CH_4 yr^{-1} (e.g., Glagolev et al., 2010a) that is very close to the above LEA estimate for this region above (3.4 TgC-CH_4 yr^{-1}). Modeling results for West Siberia are comparable to these estimates (Kim et al., 2010; Glagolev et al., 2010b).

4 Discussion

The bottom up, landscape-ecosystem approach, eddy covariance upscaling and inverse modeling present rather consistent results. The terrestrial ecosystems of Russia served during the last decade as net biosphere to atmosphere flux of at −0.6 to 0.8 PgC yr^{-1}, and forests provided 90–95 % of this value. Interannual variability of NBP is driven by seasonal weather, but is not extremely large in absolute terms, while locally regimes of natural disturbances, mostly fire and insect outbreaks may cause substantial carbon losses.

The landscape-ecosystem approach is a detailed, spatially explicit carbon account for the Russian territory (Shvidenko et al., 2010a,b). In spite of the conclusion that the country as a whole serves a net carbon sink, it finds that substantial areas are neutral or act as a relatively small carbon source. These areas are mostly confined

to permafrost territories. This could be considered and indication that substantial areas at high latitudes may switch from sink to source as a result of regional warming causing increased soil heterotrophic respiration. The application of a set of DGVM's to arctic tundra demonstrated a similar tendency (McGuire et al., personal communication). The same tendency is reported for the entire high latitude circumpolar belt (Hayes et al., 2011); however, the fire emissions in these studies are substantially higher than the empirical estimates (Van der Werf et al., 2010; Shvidenko et al., 2011). It is important to note that the balance between an earlier start of the growing season and increased autumnal respiration determines the annual net carbon balance. Parmentier et al. (2011) using eddy covariance observations over an East Siberian tundra site found that the overall variability in net carbon uptake over a period of ten years was low, and no relationship with growing season length was found. In contrast to expectations and previous studies, they also found that the highest net uptake of carbon occurred with the shortest and the coldest growing season. Low uptake of carbon mostly occurred with longer or warmer growing seasons. They conclude that the net carbon uptake of this ecosystem is more likely to decrease rather than to increase under a warmer climate.

Quegan et al. (2011) use a similar approach as in the current study to estimate the carbon budget of Central Siberia. They find an average biosphere to atmosphere flux of $-27.5 \pm 7.2\,\mathrm{gC\,m^{-2}\,yr^{-1}}$, which corresponds to about −470 TgC yr^{-1} if extrapolated to the Russian territory of $17.1 \times 10^{12}\,\mathrm{m^2}$ (Table 2). The difference is likely to be found in the different areas investigated, with the current approach covering a wider variety of land use type and climate. There are also carbon budget assessments obtained by different empirical applications of the flux-based method based on different inventory data. Overall, Zavarzin (2007), Kurganova et al. (2010), Filipchuk and Moiseev (2010) report rather consistent results in the estimation of the accumulated NBP of the country's terrestrial ecosystems or individual classes, such forests and agriculture. However, the major carbon fluxes like NPP, HSR and particularly fluxes caused by disturbances, differ in these studies by up to factor of 3–4 due to different inputs, completeness and reliability of the accounting methodologies. As an example, estimates of forest NPP were 204 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Filipchuk and Moiseev, 2003) to 275 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Zamolodchikov and Utkin, 2000) and even to 614 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Gower et al., 2001). Importantly the uncertainties of these latter estimates are not known.

Lack of knowledge and insufficient empirical data are among important reasons, which contribute to uncertainties of the results. For instance, it has been shown that assessment of forest NPP based on field measurements leads to biased conclusions because practically all measurements in situ (made in Russia by destructive methods) are not able to account for some important components (e.g., carbon turnover of fine roots, root exudates, VOC). Uncertainty of upscaled eddy covariance data cannot be assessed by formal methods due to the small amount of measured sites and, that is more important, due to lack of reliable gradients for upscaling of “point” measurements. However, these estimates do generate a “probable space” for the Net Ecosystem Exchange.

Inverse modeling supplies important top down information for verification. Our analysis shows almost identical results for the landscape-based approach, the eddy covariance approach and the average of the inverse modeling schemes. While these agreements still may fortuitous, the fact that most of the uptake is achieved by Russian forest, and the results of the LEA and eddy covariance agree in that respect, gives confidence in our overall estimate of $-659\,\mathrm{Tg\,C\,yr^{-1}}$ for the Russian carbon balance, applicable for conditions of the last ten recent years. The fact that the three methods are so close would put the uncertainty around 100 $\mathrm{Tg\,C\,yr^{-1}}$, close to the standard deviation of the three approaches.

