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The Role of Russia's Terrestrial Biosphere in Bottom-up/Top-down Emissions Accounting

Barrett, K.

IIASA Interim Report
July 2006

International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report **IR-06-024**

The Role of Russia's Terrestrial Biosphere in Bottom-Up/Top-Down Emissions Accounting

Kirsten Barrett (123kika@gmail.com)

Approved by

Sten Nilsson
Deputy Director and Leader, Forestry Program

24 July 2006

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Abstract

International accords such as the Kyoto Protocol that seek to regulate greenhouse gas emissions on a global scale necessitate methods sufficiently robust to account for uncertainties in emissions data. Any detection of changes in carbon emissions must account for such uncertainties to conclusively determine when emissions reductions have occurred. When used in combination, ground-based (bottom-up) assessments of carbon emissions and atmospheric inversion models (top-down) are powerful tools for reducing uncertainties and verifying flux estimates. Because top-down methods cannot differentiate between different ecological processes or human-induced fluxes, it is important that emissions accounting consider carbon fluxes *in toto* to properly verify flux estimates. This study compares two such comprehensive bottom-up evaluations — the Russian Full Carbon Accounting (FCA) and SIBERIA-II full greenhouse gas accounting projects. Carbon flux estimates from the terrestrial biosphere are compared in terms of mean values and uncertainties. The Russian FCA and SIBERIA-II estimates are found to be internally consistent, with a few exceptions. Top-down data may be used to further reduce uncertainties and verify flux estimates.

Acknowledgments

The author would like to thank the IIASA Forestry Program, especially Matthias Jonas, Anatoly Shvidenko, Ian McCallum and Daniela Knorr. Mykola Gusti was especially helpful with draft revisions and data checking. Special thanks to Sam Ratick for checking the statistical calculations. Finally, thanks to the YSSP program organizers and the American National Member Organization (US NMO) who sponsored the author during her stay at IIASA.

About the Author

This report is the result of the author's participation in IIASA's 2005 Young Scientist Summer Program. The author was supervised by Matthias Jonas, Anatoly Shvidenko, and Ian McCallum of the Forestry Program.

Kirsten Barrett graduated from Simon's Rock College of Bard with a BA in Environmental Studies in 1998, and earned an MA in Geography and certificate of Remote Sensing and Spatial Analysis from the State University of New York at Albany in 2003. She is currently a doctoral student in the Clark University Graduate School of Geography. The title of her thesis is "Effects of Land-Cover Change on Terrestrial Carbon Uptake and Storage in the Southwestern Brazilian Amazon".

The Role of Russia’s Terrestrial Biosphere in Bottom-Up/Top-Down Emissions Accounting

Kirsten Barrett

1 Foreword

This report addresses the need for combining bottom-up and top-down data in greenhouse gas emissions accounting, specifically carbon. Currently, the need to ‘close the gap’ between bottom-up and top-down flux estimates is gaining the increasing support of the scientific community, if not yet recognized by policy-makers. The need for bottom-up/top-down accounting will underscore the importance of full greenhouse gas accounting in the next few years (Jonas, 2005). While the relevance of a bottom-up/top-down, or ‘dual constraint,’ approach to verification is gaining acceptance, obstacles remain that prevent the use of bottom-up and top-down data together within the framework formalized in the Kyoto Protocol. The guidelines of the Kyoto Protocol have yet to require the full greenhouse gas accounting that is necessary for implementation of the dual constraint approach. By dividing the biosphere into those parts that will be accounted for in terms of greenhouse gas fluxes and those that will not, the Protocol allows for partial greenhouse gas accounting that cannot be verified using top-down data.

This study of uncertainties in carbon accounting for Russia provides an important link with other projects housed at IIASA including the Greenhouse Gas Initiative (GGI). To date, the GGI activity has focused primarily on scenarios of greenhouse gas fluxes and their uncertainties over the long term. On a shorter time scale, factors such as compliance with international emissions reductions accords gain importance and accounted emissions replace emissions projected under medium- to long-term scenarios. This activity seeks to outline the uncertainties associated with emissions accounting in the short-term.

2 Introduction

Understanding regional carbon budgets (pools and fluxes) is fundamental to implementation of policies such as the Kyoto Protocol that seek to manage the amount of carbon steadily accumulating in the atmosphere. The reliability of a regional carbon accounting framework depends on many factors such as data quality, appropriate methodology, and reliable models of uncertainty. This study outlines how uncertainty is manifest in two regional carbon accounting schemes, and indicates how such uncertainties may be reduced in combination with additional datasets. The purpose here is to provide a preliminary assessment of uncertainties inherent in the two accounting frameworks, not to definitively quantify these uncertainties *de novo* as a static property of the accounts.

The first of the two carbon accounting schemes to be evaluated is a flux-based full carbon accounting (FCA) framework for Russia. Russian forests account for 23% of the global growing stock (Shvidenko and Nilsson, 2003), nearly 95% of which are boreal (Shvidenko *et al*., 1996). As such, these forests are considered a significant factor in global carbon cycling, and estimation of fluxes between the terrestrial biosphere and the atmosphere is an important goal for both policy-makers and the global change scientific community. The accounting of the FCA is bottom-up in nature, meaning that they are based on observations or statistical surveys of terrestrial processes such as net primary productivity, disturbance and heterotrophic respiration. Uncertainty has been included as part of the FCA as a critical component of signal detection in emission changes. The ability to detect changes in emissions is central to policies seeking to enforce emission reductions (Gupta *et al*., 2003; Jonas and Nilsson, 2004).

The second carbon accounting framework is that of the SIBERIA-II project, a collaborative effort still ongoing at the time of writing this report to fully quantify greenhouse gas emissions (CO_2, CO, CH_4, N_2O, and NO_x) for the region of Siberia. This project uses both a flux-based approach as well as an ecosystem model, though the former is the focus of this evaluation, given its commensurability with the Russian FCA approach. The SIBERIA-II project uses semi-empirical observation data as well as some remote sensing data to quantify the amount of carbon emitted to and sequestered from the atmosphere by the terrestrial biosphere.

The combination of these two bottom-up flux-based approaches yields an initial estimate of the uncertainties contained therein. Top-down data from atmospheric inversions are another independent source of information that will aid in uncertainty reduction by providing an additional constraint. Although the two approaches address similar fluxes to estimate the carbon budget, these fluxes were calculated using different methodologies as well as different datasets. The two bottom-up accounting approaches plus top-down models provide three valuable (although not fully independent) methods for the estimation of carbon fluxes between the terrestrial biosphere and the atmosphere and the uncertainty inherent in each approach.

3 Uncertainty and Signal Detection

As initiatives such as the Intergovernmental Panel on Climate Change (IPCC) focus on stabilizing greenhouse gas emissions over the long term, short- and medium-term strategies will provide the intermediate steps towards “safe” levels. Uncertainty assessment is a necessary component of short-term measures such as accounting for Kyoto Protocol-type emissions reductions programs. The uncertainties that such short-term accounting entail are different in nature from those present in any projection. The first are amplified over the long term and contribute to increasing overall uncertainties at longer time scales. Constraining short-term uncertainty, therefore, is important in terms of implementing long-term goals and constraining long-term uncertainties.

In order to definitively ascertain a change in carbon emissions, it is necessary for the difference to outstrip the uncertainty (which can, in a first-order approach, be safely assumed to be equivalent to that of the baseline year). In this context, statistical significance is not synonymous with detectability of emission changes. The detectability of the signal depends on the signal-to-uncertainty ratio, rather than the statistical statement that emissions measured or estimated at the outset and target year have changed (Jonas and Nilsson, 2004). This is because the statistical approach measures the significance of the difference between the two measurements, while a signal-to-uncertainty ratio reflects the dynamics in the uncertainties underlying emissions estimates.

