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Can the uncertainty of full carbon accounting of forest ecosystems be made acceptable to policymakers?

Anatoly Shvidenko · Dmitry Schepaschenko · Ian McCallum · Sten Nilsson

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Abstract In accordance with the concept that only full accounting of major greenhouse gases corresponds to the goals of the United Nations Framework Convention on Climate Change and its Kyoto Protocol, this paper considers uncertainties of regional (national) terrestrial biota Full Carbon Accounting (FCA), both those already achieved and those expected. We analyze uncertainties of major components of the FCA of forest ecosystems of a large boreal region in Siberia ($\sim 300 \times 10^6$ ha). Some estimates for forests of other regions and Russia as a whole are used for comparison. The systems integration of available information sources and different types of models within the landscape-ecosystem approach are shown to have enabled an estimation of the major carbon fluxes (Net Primary Production, NPP, and heterotrophic respiration, HR) for the region for a single year at the level of 7–12% (confidential interval, CI, 0.9), Net Ecosystem Production (NEP) of 35–40%, and Net Biome Production (NBP) of 60–80%. The most uncertain aspect is the assessment of change in the soil carbon pool, which limits practical application of a pool-based approach. Regionalization of global process-based models, introduction of climatic data in empirical models, use of an appropriate time period for accounting and reporting, harmonization and multiple constraints of estimates obtained by different independent methods decrease the above uncertainties of NEP and NBP by about half. The results of this study support the idea that FCA of forest ecosystems is relevant in the post-Kyoto international negotiation process.

1 Introduction

Carbon accounting for terrestrial ecosystems that is “partial,” that is, limited to direct human activities, was introduced into international practice by the Kyoto

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A. Shvidenko (✉) · D. Schepaschenko · I. McCallum · S. Nilsson
International Institute for Applied Systems Analysis,
2361, Laxenburg, Austria
e-mail: shvidenk@iiasa.ac.at

Protocol and the subsequent decisions of the Conferences of Parties to the United Nations Framework Convention on Climate Change (UNFCCC). The 10-year period following the signing of the Protocol clearly demonstrated that the partial carbon accounting approach has a number of major shortcomings and that these are an impediment to achieving the UNFCCC goals. The shortcomings of partial carbon accounting are:

1. It distorts the real picture of the role of individual countries in climate change mitigation efforts in the sense that many emissions and greenhouse gas removals are not included in the accounting regime.
2. It excludes "climate-friendly" investment in fields of the biosphere where there is great potential: that is, in the language of the Kyoto Protocol, the Land Use, Land Use Change, and Forestry (LULUCF) sector;
3. It poses a threat to the protection of some categories of "unmanaged" ecosystems (e.g., old growth forests);
4. It gives insufficient consideration to large sources of emissions (e.g., wild fires); and
5. It restricts opportunities for developing countries to participate in the international processes of climate change mitigation.

Moreover, partial accounting does not allow for a comprehensive analysis of uncertainties, as considering the impacts on only a part of a system is not sufficient for assessing the responses and feedbacks of the entire system in any complete form. Substantial problems also arise from the large difficulties (and often, the impossibility) of strict definitions and unambiguous implementation of some of the key terms of the post-Kyoto language (e.g., managed land, anthropogenic impacts, base-lines and additionality, etc.), which raises doubt concerning some incentives and results.

Such a situation leads to the relevance of transition to a terrestrial ecosystems full carbon account (FCA), as a principal part of a full greenhouse gas account, (independently of future political decisions after the first commitment period), in terms of how these estimates should be used, either for "accounting" in the Kyoto Protocol sense or only for an "estimation" as auxiliary information for policymakers.

However, a number of studies illustrate a high level of uncertainty of biosphere carbon accounting from the regional to the global scale (Chen et al. 2000; Houghton 2003; Nilsson et al. 2007). Furthermore, two interconnected questions become crucially important: (1) what is the acceptable level of uncertainty at which the introduction of FCA results into the international accounting regime would be allowed? and (2) is there a scientifically solid, practically applicable methodology that would deliver a reasonable assessment of uncertainties at that level?

Finding the correct answer to the first question is not simple. The potential cost-effectiveness of carbon sequestration seems to be a major criterion here. However, as aiming for high accuracy significantly increases the cost of accounting, the elaboration and maximization of functions describing the difference between the benefit of carbon sequestration and the cost of the accounting is theoretically the soundest approach. In reality, however, this does not work because of: (1) the overwhelming difficulty and practical inexpediency of separating carbon issues from other ecosystem services; (2) the many unresolved economic problems involved in carbon crediting and offsetting; and (3) the existence of substantial but difficult-to-quantify political components. This leads to the conclusion that any formally defined "perfect accuracy" does not actually exist, but should be rather "acceptable" for scientific considerations, evaluation of "global utility" of ecosystems services, including carbon credits, and that it ultimately crucially depends upon the requirements and preferences of stakeholders (cf. Waggoner 2009). Through analysis of limited studies on the topic (GCP 2003; Newell and Stavins 2000), supported by simplified calculations for pared-down, averaged conditions of northern Eurasia, we may conclude that the relative uncertainty of Net Biome Production (NBP) at 20–30%, with confidence interval (CI) = 0.9, assuming that mean NBP differs substantially from 0, could be satisfactory in terms of average carbon prices and the main tendencies of the post-Kyoto market.

With respect to the second question, appropriate methodologies should consider the possibility of changing to *verified* FCA (i.e., the accounting should provide a comprehensive and reliable assessment of uncertainties at all stages and for all modules of the account). General features of such an approach have been published (Nilsson et al. 2007). As a further step, an analysis of uncertainties recognized for major components of FCA for forests of a large boreal region in Central Siberia was undertaken. For comparison, we also discuss results obtained for forests of other boreal regions of Russia and of the country as a whole. Results obtained within a landscape-ecosystem approach were further compared with available estimates obtained using other methods. Forests as an informative case study were selected because: (1) forest is the largest land class within the boreal zone and a major player in ecosystems carbon cycling; and (2) the complex structure of forest ecosystems allows us to assume that uncertainty levels achieved for forests could be achieved for other vegetation land classes.