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Table 1. Carbon fluxes ($\mathrm{Tg\,C\,yr^{-1}}$) from LEA associated with biosphere by sources and land classes. Sign "–" means an efflux to the atmosphere (Shvidenko et al., 2010a) – still unpublished.

Land class	Area	Carbon flux, $\mathrm{Tg\,C\text{-}CO_2\,yr^{-1}}$ by source					
and processes	10^6 ha	NPP	H_{SR}	DEC	Fire	Insect	Balance
Forest	820.9	2610.2	1637.0	175.0*	55.5	50.8	−691.9
Arable	77.8	409.1	330.4		0.4		−78.3
Hayfield	24.0	109.1	79.5		1.1		−28.5
Pasture	68.0	330.8	212.0		1.7		−117.1
Fallow	19.0	21.2	16.7		0.3		−4.2
Abandoned arable	29.9	151.6	104.5		1.0		−46.1
Wetland	144.6	395.2	317.5	3.3	21.0		−53.4
Open woodland	85.1	84.2	116.0	2.8	5.7		40.3
Burnt area	23.7	32.9	38.9	13.4	1.4		20.8
Grass & shrubland	315.7	618.8	611.4	13.2	9.2		15.0
Interim water****	44.0						11.8
Consumption of plant products							170.4**
Biosphere total	1709.8***	4763.2	3463.8	201.4	97.2	50.8	−761.3

* Including site effect of forest logging (6.3 $\mathrm{Tg\,C\text{-}CO_2\,yr^{-1}}$).

** Including wood products (28.4 $\mathrm{Tg\,C\text{-}CO_2\,yr^{-1}}$).

*** Including unproductive areas and infrastructure which are not indicated in Table.

**** $\mathrm{C\text{-}CO_2}$ flux from inland water reservoirs; note that results of Table 1 does not account for C export to the hydrosphere and the lithosphere.

Table 2. Estimated carbon uptake by biosphere calculated from eddy covariance observations. The values for specific forest and tundras are upscaled simply by estimating their areal extent. We give two estimates to identify uncertainty, but use eventually only the GLC estimate. This large affects the non-forest biomes. The corrected NEE is obtained by allowing for age distribution of forests (van der Molen, 2012).

Land Cover	GLC area $10^{12}\,\mathrm{m}^2$	LEA	Observed NEE $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$	Corrected NEE $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$	NEP $\mathrm{Tg\,C\,yr^{-1}}$
Tundra	3.9	2.3	−58	−30	−119
Wetlands	0.5	1.5	−52	−63	−31
Grasslands	1.1	0.7	−107	−74	−80
Agriculture	1.6	2.2	0	0	0
Larch	3	2.8	−200	−151	−448 (−296 −475)
Pine	1.4	1.3	−197	−149	−207 (−98 −157)
Spruce	0.9	1.1	1	1	−1
Fir	0.2	0.2	−279	−198	−37 (−25 −39)
Mixed/other	2.9	4.3	−119	−38	−111 (−73 −118)
Area weighted mean	17.1	16.1		−60	−1033 (−760 −1097)

Table 3. Estimates of carbon export (dissolved inorganic carbon, dissolved organic carbon and particulate organic carbon) together with basins and estimated discharge. Basin delineation from Meybeck et al. (2006).

