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Uncertainties of a Regional Terrestrial Biota Full Carbon Account: A Systems Analysis

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Abstract We discuss the background and methods for estimating uncertainty in a holistic manner in a regional terrestrial biota Full Carbon Account (FCA) using our experience in generating such an account for vast regions in northern Eurasia (at national and macroregional levels). For such an analysis, it is important to (1) provide a *full* account; (2) consider the relevance of a *verified* account, bearing in mind further transition to a *certified* account; (3) understand that any FCA is a fuzzy system; and (4) understand that a comprehensive assessment of uncertainties requires multiple harmonizing and combining of system constraints from results obtained by different methods. An important result of this analysis is the conclusion that only a relevant integration of inventory, process-based models, and measurements in situ generate sufficient prerequisites for a verified FCA. We show that the use of integrated methodology, at the current level of knowledge, and the system combination of available information, allow a verified FCA for large regions of the northern hemisphere to be made for current periods and for the recent past.

Keywords terrestrial biota · regional full greenhouse account · uncertainty · verification · certification · Northern Eurasia

1 Introduction

From what we know about interactions between the biosphere and the atmosphere, we can assume that only a full carbon account (FCA) (both in itself and as the informational and methodological nucleus of the full greenhouse gas account) corresponds to the essence and ultimate goals of the United Nation Framework Convention on Climate Change (UNFCC) (Nilsson et al., 2000a; Schulze, Valentini, & Sanz, 2002). Because of various political and economic constraints and considerations, the Kyoto Protocol and recent documents of the Intergovernmental Panel on Climate Change (IPCC) still operate with partial carbon accounting systems connected to the managed part of the biosphere. We assume from recent developments that transition to full accounting will be put on the climate change science agenda in the near future.

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Perhaps the most appropriate way of providing a transition from a partial to a full carbon account is differentiation between “assessment” (i.e., the actual exchange of greenhouse gases between the biosphere and the atmosphere) and “accounting” (i.e., what parts of this exchange are eligible for inclusion in the Kyoto and post-Kyoto accounting mechanisms).

The full carbon account has two parts that differ in terms of their nature and methodology: (1) assessing emissions caused by the anthroposphere (for example, by industry and energy); and (2) quantifying interactions of terrestrial vegetation with other components of the biosphere, in particular, the atmosphere. The share of emissions that each of these two components has in the summarized fluxes of the FCA at the national level may be of the same magnitude (e.g., for Russia, see Nilsson et al., 2003a). The experiences of some countries (European Union member states and the United States) show that the estimated uncertainties of carbon dioxide (CO_2) emissions from fuel combustion are low, as a rule in the ±2–4% range (confidence level 0.95) (EEA, 2005). In spite of the higher uncertainties for other gases (e.g., in roughly the ±17–48% range for methane (CH_4) emissions [Monni, Syri, & Savolainen 2004; Rypdal & Winiwarter, 2001]), the overall uncertainties (e.g., expressed on the basis of CO_2 equivalence) of industrial sectors are substantially less than the uncertainties of fluxes resulting from terrestrial vegetation and agriculture (Nilsson et al., 2000a; EEA, 2005). In other words, the uncertainties of the full carbon account will ultimately depend mainly on the uncertainties generated by the biosphere, and the latter is the subject of this analysis.

While the Kyoto Protocol and IPCC documents (IPCC, 1997; 1998; 2000; and 2004b) mention the importance of assessing uncertainty, they do not put this at the center of the problem (e.g., Nilsson, Jonas, & Obersteiner 2000b; Nilsson, Jonas, Obersteiner, & Victor 2001). For instance, the IPCC Guidelines stress that “uncertainty information is not intended to dispute the validity of the inventory estimates, but to help prioritize efforts to improve the accuracy of inventories in the future and guide decisions on methodological choice” (IPCC, 2000: p.6.5). The reliability level of the full carbon account that should be required at the regional and global levels is still being discussed. For the partial account, which is defined by the Kyoto Protocol and subsequent international documents, Annex 1 countries have a greenhouse gas emission reduction target of 5.2% and the European Union of 8% below 1990 levels by the first commitment period of 2008–2012. This means that the uncertainties for the full carbon account should be minimized to at least a level that is able to provide reliable identification of this reduction. Some scientific discussions (e.g., within the framework of the Global Carbon Project) indicate a presumptive level of ±20–25% for required limits of uncertainties for summarized continental carbon fluxes (expressed, for example, as net biome production) caused by terrestrial vegetation; this would obviously be too high if the full carbon account were to become a subject of the post-Kyoto negotiation process. Our tentative results for temperate and boreal regions show that FCA uncertainties for large regions could be decreased to a level of ~10–15% (confidence level 0.9); this level at least seems achievable if the FCA meets a number of system requirements and information improvements. The technical jargon, however, requires two clarifications. First, relative errors depend on the estimated mean, and a definite level of uncertainties implies a tacit prerequisite that net biome production (as an eventual estimate of the terrestrial biota full carbon account) is not zero or close to zero. Second, strictly speaking, the completeness of the FCA cannot be estimated in any formal way, and the knowledge and proficiency levels currently available reduce the chances of finding a solution to this problem. Nevertheless, the philosophy behind the FCA does make it possible to develop an approximate solution.