Signal detection in emissions changes takes three forms: preparatory, midway, and retrospective (Jonas *et al.*, 2004). In the preparatory phase, the emissions of a country are calculated and a target for emissions reduction some time in the future is specified. At this point, the critical relative uncertainty (Figure 1) is calculated to determine the critical target, or the point at which a reduction in emissions outstrips the uncertainty of emissions estimates. It is generally assumed in preparatory signal detection that the path between the baseline and target years is a straight line and the path of historical emissions is not taken into consideration.

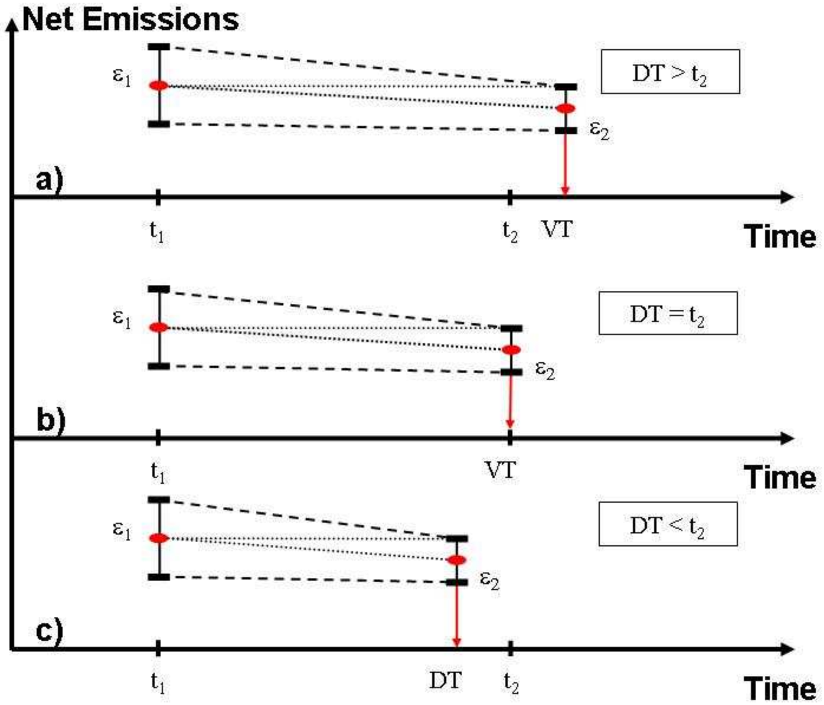

Figure 1: Illustration of the Detection Time (DT) concept (from Jonas *et al.*, 2004): The absolute change in emissions outstrips uncertainty at a) DT > t_2, or after the assessment to establish compliance under international agreement; b) DT = t_2, or at the exact time of the assessment; and c) DT< t_2, or before the time of the assessment.

Midway signal detection is an attempt to incorporate, in addition to uncertainty, information on the path of emissions between the baseline and target year. In this process, the dynamical moments of the curve are considered, which indicate whether or not it is possible for the system to achieve the target specified from preparatory signal detection. Midway signal detection may also incorporate information from emissions prior to the accounting period to determine more accurately the context of emissions changes.

Retrospective signal detection will become more important when countries seek to determine their achievements in emissions reductions as per international agreements. Before accounting for changes in carbon, it is first necessary to determine the detectability of changes or their statistical significance. If the change in emissions does not meet the requirement that it exceeds the uncertainty associated with measurement, a country cannot be considered to have complied with its commitment. Part of the measured emissions reduction will be allocated to satisfying this first requirement. Once the uncertainty has been accounted for, it is necessary to determine that a country has reduced emissions by the target amount. A risk factor that the country has not met its target must be agreed upon, and then the amount by which a country must have reduced its emissions is recalculated (Gillenwater *et al*., 2004). Countries will therefore have to undershoot their target emissions to achieve the reduction commitment both to meet the detectability requirement and to ensure that emissions have indeed decreased by the target amount given the uncertainty of the measurements in the baseline and target years.

It is clear from the above discussion that specifying uncertainties in carbon accounting is central to implementation of emissions reduction policies, and will only increase in importance as such policies come into effect. Uncertainty reduction will directly reflect upon the extra emissions reduction that a country will have to achieve to comply with its commitments based on the need for undershooting.

4 Full Carbon Accounting

If we seek to assess carbon budgets in terms of their uncertainty, we must be able to verify flux calculations. Bottom-up flux estimates can be verified using top-down data from atmospheric inversions, provided that both procedures are measuring the same thing. Top-down flux estimation begins with measurements of carbon concentrations in the atmosphere and combines these observations with atmospheric transport models to determine the source of the observed fluxes. This end-of-the-line approach for evaluating carbon fluxes necessarily includes both anthropogenic and natural sources, and cannot distinguish between different ecological processes that generate carbon fluxes to the atmosphere. Therefore, in order to be commensurable with top-down data, bottom-up measurements must account for all carbon fluxes, regardless of the source. Only full carbon accounting estimates are candidates for verification using top-down data (Jonas and Nilsson, 2004).

Current Kyoto Protocol guidelines do not require full carbon accounting. The biosphere is hence divided into Kyoto (the portion of the biosphere to which the Protocol pertains) and non-Kyoto portions (Jonas and Nilsson, 2004). The partial carbon accounting permitted under current guidelines cannot be verified using top-down methods because of data incommensurability. Partial carbon accounting may serve to *validate* models of carbon cycling, but *verification* can only be accomplished with two directly comparable, independent quantitative estimates of carbon fluxes as in full carbon accounting. Only in the context of a verified account can uncertainty be a known quantity. Validation serves to confirm uncertainties that have been identified from the data variability, without comparing them to an independent estimate. In this sense, only verification can provide an estimate of the 'real' uncertainties. Moreover, the potential effect of disregarding uncertainty under the Kyoto Protocol is that ultimately two countries may report the same reduction of carbon emissions, and though one may have markedly greater uncertainty, both are considered compliant under current Kyoto guidelines (Gupta *et al*., 2003).

It is likely that as time progresses towards the point where emissions changes must be accounted for, the importance of full greenhouse gas accounting will be recognized by policy-makers. The reason is that the confusion resulting from different uncertainties will make compliance with emissions reductions commitments unclear. At present an incentive exists to have greater emissions uncertainty, which make it more likely that the reduction requirement will fall within the uncertainty bounds of calculated emissions changes. Uncertainty will only be penalized if an independent review panel finds the reporting data problematic. Uncertainty must be incorporated in a more systematic way to ensure that emissions reductions commitments are indeed met.

Both of the datasets reviewed below represent spatially explicit, bottom-up flux-based full carbon accounts. The first is a full greenhouse gas accounting framework for the Siberia region. The second expands the geographic focus to all of Russia, but is restricted to carbon accounting. These datasets are particularly important in light of the large carbon sink believed to exist in the northern extratropical regions of Eurasia and North America (see Figure 2 for spatial extent of both datasets).

5 SIBERIA-II

The SIBERIA-II project is a multi-sensor approach to full greenhouse gas accounting for the region of Northern Eurasia, funded by the European Commission. *In situ* observations from forest inventories are combined with global dynamic vegetation models as well as remote sensing data to quantify carbon pools and fluxes. Two different approaches are used simultaneously to determine the full carbon account in the region — both a process-based ecological model as well as a flux-based framework. The flux-based approach is the focus of this report, as it is commensurable with the full carbon account for all of Russia.

Any full carbon accounting framework must necessarily be exhaustive in its monitoring of carbon pools and fluxes, as well as temporally continuous (Steffen *et al*., 1998). The full carbon budget, therefore, can only be approximated by current methods. Any portion of the full carbon account cannot provide an accurate estimate of uncertainties in isolation. The need for integration of data is highlighted in the SIBERIA-II full carbon accounting philosophy. It is necessary to combine all available information from remote sensing, inventory data and ecological and atmospheric models to gain the most accurate characterization of the full carbon budget (Nilsson *et al*., 2004a).