All definitions of forest land cover classes and biometric characteristics used in this study correspond to Russian forest inventory and forest management manuals (FFS'RF 1995; Shvidenko et al. 2008b). In particular, forest (forested area) is represented by stands with relative stocking >0.35 for young and >0.25 for other age groups, and growing stock is the sum of volumes of the stems of all living trees that constitute a stand.

2 Methods and material

2.1 Major features of FCA

Four major approaches are currently used for terrestrial carbon accounting: (1) inventory-based (landscape-ecosystem) approaches; (2) measurements of net ecosystem exchange (eddy covariance method); (3) process-based terrestrial biosphere models; and (4) inverse modeling. All these methods have inherent strengths and weaknesses. However, none—if individually applied—is able to provide comprehensive and reliable assessment of uncertainties because estimation of structural uncertainties cannot be based only on the consideration of an "individual" case. This leads to the conclusion that only an integration of different methodologies is capable of generating a promising solution (e.g., Nilsson et al. 2007). To provide integration of different FCA methods, one of them should be selected as the basis of the accounting system. We assume that a landscape-ecosystem approach (LEA) is most appropriate for this goal for the following important reasons: (1) LEA presents a comprehensive geo-referenced description of ecosystems and landscapes (i.e., the information necessary for intelligent applications of any other methods of carbon accounting); (2) the information background of the LEA—an Integrated Land Information System (ILIS)—is an appropriate tool for monitoring temporal changes of land use–land cover (Nilsson et al. 2007).

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

$$\mathrm{NEP} = \mathrm{NPP} - \mathrm{HSR} - \mathrm{DEC} - \mathrm{FLIT} - \mathrm{FHYD}, \mathrm{NBP} = \mathrm{NEP} - \mathrm{DC}, \tag{1}$$

where *NBP*, *NEP*, *NPP*, are, respectively, Net Biome Production, Net Ecosystem Production, and Net Primary Production, *HSR* is heterotrophic soil respiration, *DEC* is flux due to the decomposition of dead wood, *FLIT* is flux to the lithosphere, *FHYD* is flux to the hydrosphere, and *DC* is fluxes caused by natural and human-induced disturbances, including consumption of forest products. For the pool-based approach:

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

where $\Delta(C)$ is the change of carbon pools and $C_{syst,t+\Delta t}$ and $C_{syst,t}$ are carbon pools considered in the accounting system at the end and at the beginning of the period Δt, respectively.

In this study, carbon pools were classified as carbon of live biomass, dead wood, and soils. In turn, live biomass of forest ecosystems was estimated by seven fractions (stem wood over bark, bark, wood of branches, foliage, roots, understory, and green forest floor) using a set of multidimensional models developed according to tree species and including age, site index, and relative stocking of stands (Shvidenko et al. 2007). The stock of above-ground dead wood (snags, logs, and dead branches of live trees) was estimated based on sets of available measurements on sample plots in taiga regions of Northern Eurasia, estimates of forest inventory aggregated by forest enterprises, and data on mortality derived from empirically based models of growth of modal stands (Shvidenko et al. 2005). A special method was developed for assessing NPP of forest ecosystems (Shvidenko et al. 2007). The remaining major fluxes (*HSR*, *DEC*, *DC*, *FLIT*, *FHYD*) were estimated using state statistical data, various inventories, surveys, and empirical models. A detailed description of the methodology can be found in (Shvidenko et al. 2005).

2.2 Study region

FCA was provided for a region totaling 313 million hectares in Central Siberia (including 299.8×10^6 ha vegetated land, of which 177.6×10^6 ha are represented by closed forests), divided in 25 ecological regions (Schmullius and Santoro 2005) and about 31,000 polygons (Fig. 1). The region includes almost all the bioclimatic zones of Northern Eurasia, diverse land forms, land classes, and ecosystems. The

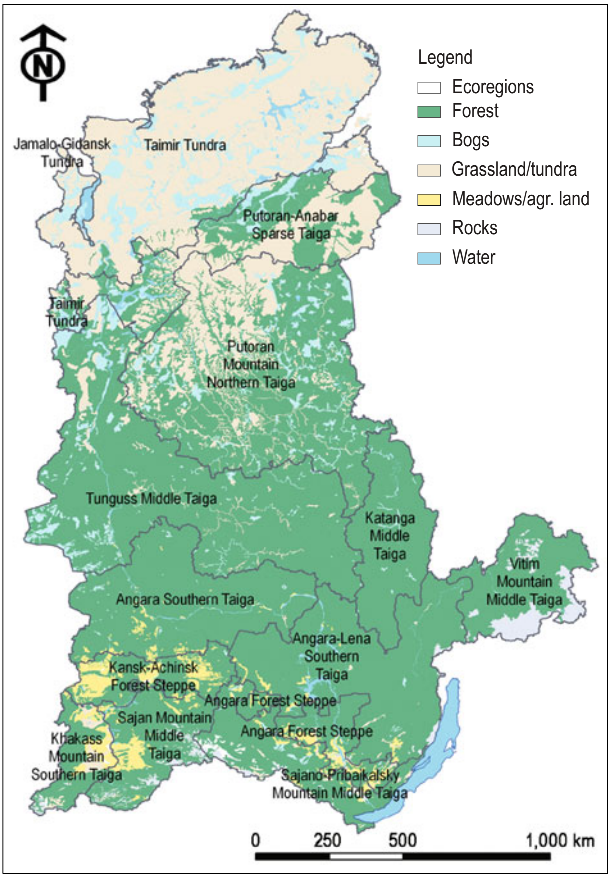


Fig. 1 Study region. Land cover of Central Siberia

integrated land information system (ILIS) for the region is represented by a comprehensive geographic information system (GIS) description of climate, landscape, soil, vegetation, disturbances, etc. (Shvidenko et al. 2005). All components of the FCA were estimated by polygons. The polygons were developed based on a combination of multi-sensor remote sensing (using 12 instruments from eight satellites) and all available ground information (State Land Account data, forest inventory, monitoring of disturbances, etc.). Major classes of land cover at the first (upper) level of the classification included unproductive areas, agricultural land, forest land, natural grassland, shrubs, and wetlands. At the second level, forest land was divided into closed forests, burn areas, dead stands, and (unregenerated) harvested areas. A more detailed classification of forests was carried out based on all available information, mainly using updated forest inventory data. Finally, the comprehensive parameterization of forest polygons included species composition, age, average height, and diameter by species, site index, relative stocking, and growing stock volume.