The full carbon account has two major goals that are equally important and interdependent: (1) quantification of all carbon pools and fluxes included in the account; and (2) reliable estimation of uncertainties. The intentions of the UNFCCC and the logic of recent post-Kyoto developments imply the need to move toward a verified full carbon account. A verified account means, following the IPCC, 2000, p. A3.20), that: (1) uncertainties at all stages and for all modules of the accounting scheme are estimated in a comprehensive and transparent way; and (2) the methodology of the FCA should present guidelines as to how uncertainties can be managed, in particular, if the results of the accounting do not satisfy required (preliminary, defined) uncertainty levels. Verification is basically a scientific notion and is (or should be) an inherent part of any accounting scheme.[1] Verification provided by a specially authorized independent body could lead to a certified account. Obviously, a certified account should provide a preliminary, defined uncertainty level. Currently, there is no clear understanding as to how it would be possible to build certified systems, particularly at continental and national scales, given the many scientific, political, and institutional problems that would need to be resolved nationally and internationally beforehand (cf. Gillenwater et al., 2007); Jonas and Nilsson (2007); Nahorski and Jęda (2007).

We should not underestimate the difficulties of the transition from the current status through a verified account to a certified account. The Global Carbon Project GCP (2003) indicates that, among inherent shortcomings in quantifying the carbon budget: (1) existing global models are unable to determine carbon sources or sinks with acceptable accuracy at the regional and continental spatial, and interannual time scales; (2) there are no agreements between top-down and bottom-up approaches; (3) there are substantial inconsistencies between global and regional budgets; (4) temporal patterns are poorly understood at timescales greater than a few years; and (5) there are big gaps in our comprehension of the spatial and temporal pattern of human-induced fluxes.

Several methods are used to provide the scientific basis for the terrestrial biota carbon account. The majority of the results at the continental and national levels are received from process-based models and inventory approaches. Each of these methods has well-recognized strengths and weaknesses. During the last decades, advances have been made in process models so that the model structure now explicitly incorporates current knowledge regarding ecosystem processes; process models are practically the only tool available for diagnosing the interannual variation of major carbon fluxes. However, these models operate with a simplified, mostly "potential" world and do not have an adequate system of uncertainty estimation. While they allow the uncertainties in model projections caused by propagation of uncertainty in model output to be partitioned, they cannot answer the major question of any serious modeling effort, namely, how distant is the model structure from the modeling phenomenon? Attempts to improve uncertainty assessment in process-based models (e.g., MacFarlane, Green, & Valentine, 2000; Parysow, 2000; Zaehle, Sitch, Smith, & Hatterman 2005) are limited by intramodel considerations, such as the introduction of variability into input parameters and the assessment of how sensitive model results are to this variability. On the other hand, inventory-based methods, while strong in terms of their empirical basis, are unable to indicate rapid environmental changes or to take into account the temporal trends of major drivers. Other methods used in the FCA, although very important, either serve separate controlling blocks of the accounting system (inverse modeling) or deliver information for parameterization of the two above background methods (e.g., measuring carbon fluxes in situ).

This paper presents a brief analysis of the experiences and lessons of assessing uncertainties of the terrestrial biota full carbon account at the regional scale for a large region of Siberia through an EU-funded project entitled 'SIBERIA-II' (Multi-sensor Concepts for Greenhouse Gas Accounting of Northern Eurasia), and from the full carbon account of the entire Russian terrestrial vegetation carried out by IIASA's Forestry Program during recent years. We (1) attempt to illustrate the fact that only a consecutive holistic approach can serve as the background for a verified FCA; (2) briefly analyze the systems requirements of its structure and methodology; and (3) present typical examples (see Jonas et al., 1999).

2 Basic Definitions

There are many different approaches to dealing with uncertainty, and selection of the language and dimensions involved is of primary importance. We limit our analysis to informational and methodological aspects of the regional FCA, leaving out consideration of the different social, economic, cognitive, institutional, and ethical aspects of the problem.

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[1] We note that Jonas and Nilsson (2007) go one terminological step further than we do here and strictly distinguish between "validation" and "verification" by applying science-theoretical principles. However, although we use the term "verification" somewhat indifferently, our ultimate understanding of verification, especially in the context of our integrated (multimeasurement/modeling) approach presented here, is in line with the bottom-up/top-down accounting/verification approach discussed by Jonas and Nilsson.

The terminology used below is generally accepted in statistical theories and risk analysis. The conventional terms for standard statistical analysis are: (1) *precision* as reproducibility or a measure of random error – this deals with our inability to discriminate among values within a parameter or to deal with a parameter's imprecision; (2) *accuracy* as correctness or a measure of the systematic error (bias); and (3) a *mistake* as a measurement that is known to be incorrect due to carelessness, an accident, or the ineptitude of the experimenter. In an FCA, direct use of these terms is usually limited to partial and relatively simple statistical tasks that are based mainly on direct measurements.