Coscat name	Principal basin	Discharge $\mathrm{km^3\,yr^{-1}}$	DIC load $\mathrm{Gg\,yr^{-1}}$	DOC load $\mathrm{Gg\,yr^{-1}}$	POC load $\mathrm{Gg\,yr^{-1}}$
West Kara Sea	Ob, Taz, Pur, Nadym	878.63	2778.53	2967.01	1372.16
East Kara Sea	Yenisei, Pyasina, Taymyra, Lenivaya	699.56	5480.98	2942.18	1215.88
West Laptev Sea	Lena, Khatanga, Olenek, Anabar	583.45	6756.96	2457.63	1875.32
East Laptev Sea	Yana, Omoloy, Sellyakh	36.39	157.26	163.81	127.27
East Siberian Sea	Kolyma, Indigirka, Alazeya, Pegtymel, Khroma	184.67	1003.13	967.23	482.79
New Siberia Plateau	no important rivers	1.92	8.56	3.49	2.96
West Chukchi Sea	Rekuul, Amguema	25.79	152.30	114.96	71.06
Anadyr Gulf	Anadyr	65.07	404.48	275.63	165.31
West Aleutian Basin	no important rivers	59.67	407.18	197.69	129.00
South East Kamchatka Coast	Kamchatka	65.97	368.76	253.68	258.73
East Okhotsk Sea	Penzhina, Gizhiga	116.46	687.89	636.41	289.60
North West Okhotsk Sea	Amur, Uda, Tugur	432.57	2851.32	1897.72	1076.97
West Japan Sea	no important rivers	84.27	912.70	473.39	500.13
Endhoreic areas		600	7940.00	2772.00	2772.00
Total			29 910	16 123	10 339

Table 4. Estimates of the average net biospheric carbon balance of Russia using 12 different inversion schemes (Gurney et al., 2012, this volume). Time period and interannual variability, expressed as the standard deviation, are also given.

Inverse system	Time period	Average net biosphere to atmosphere flux ($\mathrm{Tg\,C\,yr^{-1}}$)	IAV (σ_{year}) ($\mathrm{Tg\,C\,yr^{-1}}$)
C13 CCAM	1992–2008	−820	210
CSU	2003–2006	−630	408
CARBONTRACKER-EU	2000–2007	−907	199
CARBONTRACKER-US	2000–2007	−872	242
GEOSTAT	1997–2001	27	76
JMA_2010	1985–2008	−1305	237
LSCE_PEYLIN	1996–2004	−587	97
LSCE_4DVAR	1988–2008	−895	360
NICAM_NIWA	1988–2007	−390	260
NIES_PRABIR	1993–2006	−992	259
PSU	2001–2003	−906	288
MATCH	1992–2005	−1.14	4.75
Average		−690	246

Table 5. Average DGVM results in $\mathrm{Tg\,yr^{-1}}$.

	Carbon fluxes from DGVMs Mean	IAV (σ_{year})
	1921–2008	
GPP	8401	2612
NPP	4076	2186
NBP	91	110
	1990–2008	
GPP	9239	2857
NPP	4712	1780
NBP	199	160

Fig. 1. Vegetation (land cover) classification in Russia specifically made for estimating GHG fluxes and stocks (from Schepaschenko et al., 2010a).

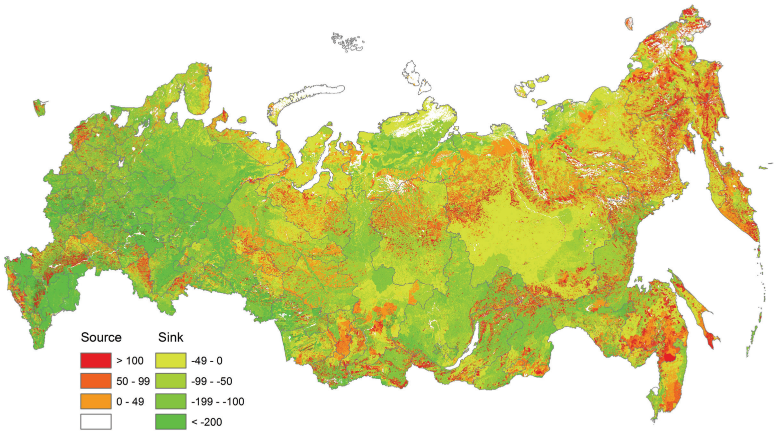

Fig. 2. NBP of Russian terrestrial ecosystems from the LEA system.

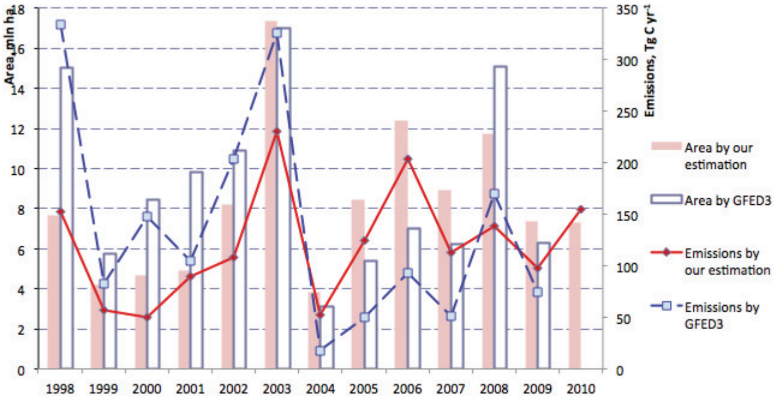

Fig. 3. Comparison of carbon emissions of vegetation fire in Russia from Shvidenko et al. (2011) between 1998–2010 with data of GFED3 (van der Werf et al., 2010).