Characteristics of soil were extracted from a soil map at a 1:1 million scale, which was produced for the region and overlapped with the polygon map.

2.3 Assessment of uncertainties

Assessment of uncertainties is based on the understanding that FCA is a large dynamic fuzzy system that comprises a sophisticated interplay between many stochastic elements and processes (Nilsson et al. 2007). In a practical implementation, such systems cannot be directly validated or verified in any strict or formal way. This means that, before the uncertainties are assessed, there are a number of prerequisites and requirements to be observed.

1. A strict system design for the FCA is a mandatory prerequisite. Explicit structuring of the accounting schemes is needed, as well as delineation both of the intrasystem and the outer boundaries that have different dimensions (spatial, temporal, processes that should be considered, etc.). This will allow strict algorithms to be developed, permit potential application of error propagation theory, and provide the basis for consideration of the structural uncertainty of the models or accounting systems used.
2. A comprehensive analysis is needed of how "full" the carbon accounting is. There are two interconnected aspects to this problem, both of which impact the estimation of results and uncertainties. The first deals with the selection of processes and modules to be included in the accounting. This is closely tied to recognizing the structural uncertainties of the FCA and, in essence, is limited by heuristic approaches and expert estimates. The second defines the "working area" of the FCA, for example, whether or not consumption of plant products or the carbon budget of inland bodies of water should be considered as part of the accounting scheme.
3. All input information should be presented in a quantitative way; this requirement also assumes the formal use of personal probabilities and corresponding confidence intervals for different assumptions and expert estimates.
4. A preliminary harmonization of major terms and definitions is needed, particularly taking into account the multidisciplinary character of the FCA.
5. Uncertainties of the initial data need to be assessed based on an analysis of the entire chain of measurement, collection, and upscaling of data. This is a very time-consuming stage, as it is very difficult to get reliable quantitative conclusions on the topic.
6. Analysis and quantification of temporal and spatial trends of data sets and empirical models used in the accounting are needed. Avoiding this step could substantially change the results (Lapenis et al. 2005).
7. A methodology should be used to assess uncertainty that takes into account the fuzzy character of FCA (Nilsson et al. 2007).

Note that the above requirements have the same goal as that declared in IPCC "Good Practice Guideline, 2006" on GHG inventories: such inventories "are those which contain neither over- nor underestimates so far as can be judged, and in which uncertainties are reduced as far as practical" (IPCC 2006, p. 1.6).

Within the landscape-ecosystem approach, the following method of uncertainty estimation was used:

1. Assessment of precision within the landscape-ecosystem approach using the error propagation theory according to the algorithms developed;
2. Provision of a standard sensitivity analysis by applying either the Monte Carlo method or systems of numerical differentiation;
3. Transition from precision to uncertainties by expert modification of formal results; and
4. Comparative analysis, harmonization, and multiple constraints of results achieved by independent methods. In this study, this step was limited by expert estimates and professional judgments.

Overall, this approach can be applied to all methods and all stages of FCA, particularly where strict formalization of uncertainty assessment is difficult or impossible. All estimations below have been made under the assumption that the models and methods used have no unrecognized biases. Obviously, such an assumption should be used with caution: much of the input data has uncertainties in terms of unknown combinations of random and systematic errors.

As all calculations are based on a strict algorithm, standard errors of a function $Y = f\ (X_i)$, where X_i is a random quantity with standard error m_i, $i = 1, 2, \ldots, k$, could be calculated approximately at each hierarchical stage of the FCA by using functional:

$$m_y^2 = \sum_{i=1}^{k} \left(\frac{dY}{dX_i} m_i \right)^2 + 2 \sum_{i>j} \left(\frac{dY}{dX_i} \right) \left(\frac{dY}{dX_j} \right) r_{ij} m_{X_i} m_{X_j}, \tag{3}$$

where dY/dX_i—partial derivatives of Y by X_i, and r_{ij}—is the correlation coefficient between X_i and X_j. Usually, inclusion of the second item of Eq. 3 is important because many X_i in Eq. 3 are statistically interdependent.

3 Results and discussion

3.1 Uncertainties of carbon pools

The average *live biomass* (LB) *of forested areas* is estimated for the region at 56.5 ± 2.2 Mg C ha^{-1}, that is, with a relative precision of 3.9% (here and below, CI = 0.9). Uncertainty of biomass of stems is ~4.5%, and below-ground LB is ~8%. Note that this result was obtained because of the availability of:

1. Long-term spatially distributed forest inventory data at the level of individual forest stands—primary units of forest inventory;
2. Remote sensing information to allow updating of obsolete forest inventory data;
3. Information on the actual species composition by polygon;
4. More precise estimation of growing stock in comparison with routine forest inventory data;

5. Statistically valid and regionally distributed multidimensional nonlinear regression equations for transition from indicators measured by forest inventory to live biomass estimates by components; and
6. Accounting methodology used for recognition of temporal trends in allometric interdependences in forest ecosystems (Lapenis et al. 2005).

Uncertainties of inventory-based estimates of LB depend upon:

1. Reliability of delineation of polygon boundaries;
2. Uncertainty of biometric indicators of forest ecosystems within polygons;
3. Accuracy and adequacy of models used for assessing LB;
4. Variability of model parameters such as amount of carbon in plant tissues (Mitrofanov 1977); and
5. Assumptions and simplifications in the accounting systems.