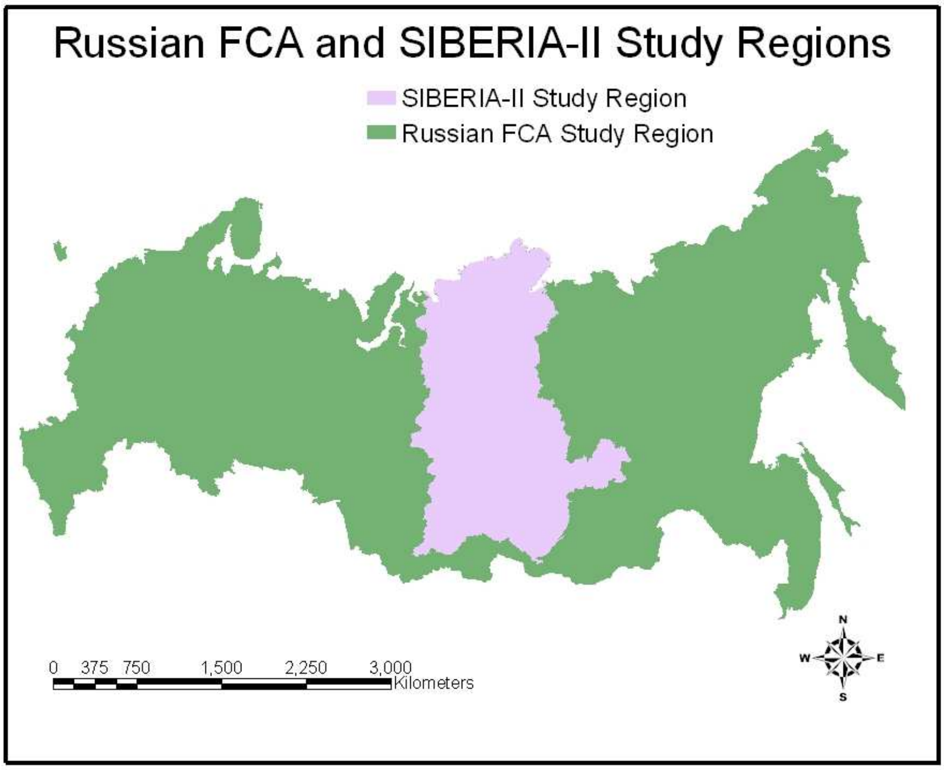

Figure 2: The two study regions, both encompassing part of the Northern Eurasian boreal forests, believed to be a significant sink of atmospheric carbon.

The fluxes calculated in the SIBERIA-II project are spatially hierarchical. Initially, the region is divided into polygons constructed from homogenous regions of vegetation type determined by soils, land cover and forest inventory class. The fluxes calculated at the polygon level are then aggregated to the ecological zone (polar, tundra, taiga temperate forests, steppe, and desert), then to administrative units (oblasts) and finally to the entire Siberian region. This method allows the calculation of greenhouse gas fluxes aggregated spatially while maintaining the more spatially detailed information used in flux calculations. Most of the information on calculations and estimates in this section was obtained from Nilsson *et al*. (2004a), unless otherwise specified.

The flux-based approach of the SIBERIA-II project seeks to quantify the carbon fluxes between the terrestrial ecosystem, atmosphere, lithosphere, and hydrosphere in the form of net biome productivity (NBP):

$$NBP = NPP - HR - D - L$$

where NPP is net primary production, HR is heterotrophic respiration of soil and above ground dead organic matter, D is the carbon fluxes caused by disturbances, and L is lateral fluxes to the hydrosphere and lithosphere (Figure 3). The algorithm used includes: (1) a baseline inventory approach, (2) introduction of environmental indicators for estimating the basic indicators of the FCA (NPP and HR), and (3) the use of some elements of process-based modeling. The baseline was calculated for 1999–2003 by defining major indicators of the full greenhouse account, calculated for each polygon, aggregated by land classes inside each ecoregion, and then to administrative units, and finally for the whole region.

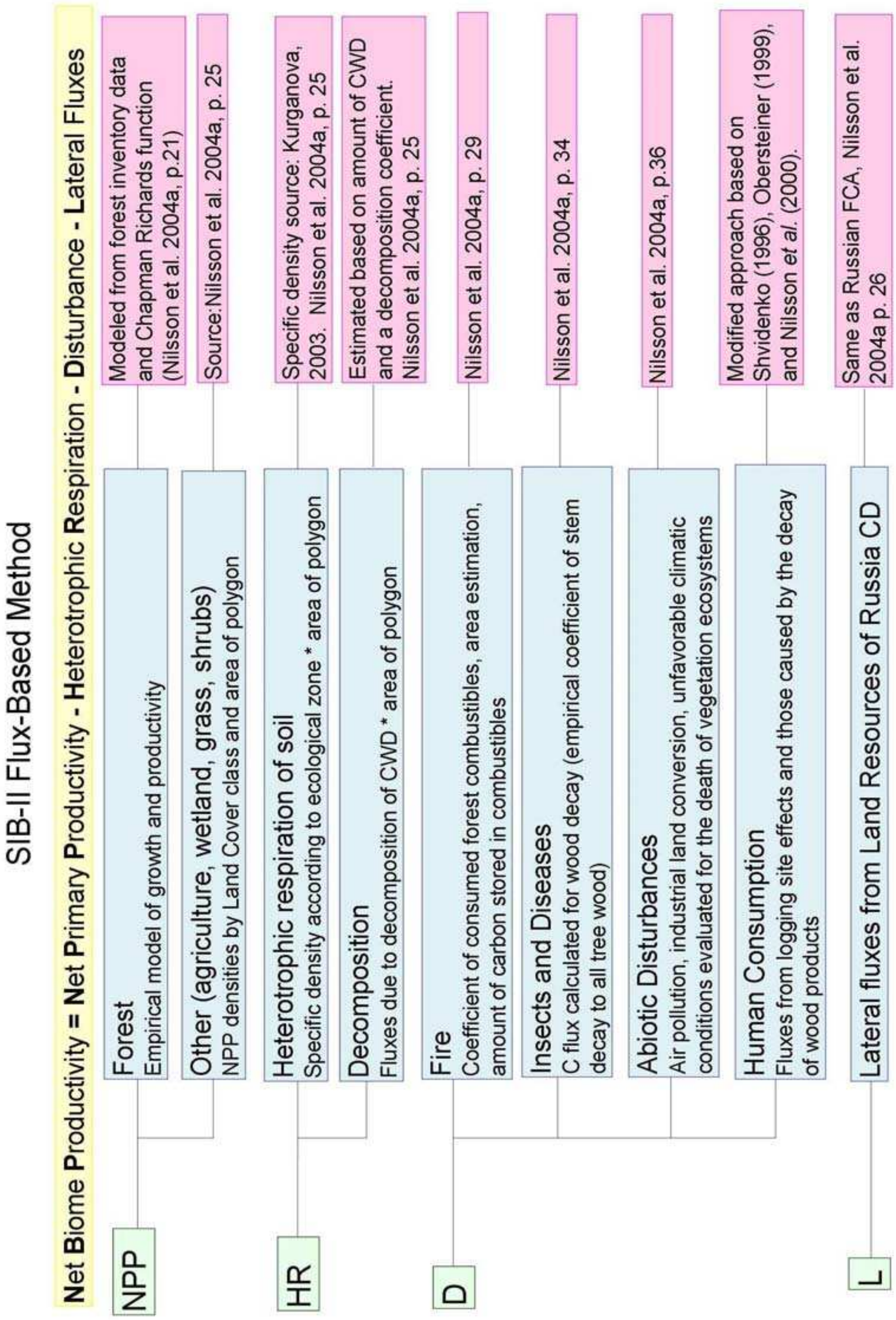

Figure 3: Illustration of the flux-based concept used in the SIBERIA-II full carbon account.