Mathematical theory distinguishes between *uncertainty* and *variability*. Although the term *uncertainty* can have different meanings: statistical variability or lack of knowledge, lack of confidence in a single value (Hattis & Burmaster, 1994; Hofman & Hammonds, 1994; Heath & Smith, 2000), its use in global change science is rather consistent. "Uncertainty" is understood as a description of imperfect knowledge of the true value of a particular quantity or its real variability in (1) an individual (e.g., measurements of biometric indicators of trees on a sample plots); or (2) a group (e.g., averages among sample plots established in a homogeneous category of forests). In essence, uncertainty is the absence of information; or it is an expression of the degree to which a value is unknown (IPCC, 2004a; 2004b; Rowe, 1994). Uncertainty can be represented by quantitative measures (e.g., a range of values calculated by various models) or by qualitative statements (e.g., reflecting the judgment of a team of experts). *Variability* is a special contributor to uncertainty. "Interindividual variability" means the real variation within a measured value of individuals or parameters. In general, uncertainty is reducible by collecting additional data or using better models, whereas real variability cannot be changed as a result of better or more extensive measurements. (However, the latter can improve the quality of the estimates used). In our analysis we defined *uncertainty* as an aggregation of insufficiencies of our system output, regardless of whether those insufficiencies result from a lack of knowledge, the intricacies of the system, or other causes (cf. Nilsson et al., 2000a). Finally, uncertainties in the FCA can be expressed as confidence intervals of probability distribution functions.

Probability is the basic term for describing the assessment of any uncertainty. The traditional approach assumes that observed frequencies are equivalent to probabilities – it requires the conditions of the phenomenon or process to remain stationary and for random measurements to take place. However, both these requirements are the exception rather than the rule in an FGA. Moreover, the fuzziness of the FCA inevitably leads to the use of subjective (personal) probabilities, the (FCA-applicable) specifics of which we consider below.

3 Uncertainties of the Regional Full Carbon Account

Strictly speaking, the "ideal" FCA should be the result of continuous monitoring of terrestrial biota in space and time. The philosophy behind this kind of monitoring leads to the idea of an integrated observing system – and beyond, to an integrated accounting system. We can conclude from recent developments that some simplified versions of this type of approach could come to fruition in the near future. Currently, all carbon accounting schemes are forced to use many heterogeneous information sources, including results from different measurements, assessments, and expert estimates over time, which means that numerous and diverse uncertainties are generated. Taking into account the methodological specifics of the carbon account, different classifications (decomposing, categorizing) of uncertainties can be relevant. For the IPCC TAR (Third Assessment Report) Assessment, Moss and Schneider (2000) considered four major groups dealing with (1) confidence in the theory; (2) observations (measurements); (3) models; and (4) consensus within a discipline. Rowe (1994), considering common aspects of risk analysis, divided uncertainties into temporal (past and future), structural (complexity), metric (measurements), and translational (explaining uncertain results). Distinguishing two broad classes of uncertainty-"statistical" (associated with parameter or observational values that are not known precisely) and "structural" (referring to causal relationships between variables)-the IPCC Workshop on Describing Scientific Uncertainties in Climate Change pointed out the substantial difficulties involved in assessing structural uncertainty and the limited opportunities for doing so in any comprehensive and formal way (IPCC, 2004b).

For structuring the FCA uncertainty calculation schemes, a more detailed classification of the sources of uncertainty in the following groups seems useful (see also Jonas et al., 1999; Nilsson et al., 2000a; Shvidenko, Nilsson, Rojkov, & Strakhov 1996):

(1) *Definitions and classification schemes used in calculations*. As a rule, the definitions and classification schemes currently used in the FCA have been introduced for purposes other than carbon accounting and often correspond to inappropriate or obsolete standards and measuring technologies.
(2) *Shortcomings of available data.* Some important data have never been and are not being measured, which leads to incomplete and sometimes inappropriate substitutions.
(3) *Unknown or insufficient precision of measured data.* Reasons for this could vary: for example, subjective (not random) sampling, biased statistics, deliberate falsification, and inappropriate measurement techniques.
(4) *Lack of a proper basis for upscaling.* Very often, there is no solid platform for estimating the accuracy of upscaled point measurements, gradients are unknown, and stratification is provided based on expert judgments.
(5) *Short time series.* Some processes require historical reconstruction for up to 150–200 years, which is not covered by existing historical records.
(6) *Lack of knowledge of some important processes.* For instance, the post-disturbance processes in soil on permafrost, some aspects of below-ground NPP, or nitrogen turnover after biotic disturbances are, to a significant extent, 'black boxes.'
(7) *Oversimplification of the modeling approach.* In both the major methodological approaches of the carbon account (i.e., pool-based and flux-based carbon account), the regional full carbon budget (FCB) is presented by a sophisticated superimposition of (almost exclusively) nonstationary stochastic processes. There is still no methodology that would use this intrinsic feature of an FCB as a prerequisite for its modeling and quantification, and the substitution of deterministic models for stochastic processes is common practice. There are many other examples of this type.
(8) *Spatially and/or temporally insufficient observing systems.* Significant remote areas (e.g., in the Russian north) are not covered by high quality remote sensing (RS) observations (because of the low sun angle and boreal winter night) or by on-ground observations. Some indicators are very dynamic, and existing monitoring systems and available data cannot grasp these dynamics (e.g., seasonal dynamics of insect outbreaks in boreal forests).