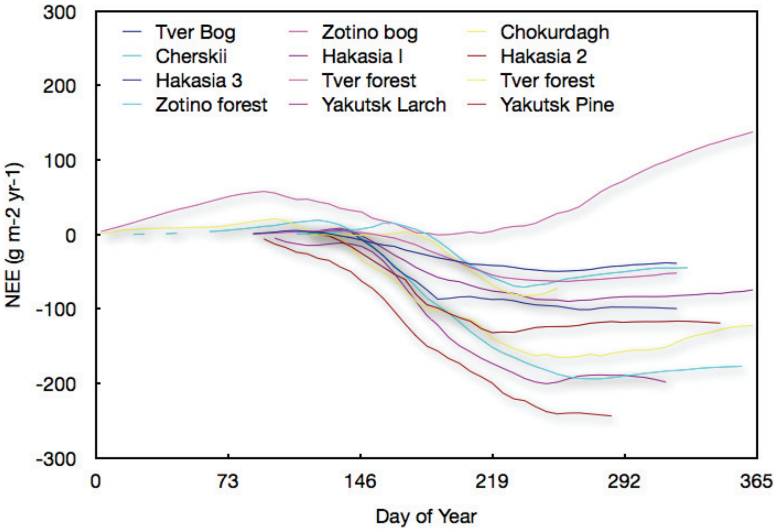

Fig. 4. Mean annual net uptake and release of carbon for a set of eddy-covariance site. For names of the sites, see text.

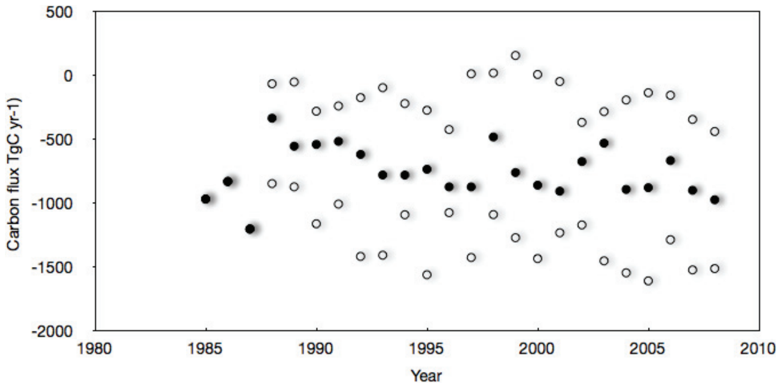

Fig. 5. Mean (closed circle) and range (open squares) of an ensemble of 12 inversion schemes for geographical Russia, Belarus and Ukraine. The range is determined by the maximum and minimum of the ensemble for each year.

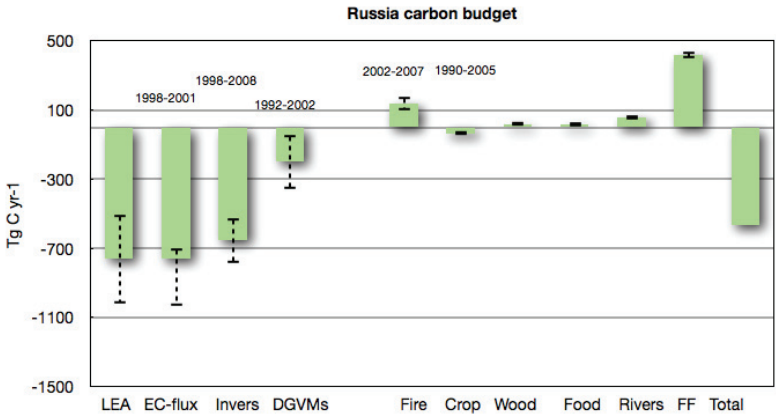

Fig. 6. The carbon balance components of Russia. The origin of the numbers used is described in the text.