5.1 NPP

NPP was estimated separately for forested lands and other classes. In the case of forests, NPP is the product of empirical models of growth and productivity. Baseline models of biological production were developed using models of phytomass dynamics from 3507 sample plots collected for the region (Shvidenko *et al*., forthcoming). A growth model was then developed by combining phytomass dynamics information with a Chapman-Richards (Richards-Chapman) growth function. Models of biological production were developed by dominant tree species, site indexes and ecological regions. The models comprise age dynamics of both ecosystems' phytomass by seven fractions (stem wood over bark, bark, crown wood, foliage, understory, green forest floor, and roots) and NPP. This database provides the baseline semi-empirical reference information on growth and productivity of Northern Eurasia's forests used in the NPP calculations.

For all other classes such as agriculture and non-forested lands, the average NPP densities were calculated by land cover, and then extrapolated for each polygon by multiplying by the area of the polygon.

The source for this data is outlined in Shvidenko *et al*. (2001), wherein a statistical method is combined with semi-empirical models as a basis for the calculations. The database, consisting of polygons and their respective productivity attribute data, was created at IIASA from data measured in more than 3000 test plots. For agricultural lands and grasslands, the phytomass stock was assumed to be equal to NPP. This is a valid assumption as the life cycle of these plants is annual. For other land use/land cover classes NPP was estimated by multiplying the average value from test plots by the area occupied by the class.

5.2 Heterotrophic Respiration

Heterotrophic respiration in this project is the sum of soil respiration and fluxes from the decomposition of coarse woody debris. Heterotrophic soil respiration is calculated by multiplying the specific density of respiration by the area of the polygon. The specific density was derived from a database (Kurganova, 2003: Tables A5 and A6). Averages for land use/land cover classes and ecological zones were used as a control.

Decomposition of coarse woody debris (CWD) was estimated for forest land based on the amount of CWD and modifying coefficients according to ecological zone. The estimate was then multiplied by the area of the polygon.

5.3 Disturbance

Disturbance fluxes from the Siberia region are calculated for forest fires, biotic and abiotic factors. Decay of detritus is calculated for three different pools — fast (on-ground litter), medium (wood residuals with diameter at thin end 8 cm $\geq$ d $\geq$ 1 cm; d = diameter), and slow (d > 8 cm). These pools are assigned coefficients of decay for each ecological zone where they occur.

5.3.1 Fire

The direct fluxes from fire are a function of the area burned, the storage of forest combustibles (t/ha of dry matter), a conversion from dry matter to carbon units (0.5 for forest combustibles, 0.45 for other vegetation), and a coefficient for consumed forest combustibles during the fire.

Post-fire carbon fluxes were also estimated for decomposition of incombustible (dead) matter, post-fire mortality, and changes in the content and structure of soil organic matter.

5.3.2 Biotic Disturbances

Three primary types of biotic disturbances are evaluated in the SIBERIA-II project — insects and diseases that are accounted for in official statistics, insects and disease outbreaks that occur outside these areas in forests classified as healthy, and impacts of wild fauna. The calculations for biotic disturbance fluxes are the result of collaboration between the Moscow State Forest University and IIASA's SIBERIA-II team.

For areas that are identified as affected by insects or disease in official statistics, the carbon flux is calculated as a function of the amount of phytomass per hectare, the area affected by insects or disease, and mortality expressed in terms of the percent of growing stock volume for the respective phytomass component, type of damage, dominant (forest) species, year, and spatial unit of aggregation.

The impact of wild fauna is based on the number of animals in specific groups, and their respective daily consumption of phytomass for specified phytomass component.

5.3.3 Abiotic Disturbances

In addition to those fluxes from fire and biotic disturbances, abiotic disturbances, including air pollution, industrial land-use conversion, and unfavorable climatic conditions are considered by the SIBERIA-II project. The effect of these factors considered in the analysis is only that of mortality — degradation of living species is not evaluated.

Official statistics for these abiotic disturbance factors are either incomplete or non-existent, so the study relies on special surveys and partial studies.

5.3.4 Human Consumption

Consumption of agricultural products as well as harvested vegetation phytomass on grass- and shrub lands is estimated by statistical data from agricultural yield.

Two fluxes of carbon from vegetation harvest are included in the study — those that occur due to the destructive effects of logging and those caused by the decay of wood products. The methods used are described in more detail in Shvidenko *et al*. (1996), Obersteiner (1999) and Nilsson *et al*. (2000).

5.4 Lateral Fluxes

Fluxes of carbon to the lithosphere and hydrosphere are calculated as the average amount of carbon transported from unit area for each polygon. These data were derived from the Land Resources of Russia CD-ROM (Stolbovoi and McCallum, 2002).

6 Russian Full Carbon Accounting

The Russian FCA project seeks to construct a full carbon account for all of Russia, with a focus on policy-relevant information, especially uncertainties in flux calculations. Uncertainty information became a focus of the project after its inception, and uncertainty is integrated as part of the project. Uncertainty is defined within the context of the FCA as "an aggregation of insufficiencies of system outputs, regardless of whether these insufficiencies result from a lack of knowledge, the intricacies of the system, or other causes". The FCA uses bottom-up measurements of input data based on inventories and *in situ* data. As in the SIBERIA-II project, a spatially-explicit approach facilitates the linkage of disparate datasets such as those used to calculate carbon fluxes (e.g., forest inventories, soils maps, and information on terrestrial vegetation production).

Full Carbon Accounting is preferable to Partial Carbon Accounting (provided for in the Kyoto Protocol) because the latter leaves unconsidered fluxes that are important to the carbon cycle. When combining bottom-up carbon accounting information with top-down observations from atmospheric inversion models it is impossible to partition the fluxes to individual terrestrial components. Therefore, full carbon accounting is necessary in the interests of verifiability of flux estimates.

The flux concept of the Russian FCA project is illustrated in Figure 4. The vegetation and soil carbon flux balances are calculated as a function of the input fluxes indicated by flux arrows. Hence in the case of vegetation, carbon flux is calculated as a function of NPP, divided into consumption, disturbance, and litter fluxes. Soil carbon flux is calculated as the sum of flux balances in litter and humus soil components minus lateral fluxes to the hydrosphere and lithosphere. The approach is similar to the flux-based approach of the SIBERIA-II project, with differences occurring at levels below that of fluxes in terms of such factors as disturbance and input data used to create flux estimates (Table 1). All information regarding calculations and estimations is referenced in Nilsson *et al*. (2000) unless otherwise indicated, while the data come from IIASA's Land Resources of Russia CD-ROM (Stolbovoi and McCallum, 2002).

6.1 NPP

The Russian FCA project, like the SIBERIA-II project, divides NPP into fractions from forests, non-forest natural vegetation, and agriculture. In the case of forests, a database used for NPP assessment was created from observations on 1600 sample plots. The initial dataset was developed by Bazilevich (1993), and supplemented with measurements from the 1990s (e.g., Karelin *et al*., 1995; Gower *et al*., 1994; Schulze *et al*., 1999). NPP was measured on these plots according to three aggregated fractions — total green parts, above-ground wood, and below-ground parts.