Although each class of uncertainties can be addressed separately, the classes are not necessarily independent, and their interdependence should be examined. The above list of uncertainty sources can be applied to some or all periods of the assessment: past, present, and future. However, in any prediction and forecast, many other uncertainties-arising from future drivers (climatic, ecological, social, and economic) and from responses and feedback from terrestrial ecosystems – need to be considered. The level of background uncertainties can be illustrated with reference to the uncertainties of climatic predictions. Using 12 three-dimensional general circulation models (GCMs), including seasonal cycles, a mixed-layer ocean, and interactive clouds and other features, the projected increase in global mean surface air temperature under equilibrium conditions for doubled CO_2 concentrations in the atmosphere varies approximately threefold (from 1.6 to 5.4°C, mean 3.82°C, coefficient of variation 26.3%) (Cess et al., 1993). In spite of obvious progress in climatic modeling during the last decade, the situation has not changed significantly (e.g., Collins et al., 2005). One can conclude that there is no solid background for verified FCA for future time periods. We will not consider this special (and highly uncertain) case further.

Considering the essence, as well as the learning limitations, in terms of information and methodology, of a full carbon budget of terrestrial biota, we can conclude that any FCA is a typical *fuzzy* system. In spite of thousands of publications on this topic since Zadeh (1965) published his fundamental paper, there is no single unique definition of fuzzy systems and/or fuzziness. Thus, we use this term in its rather common but wide mathematical sense (Kosko, 1994;

Wang & Barret, 2003), bearing in mind that many elements of the FCB (procedures, components, and stages of the FCA), far from presenting a crisp set, require the knowledge of multivalued membership functions. In essence, "fuzzy logic is part of a formal mathematical theory for the representation of uncertain systems" (Cogan, 2001); according to Mendoza and Sprouse (1989) "the concept has generally been associated with complexity, vagueness, ambiguity, and imprecision" which "further implies that model coefficients, parameters, or functional relationships may be fuzzy and, hence, not known with complete certainty." The comprehensive development of the formal theory, which would provide for learning about natural fuzzy systems is, to a significant extent, a matter for the future. Although fuzzy logic and fuzzy methods are recommended as a means of incorporating subjective information into different aspects of uncertainty assessment (e.g., Haimes, Barry, & Lambert 1994; Hattis & Burmaster, 1994), their applications in ecology and natural management are limited by numerous diverse, albeit partial, tasks (Bare & Mendoza, 1991; Chen & Mynett, 2003; Mendoza & Sprouse, 1989; U. Özesmi & S. L. Özesmi, 2004; Wan-Xiong, Yi-Min, Zi-Zhen, & Fengxiang 2003 etc.). In the framework of FCA, it is productive to apply "fuzzy thinking," whose philosophical approach is of great help in structuring problems, developing a relevant FCA system, and treating uncertainties. Elements of this approach are being introduced little by little into different parts of global change science. In recent years, the philosophy has also been applied to a "multiple-constraint" approach, where heterogeneous data – for example, measurements of fluxes, remote sensing data, data from different inventories – provide constraints in terms of the models used and in assessing results (e.g., Wang & Barret, 2003). Obviously, "fuzzy thinking" can include a formal definition of membership functions and inference rules, but it is not exhausted by exclusive applications of fuzzy logic methods.

Fuzzy thinking leads to an important conclusion that defines a relevant specific methodology for verified FCA: strictly speaking, no individual FCA method or model applied separately can provide a sufficient (i.e., comprehensive, transparent, and reliable) estimation of uncertainties. Fuzzy thinking thus defines the need to systematically integrate relevant methods and models, and it leads to the philosophy of *integration* in all its ramifications. For the FCA, the solution is an integration of all relevant information sources (on-ground, remote sensing data, and appropriate regional ecological models), both soft and hard knowledge. On the other hand, integration should be provided for different components of the FCA: carbon of terrestrial biota, ocean, and atmosphere. Consistency in the terrestrial biota global carbon budget is an indicator of its reliability. Comparing the results obtained by different methods is an important part of verification.

The need for *a full* carbon account generates an additional dimension of uncertainty. By definition, "a full C budget encompasses all components of all ecosystems and is applied continuously in time" (Steffen et al., 1998). However, in spite of progress over the last decade, there remain substantial uncertainties in understanding regional and global carbon budgets. This means that the completeness of the FCA can be estimated only through expert judgment.[2] However, estimating an FCB continuously in time in order to judge its completeness can also only be fulfilled in a very approximate manner. As the FCB has a "memory," up-to-date estimates of carbon (C) fluxes may depend strongly upon the previous, sometimes long periods for which relevant measurements may not be provided, and thus the required information simply does not exist. Moreover, the completeness greatly depends upon the end-point target of the user. For example, the final goal of carbon accounts can be defined either as an assessment of the amount of C–CO_2 in the exchange, or as the quantities of all gases containing carbon, or as the Global Warming Potential. Nevertheless, experiences of the FCA for some countries (like Austria and Russia) show that about 96–98% of recognized carbon fluxes are usually included in the consideration, although in essence this conclusion is an expert estimate (Nilsson et al., 2000a). The completeness allows us to implement a balance estimation and an analysis of the consistency of individual modules and blocks of the FCA. Here, we face a substantial methodological shortcoming of any partial accounting system: the inability either to close the balance or to

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[2] We distinguish between a full carbon budget (FCB) as a natural system and a full carbon account (FCA) as an artificial accounting system.

check the consistency of the accounting system. The crucial assumption underlying the partial carbon account is that some drivers and, consequently, some net carbon fluxes (especially those that are not directly human-induced) are untested, and their changes remain unknown. Thus, the FCA presents additional information that allows the (final) uncertainties of the accounting systems to be estimated and the specifics, strengths, and weaknesses of partial accounting systems to be grasped.