In this study, the major simplification included an aggregation of primary units of forest inventory in more heterogeneous polygons at scale 1:1 million. For this reason, compared with the requirements of the forest inventory manual (FFS'RF 1995), a twofold increase in random errors of biometric characteristics of polygons for individual stands (inventory primary units) was provided. Based on detailed analysis of uncertainties of biometric indicators by polygon (Shvidenko et al. 2005), a prerequisite about absence of statistically significant bias of growing stock volume was used.

An attempt to harmonize the uncertainties of forest LB assessed for Central Siberia led to the following conclusions:

1. Assuming that growing stock volume on polygons does not have systematic errors and taking into account that the number of forest polygons exceeds 10,000, the summarized error of the total average is negligible.
2. It was shown that there were temporal trends in partition of live biomass fractions (Lapenis et al. 2005) during the 1960s–2000s, and that these trends do not coincide for different live biomass components. If this trend is disregarded, the live forest biomass of Russia for the early 2000s will be overestimated by between 7% and 10% (Shvidenko et al. 2008a).
3. The non-random character of experimental data used for development of the LB models does not allow the impacts of stem and root decay to be estimated. The latter comprise on average 5–7% of the growing stock in mature and overmature stands of European Russia and 12–15% (sometimes more) in the mostly unmanaged taiga forests of Asian Russia.
4. As discussed above, precision of the total live biomass was estimated at about ±4%. The present analysis leads to a final uncertainty estimate of live biomass at the ±5–7% limit. We must stress that here (and throughout the paper) we operate with "summarized" errors (i.e., errors that have some combination of random and systematic errors, assuming that the bias is relatively small).

An independent assessment of LB for the region's forests was based on data from the State Forest Accounting (SFA) of 2003 carried out by forest enterprises. This comparison is of interest because traditional forest inventory data remain a basic information source for live biomass inventories at different scales. Uncertainties of forest inventory data in the region are basically defined by:

1. Accuracy of methods of forest inventory and reference information (models and tables) used;
2. Existence of extensive areas with obsolete inventories;
3. Simplified structure of information presented in aggregated data of SFA by forest enterprises (e.g., use of dominant species instead of actual species composition).

Forest inventory data for the region (and the entire country) use a combination of three major methods of forest inventory:

1. Ground forest inventory and planning;
2. Remote sensing technologies of different types; and
3. Aerial survey, or *aerotaxation*.

A detailed consideration of the problem is given in Shvidenko and Nilsson (2002). Here we enumerate its main conclusions.

1. Ground forest inventory and planning has underestimated the growing stock of immature, mature, and overmature forests from by about 8% to 15%;
2. Technologies based on remote sensing applications do not have statistically significant systematic errors;
3. Aerotaxation was used several decades ago, with the result that growing stock was overestimated by 20–25% depending on the date and geographical location of the survey. However, the area where this method was initially applied (and where new inventories were not subsequently done) currently comprises about 60 million hectares of remote land in the northern region. By 2003, 40% of the region had been inventoried by ground forest inventory and planning, 55% by different types of remote sensing technology, and 5% by aerotaxation. Overall, the FSA slightly underestimated the area of forests of the study region (172.1 versus 176.6×10^6 ha, or 2.5%, mostly at the expense of land reserve areas where SFA is not provided), and also underestimated average growing stock (and, correspondingly, forest live biomass) by -10 to -13%.

Another source of possible uncertainties follows from the methodologies of live biomass modeling and the structure of models used. From among several methods of live biomass assessment that were suggested in Russia in recent decades, we consider an approach developed by Usoltsev (1998, 2007). Usoltev developed a set of models of biomass expansion factor $BEF_{s,h,i}$ by tree species s, geographical region h, and live biomass fraction i as a function:

$$\mathrm{BEF_{s,h,i}} = \mathrm{f}\left(\mathrm{A},\ \mathrm{H_{100}}, \mathrm{N},\ \mathrm{D}\right), \tag{4}$$

where A, D, N, and H_{100} are age, average diameter, number of trees, and average height of a stand at age of 100 years (i.e., the latter can be scaled as a site index class). In our opinion, this method, from a scientific and information point of view, is more appropriate than others (e.g., Zamolodchikov and Utkin 2000). However, some specific features of the method impact its reliability.

1. Allometry is used as the analytical form of the equations (i.e., the components of the models are presented by a combination of logarithms of variables of Eq. 4). Allometric forms for assessing live biomass of individual stands and their combinations (as opposed to individual trees) have no solid theoretical background;
2. Allometric equations are monotonous by all variables; this is not the case for some species and live biomass components (Shvidenko et al. 2007).
3. Usoltsev (1998, 2007) used a method of a "recursive analysis" where the final results follow from a step-by-step estimation of intermediate results using a limited number of variables, and these intermediate results serve as input to the subsequent equations of the recursive chain. Clearly, such an approach does not allow uncertainties to be defined by formal statistical methods and substantially increases an expert component of modeling (i.e., the reliability of results is strongly dependent upon the qualification of the modeler). We compared the results of live biomass assessment by Usoltsev's (2007) method and by the approach examined in our study for Central Siberia using forest inventory data for 150 forest enterprises of the Urals region covering a total forested area of 68 million hectares (Fig. 2). The results are close; the total live biomass estimated by Usoltsev's method was 3% less than ours and had 5% less above-ground LB.

Several conclusions follow from this analysis:

1. Biomass expansion factors depend upon region, tree species, age, and other biometric characteristics of stands; simplified representation of BEF (e.g., as an average for forests of large regions) generates substantial uncertainties and uncontrolled biases.
2. LB of the lower layers of forest ecosystems (green forest floor, understory) could comprise up to 15–20% of the total, particularly for forests that have low productivity in high latitudes. Thus, models and approaches that account for only tree LB underestimate the results.