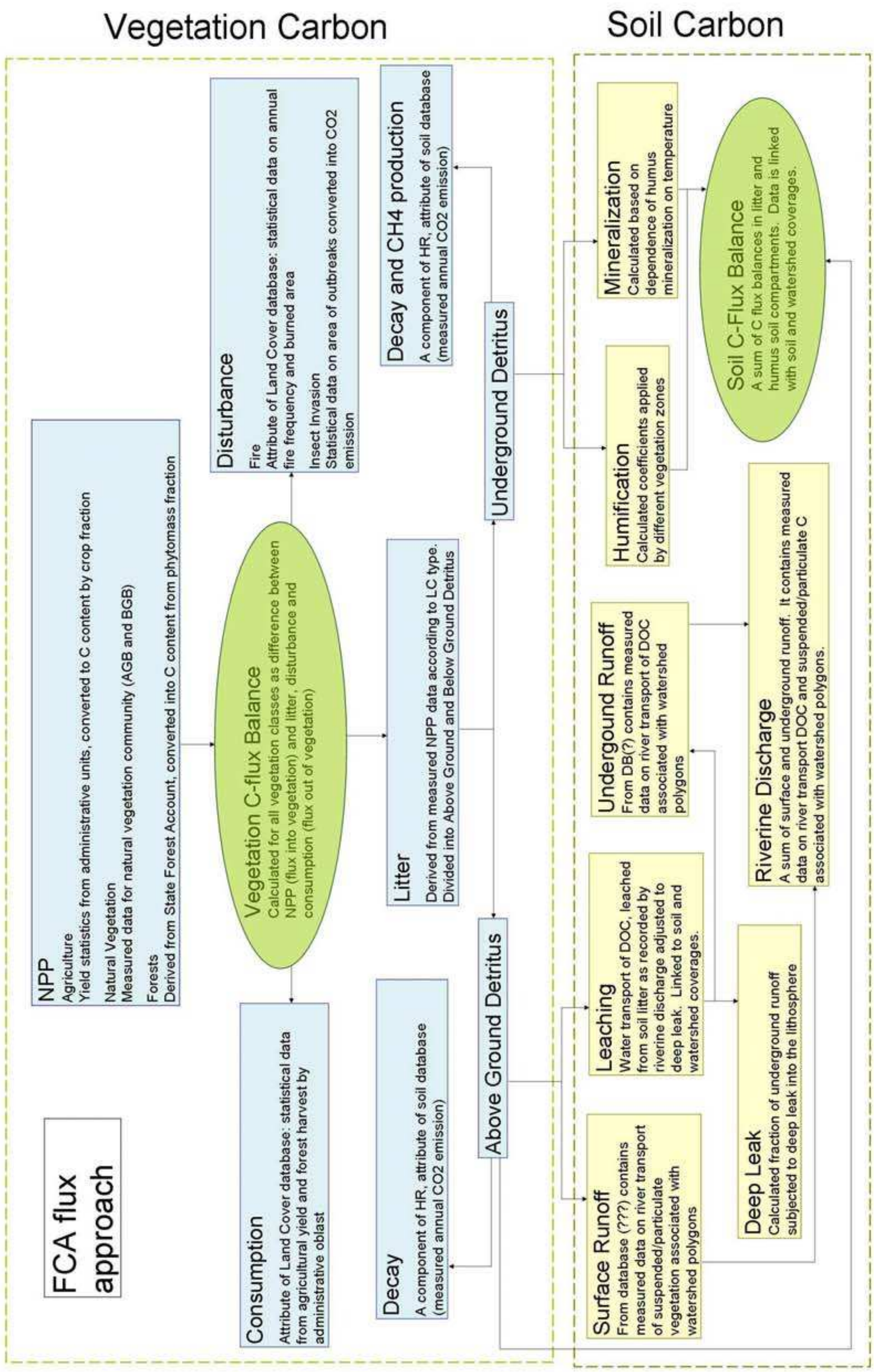

Figure 4: Illustration of the flux-based approach used in the Russian Full Carbon Account.

Table 1: A comparison of the methods used in calculating the aggregated fluxes in the Russian Full Carbon Account and SIBERIA-II projects.

	FCA Method	**SIB-II Method**
Vegetation Carbon	NPP — litter — disturbance — consumption	NPP — heterotrophic respiration — disturbance — lateral fluxes
NPP		
Agriculture	Yield Statistics from Administrative Units, converted to C content by crop fraction	NPP density by land cover class * area of polygon
Forest	Derived from State Forest Account, converted into C content by phytomass fraction	Empirical model of growth and productivity
Other Natural Vegetation	Measured data for natural vegetation community (AGB and BGB)	NPP density by land cover class * area of polygon
Disturbance		
Fire	Attribute of land cover DB, statistical data on annual fire frequency and burned area	Area estimation * amt C stored in combustibles * coefficient of consumed forest combustibles
Insect invasion	Statistical data on area of outbreaks converted into CO_2 emission	C flux estimated for woody decay (empirical coefficient of stem decay to all tree wood)
Abiotic disturbance	Not Available	Air pollution, industrial conversion, unfavorable climatic conditions
Human Consumption	Attribute of land cover DB, statistical data from agricultural yield and forest harvest by administrative oblast	Fluxes from logging site effects and those caused by decay of wood products
Heterotrophic Respiration		
HR of soils	Attribute of soil DB, measured annual CO_2 emission	Specific density according to ecological zone * area of polygon
Decomposition	Derived from measured NPP data according to land cover type, divided into AGD and BGD	Fluxes due to decomposition of CWD * area of polygon
Lateral Fluxes	Same data used in both projects	

Models of growth do not incorporate information on changing environmental conditions which may include C fertilization, N deposition, and effects from climate change. These effects, however, are estimated to be of peripheral importance to the calculations based on other studies that addressed the phenomena directly. This is true because while NPP may increase due to changing environmental conditions, the effect on NEP is likely to be smaller due to increases in soil respiration (Shvidenko and Nilsson, 2003). Anthropogenic effects, in the form of disturbances that affect productivity (increases due primarily to fire in areas of permafrost and decreases due mostly to conversion of forest areas to industrial land) and wetland amelioration were estimated in order to improve the accuracy of NPP estimates.

To reduce uncertainty in NPP estimation, an independent estimate was made using State Forest Account data from 1993 and a model of gross stem growth on forested areas. The crown growth was estimated from phytomass models for branches as a function of stem growth. This estimate calculated annual above-ground wood NPP 8.5% higher than the GIS-based estimate, which was considered acceptable for validation (Shvidenko *et al*., 2001). An unquantified uncertainty is also expected to result from assumptions regarding the NPP of fine roots, as there is considerable debate on the longevity of this phytomass component and its contribution to aggregated NPP.

For non-forest natural vegetation, NPP (kg C m^{-2} yr^{-1}) was measured in both above ground and below-ground fractions. In these calculations, NPP is a function of the land class, phytomass fraction (stem, bark, crown, foliage, roots, understory, green forest floor), and vegetation type, multiplied by the area occupied and a coefficient of carbon content (0.50 for woody parts, 0.45 for green parts) (Stolbovoi and McCallum, 2002). Averages were then used to apply these calculations to the entire region.

In the case of cropland and pastures, as for the SIBERIA-II calculations, the production was assumed to be equal to phytomass, given the annual life cycle of plants in agricultural systems. The agricultural yield statistics were provided by administrative units and then converted to C content by crop fraction (Stolbovoi and McCallum, 2002). As in the case of non-forest natural vegetation, averages were calculated to extend the calculations to the entire region.

6.2 Heterotrophic Respiration

Carbon fluxes from heterotrophic soil respiration for Russia are calculated both for CO_2 and CH_4. Emissions calculations are based on soil areas derived from a Russian soils map and mean daily fluxes excluding live root and microbe respiration. The number of biologically active days, or days with mean daily temperature greater than 0º C, was calculated by Leemans and Cramer (1991).

Carbon dioxide is calculated as the sum of the mean daily CO_2 emissions for each soil type multiplied by the number of days with mean daily temperature above 0º C by soil type and the soil type area.