4 Requirements for the Terrestrial Biota Regional Full Carbon Account

The above considerations give rise to the following important requirements for any verified FCA result:

1. Only a holistic system approach (with modifications resulting from the fuzziness of the FCA) can serve as a solid overall methodological background for the FCA. From a substantive point of view, implementation of the landscape-ecosystem methodology is one of only a few possibilities for a consecutive system analysis. Under the landscape-ecosystem approach, (1) an ecosystem (i.e., vegetation–soil ensemble at different scales) is considered as the primary unit of scientific description, modeling, and interpretation; and (2) the quantification of intra-ecosystem processes of energy and matter exchange should include the impacts of properties of an individual landscape. From an informational point of view, all relevant sources of information must used, including: (1) as comprehensive a ground-based quantitative descriptions of ecosystems and landscapes as possible (e.g., in the form of Geographic Information Systems); (2) remote sensing data; (3) numerous and diverse sets of auxiliary models (e.g., for connecting remotely sensed data with "hidden" ecological parameters of ecosystems); (4) measurements of fluxes (such as Net Ecosystem Exchange); (5) composition of gas concentrations in the atmosphere; and (6) regional ecological models of different types. From a methodological point of view, a relevant combination of pool-based and flux-based approaches allows the weaknesses of each of these basic FCA methodologies to some extent to be eliminated.
2. Use of strict and monosemantic definitions and formally complete classification schemes. This problem is not trivial. Recent activities of the Food and Agriculture Organization (FAO) on harmonizing forest-related definitions for use by various stakeholders provide many examples of how many different problems can be encountered in the rather simple field of land use-land cover classifications alone (FAO, 2002).
3. Explicit structuring of the account; use of strict intrasystem (module) spatial, temporal, and process boundaries. In this respect, a number of questions should be regulated (e.g., whether human consumption of vegetation products should be considered as part of net biome production (NBP).
4. An estimation of the uncertainties should be provided at all stages and for all modules of the FCA. This allows the gathering of any additional information needed to understand relevant ways of managing uncertainties.
5. Accounting schemes, models, and assumptions should be presented in an explicit algorithmic form. This means that the use of soft knowledge (e.g., in the form of expert estimates), which is inevitable in the FCA, should be provided in a "quantified" form and using methods that would allow any shortcomings and possible biases resulting from subjective information to be minimized.
6. The accounting scheme should provide a spatially explicit distribution of considered pools and fluxes. This means that all major components of the FCA should be georeferenced at relevant scales.
7. Temporal dimensions of the FCA should be consistent with the temporal peculiarities of processes that are quantified (modeled). The relevant length of respective timescales and the required frequency of observations are defined by specifics of the individual processes considered. Obviously, a year or a different period of accounting should be clearly identified.

Some of the above requirements are not satisfied in regional and national accounting and are not indicated in the recommendations of the IPCC (IPCC, 1997;

2000). This increases the fuzziness as well as the role of expert components in the FCA.

5 Assessing Uncertainties

Two main statistical tools – probability density functions and confidence limits – are normally used for assessing uncertainties. The IPCC Guidelines suggest the use of a 95% confidence interval. This "conventional" recommendation is usually justified in terms of the simplicity of calculating the interval corresponding to two standard errors. It is not completely clear, however, how much this traditional recommendation (1) corresponds to the specifics of the FCA; and (2) impacts interdependence of type I (alpha) and II (beta) errors. Factors that are beyond these two considerations follow.

In essence, the selection of a confidence interval should be based on a function of the losses due to an achieved level of uncertainties. However, not only has no formal theory been developed to quantify such a function but there are large practical difficulties in structuring one. Thus, the solution remains in the field of expert estimates; it should be the result of substantive analysis and, finally, of an agreement among interested parties. Taking into account the utility of the FCA for large territories and the practical consequences of its inherent uncertainties, one might conclude that the relevant confidence interval (e.g., for NBP) should correspond to probability smaller than 0.95 (e.g., in the range of 0.8–0.9) or even smaller. Moreover, such an approach would allow a decrease to a relevant value of errors of type II. This problem, as far as we know, has not been considered in any practical assessment of the uncertainties of the FCA made to date. On the other hand, the numerical expression of uncertainties (i.e., statements such as: "the uncertainty (accuracy) of the final result is at *p* percent") have a major psychological meaning, at least for the public and policy makers. The inherent uncertainties in some important components of the carbon budget of terrestrial vegetation are high and – if we use a confidence interval for high probability – could be comparable with, or even exceed, 100%. Obviously, any results with uncertainties >100% have no practical meaning. Thus, artificially setting high confidence intervals can give the wrong impression about the practical applicability of the final results of the FCA. This problem requires further elaboration. In the examples and considerations below we use a confidence level of 0.9.

We examined the following method of assessing uncertainties in the FCA: (1) estimation of precision of all intermediate and final results; (2) "transformation" of precision into uncertainty; and (3) multiple-constraint comparisons of results.