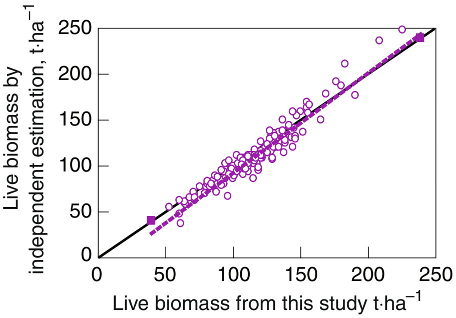


Fig. 2 Comparisons of total live biomass for forests of the Urals region (average densities by forest enterprises, expressed in tons per hectare of dry matter) obtained by different methods: *x*-axis indicates estimate received by Shvidenko et al. (2007) and line 2 (*solid*) corresponds to these estimates; *pink circles*, data received by Usoltsev's method (1998, 2007); and line 1 (*dashed*) indicates mean of these data

An assessment of two pools of *dead biomass* (coarse woody debris [CWD] and dead roots [DR]) is less certain: average estimates of uncertainty provided by two independent methods amounted to ±16 and 24%, respectively. Thus, taking into account that the LB, CWD, and DR in forests of the study region comprise 81%, 8%, and 11% of the total forest biomass, the uncertainty of the total biomass stock (for a single year of the account) is estimated at ∼±4–5%. From this, the change in biomass stock between two inventories is estimated with an average uncertainty of ∼±6 to 7%. Results delivered by other methods, such as radar and optical satellite instruments and dynamic global vegetation models (DGVMs), are more uncertain. In addition, these methods face large methodological problems regarding a formal definition of uncertainties.

Formal assessment of the uncertainty of the *soil carbon pool* for the region is difficult because of lack of data, which ideally would be temporally and spatially distributed, particularly over the vast remote territories. A soil map of Russia (Fridland 1989) at 1:2.5 million scale with a dataset of average characteristics by soil types still remains a major source of soil information for the country. For the study region, the soil map was subsequently modified to 1:1 million scale using additional information from different sources. However, drawing up the original sheets of the 1:1 million scale soil map took a long time up to half a century ago. This makes use of expert assumptions for assessing the uncertainties inevitable, and those assumptions might substantially affect the conclusions. Our calculations show that uncertainties of assessment of the soil carbon pool are at the level of 15–20%. The estimation of the soil carbon pool for the region is about 31 Pg C. This gives uncertainties of about ±5 Pg C, with unknown systematic errors; moreover, the signal of change between two consequent estimates can be detected if this exceeds ∼7 Pg C. Clearly, this makes such results impractical for verified FCA. Another way of detecting change in the soil carbon stock is by using appropriate process-based models. However, the uncertainty of the latter cannot be properly quantified. Assumption of an equilibrium state of soil organic carbon generates a substantial bias of an unknown value. Attempts to quantify such a bias using aggregated indicators of transformation of forest land and disturbance regimes lead to significant but very approximate values (Shvidenko and Nilsson 2003). Thus, although currently available information allows useful results to be obtained from the pool-based method, it cannot satisfy the main requirements for verified FCA. Note that the above considerations put in doubt any application in the post-Kyoto world of the "Average Carbon Stock" method recommended by some publications (e.g., Kirschbaum and Cowie 2004), at least for vast boreal regions.

3.2 Uncertainties of major fluxes

In theory, Net Primary Production (NPP) is defined as the difference between gross photosynthesis and autotrophic respiration of ecosystems. However, the numerous methods of field measurement of NPP in Northern Eurasian forests not only were almost all based on consecutive destructive measurements with a time interval of weeks and months but also measured only part of NPP in the plant tissues allocated. Much NPP (root exudates, volatile organic compounds, others), comprising up to 20–25% of the total NPP (Isidorov and Povarov 2001; Vogt et al. 1986), was not measured. Other barely quantified uncertainties are also inherent in these data

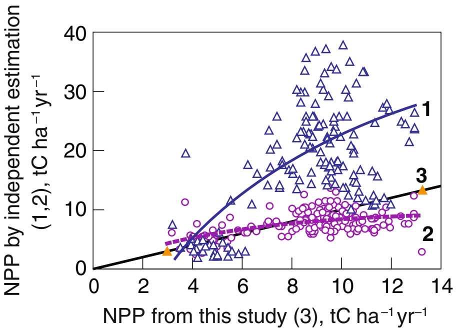
(Usoltsev 2007). Thus, the available datasets of NPP field measurements in Russian forests, which include more than 1,000 sample plots, contain a bias of unknown value. The above information problems and the use of different methods led to threefold differences in the reported estimates of the average NPP of Russian forests: from 204 to 614 g C m^{-2} $year^{-1}$ (Shvidenko et al. 2008b).

Attempting to gain unbiased estimates, we developed a new semi-empirical method for assessing forest NPP. This method is based on a spatially distributed system of models of biological productivity of forest ecosystems by major forest-forming species (Shvidenko et al. 2007). We assume that this method has no recognized bias. Uncertainty of the method is defined by: (1) spatial and parametric incompleteness of the modeling system used for NPP simulation (regional representation of models by regions, tree species, and forest types; reliability of forest inventory data, etc.); (2) accuracy of ecological indicators used in the model (e.g., life span of fine roots and needles; share of disturbed part of NPP; etc.); and (3) difference in seasonal weather of an individual year from the many-year average climatic indicators.

The method is sufficiently resilient to varied input information; the most sensitive parameters are the life span of fine roots and needles. The application of the system above to the land cover of 2003 at the polygon level and aggregation of the results by ecoregion and the region as a whole gave the following results: total forest NPP 3.06 ± 0.15 (here and below, in Mg C ha^{-1} $year^{-1}$), that is, the relative uncertainty is $\sim\pm5\%$. Of this total, above-ground wood, green parts, and below-ground live biomass are assessed at 0.550 ± 0.032; 1.293 ± 0.106; and 1.222 ± 0.130, respectively. This means that annual forest NPP is defined, quite reliably, at the level of ±6% for the part allocated in above-ground live biomass and ±11% for below-ground. However, it should be pointed out that all models used were parametrized based on many-year average data of measurements. Thus, these results do not include the impacts of seasonal climate specifics on forest NPP.