In the case of CH_4, the calculation is similar to CO_2 calculations without the number of days with mean daily temperature above 0º C.

6.3 Disturbance

The disturbance flux calculations for the Russian FCA are similar to those for the SIBERIA-II project. The total carbon flux is calculated as the sum of direct fluxes from disturbances, post-disturbance fluxes from previous years, and fluxes that result from post-disturbance site restoration and regrowth. The values for direct fluxes and post-disturbance fluxes depend on the type, strength, and scale of the disturbance, conditions under which the disturbance occurs, and type of ecosystem affected. The disturbances considered in the Russian FCA are fire, harvest, biotic and abiotic disturbances. Additionally the study includes an estimate of disturbances of wetlands, grasslands, and shrubs.

Similar to the SIBERIA-II project, the Russian FCA calculated the decay of three detritus pools (fast-, medium-, and slow-decaying) which are assigned coefficients for each ecological zone (see section 3.3).

6.3.1 Fire

Direct fire emissions and post-fire emissions were estimated in the same manner as in the SIBERIA-II project (see section 4.3.1) (Shvidenko and Nilsson, 2000a, b).

6.3.2 Biotic Disturbance

For biotic disturbances, estimates of fluxes were made based on available statistics, publications and fragmentary data.

6.3.3 Abiotic Disturbance

Abiotic impacts were assessed from data for specific regions and expert estimates due to the lack of complete surveys. The amount of carbon released due to abiotic factors was estimated, and fluxes from fire, harvested wood, increased coarse woody debris pool, and landfills were subtracted from the average to yield the estimate from industrial pollution, land-use change, and unfavorable climatic conditions.

6.3.4 Human Consumption

Only the site-located impacts of industrial harvest are considered in the FCA. The harvest components included in the analysis are decomposition of harvest residuals, post-harvest mortality, and soil respiration. The emissions are calculated based on average annual harvests.

Forest products were addressed using a separate model designed by Obersteiner (1999) that accounts for stocks and fluxes of Russian forest products. The model is comprised of the transformation of industrial wood into consumption goods and their residence time in the consumption sector. Fuelwood is considered separately from industrial wood products. Fluxes from forest products are the sum of fluxes from historical and current use of forest products. Fluxes from fuelwood consumption are calculated as the combined fluxes from commercial and residential fuelwood.

6.3.5 Wetlands, Grasslands, and Shrubs

Fluxes from disturbances on wetlands, grasslands, and shrubs include fire and consumption by domestic livestock and wild fauna. These were calculated in the same way as fire estimates (Shvidenko and Nilsson, 2000a, b).

6.4 Lateral Fluxes

Fluxes to the lithosphere and hydrosphere were estimated as a function of underground and surface runoff and leaching (hydrosphere) and humification and mineralization (lithosphere).

In the case of fluxes to the hydrosphere, runoff is collected by rivers and transported out of the terrestrial system. The runoff data are from the database of measured data of river transport of dissolved organic carbon as well as suspended particulate vegetation (Stolbovoi *et al*., 2005). This data was associated with watershed boundary polygons of the first, second and third levels. The riverine discharge is the sum of surface and underground runoff. Leaching contributes both to underground runoff and a deep leak component. The latter is calculated as the fraction of underground runoff that is subjected to deep leakage into the lithosphere.

For fluxes to the lithosphere, humification is calculated by coefficients for different vegetation zones. These coefficients were produced for underground detritus by Grishina (1986). Mineralization is based on the relationship between humus mineralization and temperature, also observed by Grishina (1986).

7 Comparison of SIBERIA-II/Russian FCA Data

The SIBERIA-II and Russian FCA data are commensurable in a general sense, though they span different spatial and temporal extents. The Russian FCA flux data cover the period from 1988 to 1992. The SIBERIA-II data are used to calculate a long term flux estimate (about a 40-year average from the early 1960s to 2003). The long term estimate[1] is then corrected for climatic (growing) conditions for 2003 to produce flux estimates for that year. The SIBERIA-II region covers ~20% of the total area of the Russian FCA (see Figure 2). For the purposes of this study both regions are stratified by the bioclimatic zone. This method of separating aggregated fluxes will show how the ecological processes that determine most of the carbon fluxes in the region differ according to climatic and vegetation classes. Both datasets span various bioclimatic regions, and such heterogeneity is hypothesized to contribute to the uncertainty of aggregated flux estimates. This study examines the two largest vertical fluxes of carbon between the terrestrial biosphere and the atmosphere, namely net primary production (NPP) and heterotrophic respiration (HR), the difference between which is equal to net ecosystem productivity (NEP).

The bioclimatic zones used in the analysis are not exhaustive of the categories found in the study regions, though they cover most of the area. Some categories were not directly comparable, or were not important in terms of carbon fluxes (e.g., water). The classes used to stratify the flux data; southern taiga, middle taiga, northern taiga, steppe,

[1] The NPP data of the Russian FCA were taken from the vegetation map on IIASA's Land Resources of Russia CD-ROM (Stolbovoi and McCallum, 2002), while the HR data were taken from the CD's soil map. In the case of the vegetation map, it must be kept in mind that it reflects "actual vegetation, which is characterized by natural plant communities and their anthropgenic modifications. Potential vegetation is shown for agricultural land with the exception of oases" (Stolbovoi, 1998).

temperate forest, and tundra; are the categories for the most straightforward and meaningful comparisons can be made. Even within this stratification some significant variation exists that may affect the resulting uncertainty analysis. For example, the SIBERIA-II region is divided into four categories of tundra that had to be combined to be commensurable with the Russian FCA classification, which only has one tundra category.

Another issue regarding data commensurability is that of the time period observed. In the case of SIBERIA-II, long-term flux data are available for the period from about 1960 to 2003. For the Russian FCA project, the data span the period from 1988 to 1992. This may lead to some disagreements between the flux calculations,[2] however it is still possible to gauge the uncertainties present in both datasets based on a direct comparison.

7.1 Net Primary Productivity

The first aggregated flux category is area-averaged carbon fluxes from NPP in Kg C m^{-2} yr^{-1} (Table 2). In the SIBERIA-II project, NPP is derived from biological production models of aggregated above-ground woody biomass, below-ground, and green parts fractions. For the Russian FCA, NPP was estimated from field observations of the same components. Information on the distribution of NPP values is available for the Russian FCA and SIBERIA-II long term data, though not for 2003. Area-weighted standard deviations and variation coefficients are therefore not available for the latter. All of the SIBERIA-II 2003 NPP estimates fall within one standard deviation of the long term SIBERIA-II data. The SIBERIA-II NPP estimates disagree with the Russian FCA data (1988–1992) in one bioclimatic zone (see section 7.1.1), demonstrating the general consistency of the different accounts. The disparities between the Russian FCA and long term SIBERIA-II data are discussed below.

7.1.1 Comparison of FCA and Russian Long-term SIBERIA-II NPP

Comparing the Russian FCA and long term SIBERIA-II NPP estimates, we see that in five of the six bioclimatic zones the mean flux values of estimates fall within one standard deviation of the comparison dataset. The fact that the means of all but one bioclimatic category are within one standard deviation of another is understood to signify that the two independent bottom-up carbon flux estimates are largely consistent. Steppe, the case in which the estimates disagree (means are not within one standard deviation of each other), exhibits large areas that are used agriculturally. However, the FCA data are characterized by potential vegetation in the vegetation map on IIASA's Land Resources of Russia CD-ROM (cf. Footnote 1), which can be considered as a major difference for explaining this particular difference.

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[2] We assume here that there are no significant differences between the fluxes in the two different time periods studied, though this may not always be accurate. For example, the Norilsk Metallurgical Combine is a large-scale mining effort, extracting nickel and other minerals. The mine has contributed to significant decline of forests in the region and is responsible for significant ongoing environmental degradation (Shvidenko, 2005).