Estimation of precision The FCA is presented as a hierarchical structure of analytical expressions. It allows the formal use of error propagation theory, assuming that the variables used in the calculations are more or less normally distributed. However, only some of the initial data result from direct measurements for which, for example, standard errors and probability distribution functions can be estimated using conventional statistical methods. This generates some open issues: (1) the need to use estimates of the precision of initial variables "by analogy" (i.e., average values by classes of the classification used), or based on expert estimates and subjective probabilities; and (2) the use of "summarized errors" as a substitute for random errors. As a rule, it is impossible to divide the many initial variables used in the FCA into random and systematic errors. Thus, summarized errors are considered functions of both random and systematic errors. In practical situations, the share of bias is relatively small (estimated to be in the order of 10–15% of the random error). In such cases, applying the error propagation theory does not change the essence of statistical conclusions.

"Transformation" of precision into uncertainties The precision calculated is transformed into uncertainty based on sensitivity analysis and expert estimates of unaccounted impacts and processes. The Monte Carlo method is often used as a tool for sensitivity analysis. How this procedure works depends on the end-point target of the assessment.

1. The end point is a fixed but unknown value (e.g., net biome production). Values are sampled at random from distributions representing various "degrees of belief" about the unknown "fixed" values of the parameters (i.e., the true but unknown value is equal to or less than any value selected from distribution). The subjective confidence statement about the true but unknown

assessment end point accounts for multiple sources of uncertainties including, (1) inventory or model structure; (2) presence, variability, and representatives of data; and (3) quantified expert opinions. Uncertainty about a quantity that is fixed (or deterministic) with respect to the assessment end point is often called Type B uncertainty. Variation of input data allows the selection of "important input parameters," which contribute most to the spread in the distribution of the FCA results.

2. The end point is an unknown distribution of values. In such a case, the Monte Carlo simulations are performed in two dimensions producing numerous alternative representations of the true but unknown distributions (assessment of uncertainty of Type A). In practical applications of the FCA, both the above procedures are used; however, it often occurs that a mixture of both types of uncertainties is presented.

Although Monte Carlo calculations are not free from some subjective elements (e.g., a "selection" of the type of unknown distribution), this method presents both comprehensive information about uncertainties of the accounting scheme (model) and important information for management of uncertainties. These results often serve as an iterative step in a process to improve model estimates.

We must note, however, that all these results are true only within the approach (model) used and under given inputs and assumptions; they can have little to do with reality, if the model or assumptions are not "comprehensive" or if they are oversimplified. Thus, if, for example, the model FORCARB (carbon inventory for 2000 for private timberland of United States, which covers about 75% of that country's productive forests) estimates uncertainty as ± 9% of the estimated median of total carbon in the year 2000 and as ± 11% in the projection year 2040 (Heath & Smith, 2000), this just tells us that these results are derived from Monte Carlo calculations within the (rather simple) FORCARB model; they tell us nothing about any "real uncertainty." We have no wish to criticize this particular model – we just use it as an example to demonstrate specifics that are inherent in any model, even the most complicated. Moreover, this explains why an independent and thorough analysis of the completeness and structural rationality of the FCA used is necessary. One way of providing this analysis is by using expert judgments on the topic; such judgments are quantified and embedded (in addition to Monte Carlo or other methods of sensitivity analysis) in final values of uncertainties (Shvidenko & Nilsson, 2003).

Multiple-constraint comparison of results Three important techniques that allow us to make a final judgment about the FCA are: (1) the balance and consistency analysis of carbon budgets of relatively closed blocks (modules) of the FCA; (2) comparisons of independently calculated intermediate results; and (3) multiple-constraint analysis of final results. We must point out the crucial importance of the multiple-constraint methodology. The "top-down/bottom-up" analysis is currently a major tool for understanding the "real" range of uncertainties of the global carbon budget (see Jonas & Nilsson, 2007). This could be very useful in continental and other macroregional FCAs. Hence, the FCA for Russia shows that the former problem of the missing sink, which has been the subject of intense debate, results from the incompleteness of the account (Nilsson et al., 2003a, 2003b).

The problem of bias A usual prerequisite of uncertainty analysis is that the approaches used do not generate significant bias. As a rule, this assumption is very difficult to check in practical assessments. Bias is often caused by temporal or spatial nonstationarity of processes or of the ways in which measurements are provided. Improving the measurement techniques or methodologies used, as well as integrating new knowledge, could generate a substantial shift in results, indicating previously unrecognized biases. We present two recent examples that illustrate the magnitude of the possible impacts.

1. The first detailed inventory estimate of the net primary production (NPP) of Russian forests for 1993 was based on a database that contained approximately 3,000 sample plots, where measurements were performed by traditional destructive sampling (Nilsson et al., 2000a). These measurements did not account for some of the important components of NPP (e.g., root exudates, which comprise about 15% of the total NPP of boreal forest ecosystems), and they probably underestimated the NPP of fine roots. The transition to a semi-empirical inventory-based modeling system

that does not have significant recognized biases (at the current level of understanding), has increased the average forest NPP in Russia by approximately one-third (Shvidenko, Shepashenko, Nilsson, & Vaganov, 2007). Tendencies of the same magnitude have been also recognized for the NPP of wetlands in Siberia (Vasiliev, Titlyanova, & Velichko, 2001).