A comparison of the results mentioned above with recent NPP estimates by different modeling approaches for 150 forest enterprises in the Urals region (the same area used above for live biomass assessments) reveals interesting results (Fig. 3). Application of multi-dimensional equations developed by Usoltsev (2007) gave a result very close to that obtained by the method applied in this study—only 8% lower (line 2 in Fig. 2). For this area, Usoltsev (2007) examined a simplified method developed in Russia (Utkin et al. 2003; Zamolodchikov and Utkin 2000)

Fig. 3 Estimates of forest NPP obtained by different methods (average densities for 150 forest enterprises, tons per hectare per year of dry matter). *1 Triangle markers* method of Zamolodchikov and Utkin (2000) calculated by Usoltsev (2007); *2 circle markers* method of Usoltsev (2007); *3 solid line* method of Shvidenko et al. (2004)



and obtained the results averaged by line 1. This latter estimate produced a roughly twofold overestimation (+118%) for the result of this study.

Heterotrophic respiration of forest ecosystems includes two components: heterotrophic soil respiration (HSR) and the flux caused by decomposition of coarse woody debris (DEC). Average values of HSR were calculated by soil type, dominant species, and ecoregion based on the IIASA database which contains ~650 sets of field measurements in Northern Eurasia. A substantial part of the study region has not been subject to measurement, and we used all available measurements from similar soil and forest classes of other regions of the country (for example, Kurganova 2002; Mukhortova 2008 etc.). We made the assumption that the variation in the HSR fluxes measured outside the region is 30% higher than the variability of the fluxes measured within the region. For corrections of HSR for each forest polygon, the regression between NPP and HSR by dominant species within each ecoregion was used. Uncertainty of estimation of HSR depends on:

1. Amount, seasonal and parametric completeness, and spatial distribution of in situ measurements;
2. Understanding of the processes that control total soil respiration and its separation into autotrophic and heterotrophic parts (where substantial uncertainties exist. See, for example, Bond-Lamberty et al. (2004); and
3. Reliability of spatial delineation of basic units of calculation (soil polygons) and their compatibility with vegetation polygons. The overall average forest HSR for the region was estimated to be 2.16 ± 0.19 Mg C ha^{-1} $year^{-1}$ (i.e., relative uncertainty is ~±9%) Uncertainty of HSR in this study was substantially lower than in studies for the whole of Russia defined by Gusti and Jonas (this volume) which can be explained by the availability of more detailed information and different methods of uncertainty estimation.

Uncertainty of *the decomposition flux* was estimated based on a simple model, $DEC = M_{CWD} \bullet \delta_{ji}$, where M_{CWD} is storage of coarse woody debris (CWD) in a polygon and δ_{ij} ($i = 1, \ldots, 9$; $j = 1, 2$) is a coefficient of decomposition by nine bioclimatic zones and two classes of CWD. Uncertainties of these two components were estimated at ±16% and 14% based on results of measurements and different auxiliary sources, that gave the estimate of DEC at 0.219 ± 0.047 Mg C ha^{-1} $year^{-1}$ (i.e. the relative uncertainty is ~±22%).

The assessment of *the fluxes to the hydrosphere* (FHYD) was made by combining two methods: (1) based on measurements of the amount of dissolved and particulate organic carbon in rivers and other water reservoirs; and (2) by using measurements of carbon concentration in the soil solution. The average estimate was 0.049 ± 0.011 Mg C ha^{-1} $year^{-1}$ (23%). Direct empirical data for assessing *the fluxes to the lithosphere* (FLIT) were scarce, and the assessment of this indicator was mostly made in a heuristic way based on all available data from the boreal biome. The estimated uncertainty of FLIT (0.017 ± 0.005 Mg C ha^{-1} $year^{-1}$ or ~30%) contains substantial assumptions and expert components.

Major types of *disturbances* (DC) included in the analysis were fire, insect and disease outbreaks, and harvest and consumption of wood products. Carbon emissions due to natural and human-induced disturbance (D) and corresponding uncertainties were estimated by the method described in Shvidenko and Nilsson (2000), Kajii et al. (2002), Soja et al. (2004), French et al. (2004) and McRae et al. (2006).

The main factors affecting uncertainties of the emissions caused by disturbances, include area by type of D; severity of D and its impact on the amount of consumed organic matter; reliability of estimation of gas composition, particularly, after fire; and way of estimating post-disturbance fluxes (most publications on the topic do not consider this flux). The impacts of these factors vary for different types of D. Estimated uncertainties were: direct emissions due to fire 37.3 ± 8.6 Tg C year^{-1} (or 23%); harvest (including impacts of logging, wood removal, and decomposition of previously produced wood products) 20.6 ± 5.0 Tg C year^{-1} (24%); and direct emissions due to insect and disease outbreaks 2.2 ± 0.8 Tg C year^{-1} (36%). This means that uncertainty of the total flux due to all accounted-for D is estimated to be 60.1 ± 10.1 Tg C year^{-1} (17%). The average value of the flux DC for all forest area in 2003 is estimated to be 0.337 ± 0.057 Mg C year^{-1} ha^{-1}, or 17%. Note that the extent of wild fire for the year considered (2003) was about three times higher than the many-year average for the region.

3.3 Uncertainty of aggregated fluxes

As follows from the results above, Net Ecosystem Production (NEP) of the region's forest ecosystems is estimated to be 0.62 ± 0.23 Mg C ha^{-1} year^{-1} (the relative uncertainty ~37%) and Net Biome Production (NBP) 0.28 ± 0.25 Mg C ha^{-1} year^{-1} (89%) or ~49 Tg C year^{-1} for the region The total NBP for all vegetation of the region comprises 75 Tg C year^{-1}, if the complete technological lifecycle of plant products is considered, and 110 Tg C year^{-1} if the consumption of plant products (that is common in ecological estimations) is not included in the accounting (Shvidenko et al. 2005). Thus, forest NBP comprises two-thirds of the total. All these estimates are calculated for an individual year, while the parametrization of the models used was provided based on measurements over a long period of time (sometimes several decades). This eliminates an unaccounted-for part of the variability of NEP and NBP that depends on differences in weather conditions during the year of the accounting and average long-period indicators. Responses of plant and ecosystem physiology to weather conditions are indicated in many studies and used in numerous models of various types (Dunn et al. 2007). Most interactive vegetation-climate models usually represent respiration as a strongly increasing function of temperature, with photosynthesis assumed to be a function of light, subject to limitation by temperature, length of growing season, and availability of water and nutrients. Some studies indicate the crucial impact of temperature in cold regions, for example, Liski et al. (2003); Lucht et al. (2002). This encourages the use of seasonal climatic indicators to correct major components of the FCA, primarily NPP and HR.