Table 2: Comparison of the mean values, standard deviations (SD), and variation coefficients (VC) of carbon fluxes from net primary production for SIBERIA-II and Russian FCA, stratified by bioclimatic zone.

NPP Kg C m^{-2} yr^{-1}									
	FCA 1988–1992 Mean	*n* (min–max)	SIB-II Long-term Mean	*n* (min–max)	SIB-II 2003 Mean	FCA SD (68%)	SIB-II Long-term SD (68%)	FCA VC	SIB-II Long-term VC
Southern Taiga	0.26	*2410* (0.00–1.27)	0.31	*5679* (0.00–0.79)	0.29	0.21	0.10	0.80	0.34
Middle Taiga	0.21	*6593* (0.00–1.27)	0.24	*3232* (0.00–0.61)	0.26	0.15	0.10	0.69	0.43
Northern Taiga	0.17	*2553* (0.00–1.27)	0.14	*2949* (0.00–0.44)	0.22	0.08	0.09	0.47	0.63
Steppe	0.86	*2100* (0.00–1.79)	0.50	*31* (0.00–1.19)	0.45	0.24	0.23	0.28	0.46
Temperate Forest	0.36	*1692* (0.00–1.79)	0.32	*617* (0.00–1.01)	0.32	0.11	0.13	0.32	0.39
Tundra	0.13	*4214* (0.00–1.00)	0.08	*1487* (0.00–0.36)	0.12	0.08	0.06	0.67	0.76
within 2 Standard Deviations									

7.2 Heterotrophic Soil Respiration

Heterotrophic soil respiration is the carbon flux from respiration of micro-organisms in the soil that are not connected with the root matter of plants, as well as those fluxes from the decomposition of coarse woody debris. The SIBERIA-II long-term and 2003 HR estimates agree for each bioclimatic zone, demonstrating the internal consistency of this accounting approach (Table 3). The comparison of heterotrophic respiration flux estimates for Russian FCA and SIBERIA-II data shows four bioclimatic zones for which the datasets are in agreement (mean values are within one standard deviation of the comparison dataset) — southern, middle, and northern taiga; and steppe. The differences are discussed below.

7.2.1 Comparison of FCA and Russian Long-term SIBERIA-II HR

All of the mean SIBERIA-II long-term HR carbon flux estimates are within one standard deviation of those of the Russian FCA. This is due to consistency of estimates as well as the broad distributions of FCA estimates (variation coefficient (VC) min = 0.32, max = 1.09). Two mean flux estimates from the FCA do not agree with the SIBERIA-II estimates. The variation coefficient for SIBERIA-II VC is smaller than that of the FCA for these categories, which may have contributed to the exclusion of the Russian FCA mean values.

The number of samples from the SIBERIA-II temperate forest flux estimate is considerably smaller than that of the FCA (*n* = 617 and *n* = 1692, respectively), which may have constrained the variability of the estimate (VC = 0.41, VC = 0.53, respectively). The smaller number of samples is partly because of constraints of the data collection and also reflects the fact that Siberia is a subregion of the Full Carbon Account for Russia.

Table 3: Comparison of the mean values, standard deviations (SD), and variation coefficients (VC) of carbon fluxes from heterotrophic respiration for SIBERIA-II and Russian FCA, stratified by bioclimatic zone.

HR Kg C m^{-2} yr^{-1}									
	FCA 1988–1992 Mean	*n* (min–max)	SIB-II Long-term Mean	*n* (min–max)	SIB-II 2003 Mean	FCA SD (68%)	SIB-II Long-term SD (68%)	FCA VC	SIB-II Long-term VC
Southern Taiga	0.23	*2410* (0.00–0.80)	0.23	*5679* (0.00–0.79)	0.19	0.25	0.06	1.09	0.24
Middle Taiga	0.17	*6593* (0.00–1.27)	0.18	*3232* (0.00–0.61)	0.18	0.12	0.07	0.72	0.38
Northern Taiga	0.13	*2553* (0.00–1.27)	0.11	*2949* (0.00–0.44)	0.07	0.07	0.06	0.52	0.59
Steppe	0.38	*2100* (0.00–1.79)	0.30	*31* (0.00–1.19)	0.32	0.12	0.14	0.32	0.47
Temperate Forest	0.40	*1692* (0.00–1.79)	0.22	*617* (0.00–1.01)	0.15	0.21	0.09	0.53	0.41
Tundra	0.12	*4214* (0.00–0.50)	0.06	*1487* (0.00–0.36)	0.02	0.11	0.05	0.96	0.83

within 2 Standard Deviations

Tundra is a problematic class because it represents an aggregate of different bioclimatic zones in the case of SIBERIA-II data, which had to be combined to be comparable with the FCA data. The tundra category displays similar characteristics to the temperate forest flux estimates. The number of samples for the SIBERIA-II estimate, while much greater than the temperate forest estimate, is still much smaller than that of the Russian FCA (*n* = 1487 and *n* = 4214, respectively). The variation coefficient demonstrates that the variability for this bioclimatic zone is great (VC = 0.83 for SIBERIA-II, VC = 0.96 for the FCA).

7.3 Net Ecosystem Productivity

The amount of carbon sequestered by the terrestrial biosphere and not returned to the atmosphere via heterotrophic respiration is known as net ecosystem productivity, or NEP. This is a valuable measure because carbon sequestration is of particular interest in Northern Eurasia, which is believed to be a sink of atmospheric carbon. The NEP calculations reflect the disagreements between the SIBERIA-II and Russian FCA accounting schemes in different bioclimatic zones. The inconclusiveness of NEP estimates indicates that the NPP and HR estimates are not directly comparable at the disaggregated scale of bioclimatic zones (see Table 4).

Table 4: Net ecosystem productivity, or the difference between net primary productivity and heterotrophic respiration, according to Russian FCA and SIBERIA-II flux estimates.

NEP [NPP-HR]	FCA 1988–1992 Mean	SIB-II Long-term Mean
Southern Taiga	0.03	0.08
Middle Taiga	0.04	0.06
Northern Taiga	0.04	0.04
Steppe	0.48	0.21
Temperate Forest	-0.04	0.10
Tundra	0.01	0.02

In the case of steppe, the two estimates disagree as to the magnitude of the flux (0.21 Kg C m^{-2} yr^{-1} according to SIBERIA-II data, 0.48 according to the Russian FCA). As discussed above, this may be due to the actual-versus-potential vegetation difference underlying the NPP data.

The more striking disagreement between the two estimates is for temperate forest, which actually disagree as to the sign of the flux (-0.04 Kg C m^{-2} yr^{-1} for the FCA, 0.10 Kg C m^{-2} yr^{-1} according to SIBERIA-II estimates). The disagreement reflects the difference between the two estimates, the FCA being based on potential vegetation and SIBERIA-II using actual vegetation. The inconsistency certainly warrants further investigation, as it is a central question regarding carbon uptake in Northern Eurasia.

8 Comparison with Atmospheric Inversion Models

The combination of bottom-up and top-down measurements is a useful method for evaluating and reducing uncertainty in carbon flux estimation. Using two independent measurements of the same phenomenon is termed the 'dual constraint approach.' This is the only appropriate method for the verification of carbon flux estimates (Nilsson *et al.*, 2004b).

Top-down methods require ground-based measurements to constrain their atmospheric inversion models. Using frequentist Bayesian probabilities to constrain a cost function, inversion models incorporate prior estimates of fluxes from fossil fuels and models of the ocean carbon cycle and the terrestrial biosphere (Roedenbeck *et al.*, 2003, Tarantola, 1987). In this way, bottom-up data are particularly useful in reducing the uncertainty of top-down data. In this report, however, the potential of top-down data to evaluate uncertainties in bottom-up data is of greater concern.