2. Based on the remotely sensed normalized difference vegetation index (NDVI), Myneni et al. (2001) have estimated the sequestration of carbon in the above-ground wood of Russian forests to be 283 Tg C yr^{-1} for the period of 1992–1998. This accumulation corresponds to an increase in growing stock volume of about one billion m^3 annually. The forest inventory data for the same period indicate the increase in growing stock to be almost three times less (Shvidenko & Nilsson, 2003). This contradiction has recently been explained (Lapenis, Shvidenko, Sheschenko, Nilsson, & Aiyyer, 2005). The recent analysis of temporal dynamics of the allometric ratios of different phytomass fractions during the last 50 years has recognized the substantially different trends in above-ground wood, green parts, and roots. The calibration procedure provided by Myneni et al. (2001) did not take these dynamics into account. If the findings by Lapenis et al. (2005) are taken into account, the remote sensing estimate is decreasing to a level that is compatible with the forest inventory data.

6 Some Practical Implementations and Results from Case Studies

We attempted to introduce (to the extent possible) the above requirements and techniques while estimating the FCA for two regions with different conditions: (1) Russia as a whole country; and (2) a large (~3 million km^2) region of Northern Eurasia (SIBERIA-II study area, see Box 2). In spite of the availability of information and appropriate levels of detail available for these two subjects being different, the methodology of the two FCAs had many common features. The information base was developed in the form of an integrated land information system (ILIS) which comprises multilayer GIS and corresponding attribute data (at scale 1:2.5 million for the entire country and 1:1 million for the SIBERIA-II region). All relevant information sources were used for the development of the ILIS: available maps and legends; data from different inventories (in particular, forest inventory) and surveys; various scientific archives; and official statistical data. The landscape-ecosystem methodology served as the overall scientific basis of the account, which was based on an integration of pool-based and flux-based approaches. The flux-based approach is expressed as assessing fluxes (measured in units of carbon per unit of time (e.g., Tg C yr^{-1}) at boundaries of terrestrial ecosystems with other components of the biosphere (atmosphere, lithosphere, hydrosphere)

$$\mathrm{NBP} = \mathrm{NPP} - \mathrm{HSR} - \mathrm{DEC} - \mathrm{D} - \mathrm{TL} - \mathrm{TH}, \qquad (1)$$

where NBP and NPP are net biome and net primary production; HSR is heterotrophic soil respiration; DEC is flux due to decomposition of coarse woody debris; D is flux due to disturbances; and TL and TH are fluxes to lithosphere and hydrosphere. The pool-based method estimates carbon pools at the beginning and end of the assessment period. A combination of these two approaches (or – in an ideal case – a comparison of independently obtained results) allows us to estimate the methodological consistency of the FCA.

We present some typical examples from the above two case studies. For the whole country we provide our estimation of the FCA for the initial period of the Kyoto Protocol (1988–1992). We must note that the terminology of the Protocol ("since 1990") is not completely appropriate for an independent estimation of any solid carbon budget at the national level, whether full or partial carbon account is considered: information required for an FCA of large territories cannot be made operational at the yearly timescale. Thus, the estimation of uncertainties was provided for 5-year averages (1988–2002).

Two major conclusions follow from the FCA for terrestrial biota of all Russia: (1) the resulting uncertainties in the FCA are relatively high, the net biome production (including human consumption of vegetation products) being estimated as 0.35 ± 0.18 Pg C yr^{-1}; (2) the greatest uncertainty lies in assessing soil processes (the change of soil organic carbon was estimated as -0.04 ± 0.16 Pg C yr^{-1}). Attempts to apply the pool-based method to assessing soil carbon dynamics were insufficient because the requisite information was lacking. It has been shown, however, that major improvements in the reliability of results are possible only in the framework of the full account, and that the problem of the "missing sink" is a problem of the incompleteness of assessments (Nilsson et al., 2003a, 2003b). The overall methodological lesson from this study was that any crucial decrease in uncertainties in the FCA at the national level requires substantial improvements to input information, which could probably be adequately carried out within the framework of integrated observing systems like GEOSS (Global Earth Observation System of Systems). Comprehensive use of (only) existing information could supply satisfactory results in assessing relatively simple components of the FCA, although even in such cases substantial expert elements remain (see Box 1 for assessing uncertainties of forest phytomass, as an example).

Box 1 Uncertainties of estimation of the total amount of phytomass in Russian forests based on forest inventory data

Initial assumptions: Data of the state forest account (SFA; i.e., aggregated data of forest inventory by ~2,000 forest enterprises) and regression equations of phytomass do not have any bias at an accepted level of significance. To check these assumptions, a special statistical and expert analysis of data and procedures has been provided.

Indexes used: i is phytomass fraction, i=1, ..., 7; ρ is dominant species, ρ=1, ..., 27; m is ecoregion, m=1, ..., 141, k-number of forest stands.

Variables: M-mass (dry matter) of fractions, Tg; GS-growing stock volume, m^3; A, SI, RS-age, site index, and relative stocking, respectively; δ-content of carbon in phytomass.

Initial data are presented in the form of a matrix for each of the 141 ecoregions across the country; these contain area and growing stock distributed by age classes A for dominant species ρ and types of inventory r (r=1, 2, 3), as well as average SI and RS by species and inventory types.