We provided statistical analysis of dependencies of NPP and HSR of both the Siberian and entire Russian forests on different climatic indicators. About 20 indicators, such as average annual temperature and precipitation; length of growth season with daily temperature >0°C, >5°C and >10°C; sum of temperature, precipitation and hydro-thermal coefficient by Seljaninov for the above three periods; temperature of the warmest month, etc., were examined. As a general conclusion, corresponding regressions are statistically significant, but the correlations are low. For example, the multiple correlation coefficients for total soil respiration were within the limits of 0.5–0.7 (Mukhortova 2008). One of the probable explanations for this result may stem from the incompleteness of simplified functional representations or the need to use more frequent (e.g., daily) climatic indicators.

Climatic variation is directly responsible for short- but not long-term variation in forest-atmosphere carbon exchange (Richardson et al. 2007). Factors acting over long time scales, for example, soil moisture regime and water table depth, substantially control the carbon budget on annual time scales in boreal forests and peatlands. In particular, elevated soil moisture causes a decrease in overall respiration, which leads to decreased NEE; the long-term ecosystem water balance, and particularly, the water table depth may explain much of the interannual variability and trends observed (Dunn et al. 2007). Nevertheless, our analysis shows that the introduction of seasonal weather corrections decreases the uncertainty of major carbon fluxes by about one-third.

Selection of a reasonable length of period for reporting results of the FCA is also important. Gathering information for large regions on an annual basis is expensive and resource-consuming. The operational supply of some data (e.g., changes in land use–land cover) is difficult and requires the development and implementation of integrated observing systems, which still do not exist in Northern Eurasia. Conversely, in order to be used in different climate change negotiations and decisions, FCA results are required for given periods (e.g., 5 years) rather than annually, as the latter contain additional noise and seasonal variation caused by weather and other specific features of individual years. To conclude, the improved estimates for a 5-year period have uncertainties at the level of 15% for NEP and 30% for NBP of forest ecosystems of the region studied.

We would like to point out that all relative uncertainties above (expressed as percentages of estimated means) are reasonable for illustrative purposes. Overall, they could have a limited meaning in measuring the reliability of the account, as they properly characterize variability of fluxes that differ substantially from 0.

3.4 Comparative analysis with other approaches

The results of carbon accounting obtained by the landscape-ecosystem approach are impacted by a number of assumptions and expert estimates that hinder a strict statistical validation of uncertainties. Thus, independent control of the intermediate and final results is an important procedure for assessing the uncertainty. One way to do this is a non-contradictory closing of the balance of the carbon budget. The second way is to build independent estimates into the comparative analysis. Unfortunately, there are very few independent results for the study region. To illustrate the variation among the results, we use some comparisons (below) for the entire Russian forests.

Dynamic Global Vegetation Models (DGVMs) explicitly describe major physiological processes in ecosystems. Basically, only DGVMs or other process-based models can serve as a tool to predict the interaction between vegetation and the environment. However, there are a number of reasons why it is not feasible to use DGVMs for formal assessment of the uncertainties, for instance:

1. They provide an over-simplified description of the land cover (as most models have a very limited number of plant functional types, they cannot give a proper description of ecosystem diversity at a regional level);
2. Most of the models are oriented toward potential rather than actual vegetation cover;

3. They lack or have an incomplete description of disturbances and "artificial" (e.g., agricultural) systems. Nevertheless, recent developments show substantial progress and promising prospects for the future (Grace et al. 2007).

The application of 17 DGVMs previously analyzed by Cramer et al. (1999), to all Russian forests gave the average NPP at 338 g C ha^{-1} $year^{-1}$ (M. Gusti, personal communication), while a landscape-ecosystem estimate is 297 g C ha^{-1} $year^{-1}$ (Shvidenko et al. 2008a), that is, about 14% higher. However, the variability of estimates given by the individual models was very high—from 20% to 70% depending on the climatic zone. Based on a "regionalized" version of the Lund–Potsdam–Jena model (including actual land cover, impact of fire, and a new permafrost-hydrological module), Beer et al. (2006) produced estimates of important components of the carbon budget that were very close to the results based on forest inventory data (Shvidenko and Nilsson 2003).

The eddy covariance method presents a unique possibility to directly measure Net Ecosystem Productivity (in the form of accumulated Net Ecosystem Exchange), as well as fluxes of water and energy in response to variability in environmental conditions. Although the method has a clear strength in terms of uncertainty estimation (the net flux is the sum of individual half-hourly or hourly flux measurements rather than a small difference between several large fluxes), the results are impacted by a sophisticated interconnection of random and systematic errors (Falge et al. 2001; Goulden et al. 1996; Moncrieff et al. 1996; Papale et al. 2006; Papale and Valentini 2003). The eddy covariance method is accurate when atmospheric conditions are steady, the underlying vegetation is homogeneous, and towers are situated on flat terrain for an extended distance upwind. Under such ideal conditions the error of annual NEE of CO_2 was reported to be less than ± 50 g C m^{-2} $year^{-1}$ (Baldocchi 2003). Some elements of field measurement techniques (e.g., nighttime fluxes in dense canopies, flow distortion over heterogeneous terrain, filling in measurement gaps) need to be developed in the future to achieve a more reliable estimation of uncertainties. Complete model validation, particularly over the full annual cycle, requires additional information on the balance between assimilation and decomposition processes (Friend et al. 2007). The method does not measure NPP directly, and rather complicated calculation schemes that exploit unjustified assumptions are used (e.g., Schwalm et al. 2007). One of the biggest methodological problems of eddy covariance measurements is upscaling the results to large areas. The footprint of an individual tower is typically 1 km × 1 km, and within Russia there were only 17 measuring points for all vegetation types in 2007. A number of advanced methods for upscaling results of measurements have been suggested (e.g., Papale and Valentini 2003). However, they cannot compensate for the lack of spatially distributed information. That is why the major value of eddy covariance methodology is considered to be the supply of data for global cycle modeling and evaluation process representation, rather than in providing unbiased estimates of NEP for large territories (Friend et al. 2007).