Atmospheric inversion data for the Russian region are available from Le Laboratiore des Sciences du Climat et l'Environnement at the Commissariat à L'Energie Atomique (CEA) in France. Atmospheric observations are currently available from 17 sites in the region, primarily from air flasks measured twice weekly (see Figure 5). Most of the sites were established in 1997 and 1998 or in the early 2000s (see Table 5). Only two sites have data going back further than this period, which means that the historical dataset is likely to be sparse. The nominal uncertainty of these data is ~0.05 ppm (Rivier, 2005).

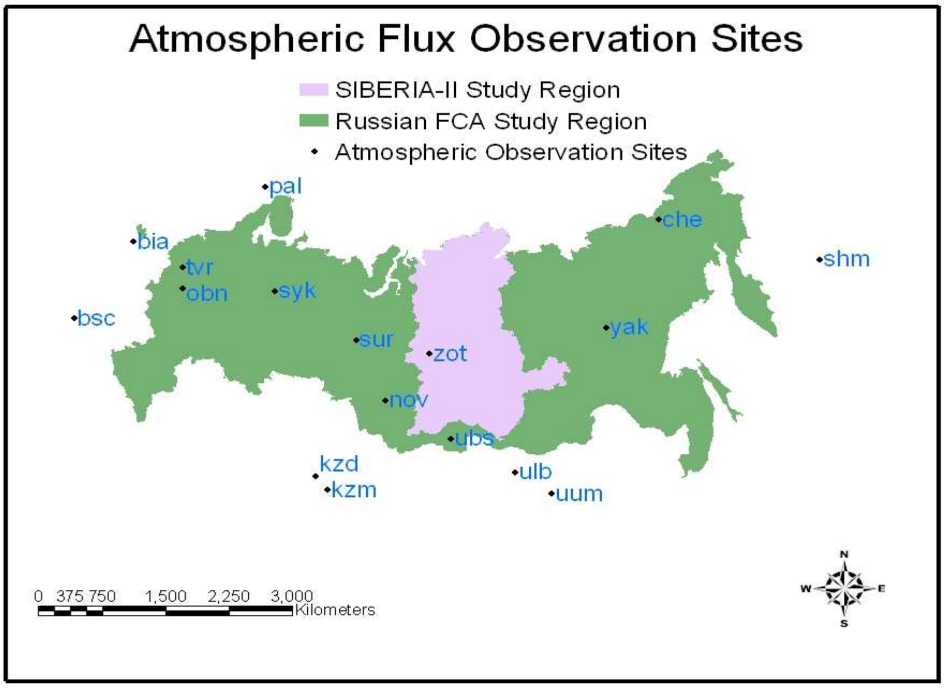

Figure 5: The constellation of atmospheric observation sites that provide top-down data used in atmospheric inversion models of carbon fluxes to the atmosphere (coordinates provided by Leonard Rivier of Le Laboratiore des Sciences du Climat et l'Environnement at the Commissariat à L'Energie Atomique (CEA) in France).

Table 5: Locations of atmospheric observation sites shown in Figure 5 and the years for which observations of atmospheric CO_2 concentration.

CODE	SITE	LONGITUDE	LATITUDE	START	END
bia	Byalistok	22.72	53.53	2002	2005
bsc	Black Sea Coast	28.68	44.17	2004	2005
che	Cherskii	161.30	68.80	2002	2005
kzd	Sary Taukum, Kazakhstan	75.57	44.45	1997	2005
kzm	Plateau Assy, Kazakhstan	77.88	43.25	1997	2005
nov	Novosibirsk	83.00	55.00	1997	2003
obn	Obninsk	36.60	55.11	2004	2005
pal	Pallas	24.12	67.97	2002	2005
shm	Shemya Islands, Alaska	174.10	52.72	1985	2005
sur	Surgut	73.00	61.00	1993	2003
syk	Syktyvkar	50.80	61.70	1998	2005
tvr	Tver	32.92	56.47	1998	2005
ubs	Ubs-Nur	95.58	51.48	2002	2005
ulb	Ulaanbaatar, Mongolia	106.00	47.40	2004	2005
uum	Ulaan Uul, Mongolia	111.10	44.45	1992	2005
yak	Yakutsk	130.00	62.00	1997	2003
zot	Zotino	89.60	61.30	1998	2005

The top-down data will be used to evaluate how well the bottom-up methods performed in terms of calculating total fluxes of carbon to the atmosphere. Because top-down data cannot discriminate between flux-inducing processes, the individual components of the bottom-up accounts cannot be verified using top-down data. While inversion data can indicate uncertainty in bottom-up accounts, there are also factors that contribute to error in top-down data that should be considered (House *et al*., 2003). First, the configuration of observation sites may not be optimal for estimating fluxes from a particular region. The coverage is improving as more sites become available, but as the network is still sparse (e.g., only one site, Zotino, is located in Siberia), inversions from this time period will have greater uncertainty related to future estimates. Second, there are multiple methods of performing atmospheric inversions to estimate fluxes. It is advisable to use time-dependent methods, or to use meteorological observations from the same time period as flux observations rather than relying on yearly/seasonally average conditions (Roedenbeck *et al*., 2003). Finally, model specification and prior fluxes are factors which affect the effectiveness of the inversion model.

In summary, top-down data are an invaluable tool for verifying full carbon accounts such as the SIBERIA-II and Russian FCA projects. While the top-down data are not objectively "true," they represent an independent measurement of carbon fluxes with lower uncertainty than most bottom-up accounting methods. The limitation of top-down measurements is their low spatial resolution. Bottom-up accounts are more suitable for smaller spatial scales, while atmospheric measurements become more reliable with increasing spatial resolution. As such they can provide us with an estimate of the uncertainty present in bottom-up full carbon accounts at a regional scale such as Siberia or Northern Eurasia. While top-down data cannot tell us about uncertainties within the individual components of a full carbon account (e.g., NPP, disturbance, lateral fluxes), they can be used to constrain the amount of carbon that bottom-up methods estimate is emitted to the atmosphere.

9 Conclusions

The importance of uncertainty considerations in greenhouse gas emissions accounting cannot be underestimated. The failure of Kyoto Protocol-type emissions reductions programs to systematically address uncertainty will contribute much confusion to emissions accounting. Under the current framework, it is impossible to assess which countries are compliant with their emissions reductions commitment within a given confidence interval and which are not. The treatment of all uncertainties as equal will lead to inconsistencies in the way emissions reductions commitments are enforced.

The results of this study indicate that the bottom-up full carbon accounting data for Russia are generally consistent between the Russian FCA and SIBERIA-II projects, at least for fluxes from net primary productivity and heterotrophic respiration. Because these data ostensibly account for all terrestrial vegetation-based fluxes, they are directly comparable with top-down flux estimates from atmospheric inversions. Further work will indicate how well the two accounting frameworks compare with top-down data, which will be used to verify bottom-up flux estimates.

As more data become available, further comparisons will be possible. For example, it will be useful to compare the accounting frameworks for the same time period, which may yield better agreement for some bioclimatic zones. Also, it was not possible to compare all flux categories at this time, due to limited data availability. Fluxes from disturbance may show considerable variation given the different time periods evaluated and the different methods used. Finally, if the bioclimatic zones could be further disaggregated to evaluate carbon fluxes from different types of tundra, it is likely that the two approaches would show better agreement for this zone.

The general agreement of the two accounting approaches, even for different time periods, indicates that carbon fluxes from NPP and HR can be estimated with reasonable uncertainties. While this study is not an exhaustive comparison of the two accounting frameworks, it is a beginning from which to approach such a comparison as the necessary data become available.

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