Inverse modeling of atmospheric concentration is the sole approach that presents the possibility of a top-down assessment of exchange between land and the atmosphere. The estimates of CO_2 fluxes include mainly the land use change and net ecosystem uptake for land regions. Uncertainties of the approach are basically defined by the amount and distribution of measurement stations and by the imperfection of the transport models used. The errors for observation over the land

Table 1 Assessment of fluxes for boreal Asia by inverse modeling

Source	Flux (Pg C year^{-1})	Period	Comments
Maksyutov et al. (2003)	-0.63 ± 0.36[a]	1992–1996	Includes observations in Siberia
Gurney et al. (2003)	-0.58 ± 0.53	1992–1996	Average flux from 17 transport models
Baker et al. (2006)	-0.37 ± 0.24	1988–2003	
Patra et al. (2006)	-0.33 ± 0.45	1999–2001	All sites; 16 transport models were used; uncertainties "within" models were ±0.78
Average flux	-0.48 ± 0.41		Upscaling the result of this study for all boreal Asia gives ~0.40 Pg C year^{-1})

[a] The reported uncertainties are "between" models

are generally larger than those for observation over the ocean (Patra et al. 2006). The amount of measurements in boreal Asia is very small, which substantially impacts assessed uncertainties at the regional level. Recently, a number of results from inverse modeling have been reported for terrestrial ecosystems of boreal Asia, namely, the area of the continent north of latitude 50 (Table 1). The results are rather consistent, ranging from −0.33 to −0.63 Pg C year^{-1}, with the overall average being about −0.48 Pg C year^{-1}, while the uncertainties, both "within-model" (the multi-model root mean square of the flux uncertainties) and "between-model" (1 standard deviation of the estimated fluxes by different transport models) remain high. Assuming the approximate area of boreal Asia of 1.1×10^9 ha and taking into account the area of the study region, we gain results that are very close to the average obtained by inverse modeling (Table 1).

Overall, it can be concluded that comparison of the results obtained by the LEA with published data derived from flux measurements, some global vegetation models, and by inverse modeling showed a general consistency in terms of the sign and magnitude of NBP. This is in line with papers published on the consistency of results derived from process-based models, remote-sensing-based observations, and inversion of atmospheric data (Friend et al. 2007). For a number of reasons, our comparison is approximate; for example, the regions and time periods of the assessments did not coincide exactly; there was a lack of explicit gradients for upscaling of flux measurements in situ; and there were differences in some of the main definitions used.

4 Conclusion

Overall, this study concludes that verified FCA for forests of large boreal regions, while possible, requires a systems approach and a substantial effort to carry through. However, some precautions should be taken and a number of questions need to be resolved. The information for large regions already in existence tends to be unsatisfactory for an accurate assessment of the final results (i.e., for NBP and, to some extent, NEP) for individual years; moreover, the reported period should be compatible with the practical possibilities of detecting changes in land use and the distribution of natural and human-induced disturbances. Empirical and semi-empirical models are based on multi-year sets of measurements and require environmental and climatic indicators of individual seasons and temporal trends to be introduced.

The process of multiple constraints requires a "convergence" of different methodologies, for example: proper regionalization of dynamic process-based vegetation models; search for common gradients to upscale flux measurements; advances in field measurement techniques. The results of the study, together with recent methodological developments in carbon accounting of terrestrial ecosystems reveal substantial potential for future improvements. There is an evident convergence of empirical (e.g., landscape-ecosystem) approaches and process-based models. However, the major approaches to carbon accounting have different strengths and weaknesses. Although the landscape-ecosystem approach, may have been suitable as a past and present background for accounting, only process-based models are able to provide satisfactory predictions in today's changing world. Geo-referenced and quantitative descriptions of land cover classes, an obligatory component of the landscape-ecosystem approach, could serve as a spatial gradient for upscaling the "point" flux measurements.

The idea of verified FCA and understanding of the fuzzy essence of FCA for large territories has substantial implications for the overall philosophy and major methodological decisions behind carbon accounting as a whole. It is vital to understand that heuristic methods and expert estimates cannot be avoided within FCA, which demonstrates the need for further developments in assessing uncertainties. Indeed, analysis of the "uncertainties of uncertainties" becomes no less important than assessing uncertainties of the major components of FCA exercises themselves. The estimation of uncertainties by "conventional" methods of mathematical statistics (e.g., by those recommended by IPCC in Best Practice Guidelines 2006) could provide conclusions that are quite far from reality.

Some theoretical improvements and developments are needed. Harmonizing and the mutual constraints of individual results delivered by different methods should be provided by strict mathematical methods. This is an important task for the future.

Relevant economic problems ("cost-effectiveness of uncertainties") are extremely important in terms of understanding the required FCA certainty levels. Limits of relevant use of standard normal theory for assessing heterogeneous and "contaminated" data sets should be clearly defined and appropriate statistical approaches introduced. Some "conventional" statistical agreements should be reconsidered. For instance, the typically used high confidential intervals (0.9 or even 0.95) seem excessive for carbon accounting, because this could generate the impression of an unsatisfactory accounting level in the wider public, specifically policymakers.

This paper considered uncertainties of a forest carbon budget. The inclusion of other greenhouse gases and other land classes in the accounting leads to particular problems (especially for land classes for which there are no long-term series of biometric inventories). A way of transitioning to verified accounting of terrestrial carbon budgets and other major greenhouse gases would be to develop integrated observing systems combined with existing national systems for the accounting of natural resources, such as land, forest, and wetlands.

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