Mass M of fraction i, dominant species ρ, ecoregion m is calculated as

$$\begin{aligned} M_{i\rho m} &= \delta_i \sum_{A=1}^{q} R_{i\rho m A}\cdot GS_{\rho m A} \\ &= \delta_i \sum_{A=1}^{q} c_0 \mathrm{SI}^{c1} \mathrm{A}^{c2+c3\mathrm{RS}+c4\mathrm{RS}2} \end{aligned} \qquad (\mathrm{B1.1})$$

where R is ratio of phytomass fraction to growing stock (expressed as a multidimensional regression of A, SI, and RS) and c_0, ... c_4 are regression coefficients. Thus, the total phytomass of Russian forests is

$$M = \sum_{m=1}^{141} \sum_{\rho=1}^{27} \sum_{i=1}^{7} M_{i\rho m} \qquad (\mathrm{B1.2})$$

Based on standard methods of error propagation theory, the summarized error of Eq. B1.2 could be expressed in an explicit way (Nilsson et al., 2000a). Applying the set of equations for $R_{i\rho m}$ (Shvidenko, Shepashenko, & Nilsson, 2002), we have the summarized error of forest phytomass by ecoregion in the range of ±5–14% (here and below the confidence level is 0.9) and the final precision (weighted by total mass of phytomass of the ecoregion) is estimated at about ±3%. Assuming the relative error of δ_i=±2%, we come to the final conclusion that the total summarized error is ±3.7%, and the confidence interval is 32.9±1.2 Pg C. This result represents a formal estimate of precision. To assess the extent to which the expert estimates and assumptions used were able to impact this conclusion, five Russian experts were requested to estimate the completeness of the accounting. They unanimously concluded that the assessment accounted for "not less than two-thirds of all uncertainties," that is, the final uncertainty was estimated to be about ± 4.5%. Additional information can be presented by comparison with independent estimates from other sources. However, from nine different estimates of forest phytomass in Russia reported during the last two decades, we were able to select only four that used sufficient information and accepted methodologies. The average densities for forest phytomass in Russia from these sources were: Alexeyev and Birdsey (1994): 3.63 kg C m^{-2}; Isaev, Korovin, Utkin, Pryashnikov, and Zamolodchikov (1995): 4.55 kg C m^{-2}; Isaev and Korovin (1998): 4.51 kg C m^{-2}, and IIASA (independent GIS-based method; Nilsson et al., 2000a): 4.403 kg C m^{-2}. The average of these estimates is 4.27 kg C m^{-2}, or −0.7% of our estimates of 4.30 kg C m^{-2}.

Nevertheless, the following considerations illustrate some "hidden" uncertainties that cannot be recognized by any formal analysis. The estimate of 4.30 kg C m^{-2} was obtained based on a set of models developed using experimental data available before 1997. The models were recalculated using additional experimental data accumulated in 1997–2004 (the number of sample plots was increased by about 10% to about 3,600). The new set of models was applied to the same data of the (State Forest Account) SFA–

1993, and a new estimate of the density was 4.43 kg C m^{-2}, or about 3% more than the previous one. Obviously, this is within the probabilistic limits of the uncertainty estimated above. Finally, the assumption that the SFA growing stock has no bias is not true: an estimate of the bias for 1993 is +2.5% (Shvidenko & Nilsson, 2002). However, 59% of Russian forests (by growing stock) were composed of mature, overmature, and uneven-aged forests with a substantial amount of trunk and root decay. An approximate conservative estimate gives the values as 2–3% of the growing stock (i.e., we have an approximate compensation of the bias of the growing stock estimation). Thus, the overall conclusion is that the uncertainties inherent in our knowledge of the phytomass of Russian forest ecosystems in 1993 are at the level of 5–6% with high probability (not less than 0.9).

SIBERIA-II aimed to make a full greenhouse gas account based on a fusion of (1) multisensor remote sensing; (2) comprehensive description of individual ecosystems and landscapes in the form of an ILIS; and (3) use of different types of ecological model. SIBERIA-II had a number of features that helped substantially increase the reliability of the regional FCA. First, the introduction of multisensor remote sensing greatly increased the quality and efficiency of information. Considering the large scale and remoteness of the region, the information presented by RS (12 different sensors were examined) was of crucial importance for, inter alia, updating land cover, estimating disturbances, and assessing environmental indicators. However, there were many inconsistencies in the technical capacities of RS sensors, the spatial and temporal resolution needed, and the requirements of the FCA. There was an obvious need for new technical RS tools designed specially for studying the biospheric role of terrestrial biota, a good example being a satellite with P-band radar on board for assessing vegetation (particularly forest above-ground biomass). Second, the objective in using diverse information was to increase the synergy from combining the various relevant information sources. Third, applying different ecological models presented the possibility not only of multiple constraints of the results but also of independent estimates of many components of the FCA.

The examples presented below are typical. They are limited by the approach, which is based on the ecosystem-landscape methodology. An FCA-relevant GIS layer and corresponding databases were developed at the polygon level. An FCA is provided for each of the polygons (which serve as a primary ecosystem landscape unit and are aggregated into ecoregions). Some of the components of the FCA are estimated based on regional ecosystem-landscape models. This puts special requirements on the hierarchical structure of the classification of land classes used to limit the variability of the FCA components within the classes. From a modeling point of view, the approach consecutively examines three FCA varieties: (1) "baseline" inventory, assessing average values; (2) introduction of a number of environmental indicators by using empirical and semi-empirical ecosystem and landscape models; and (3) use of process-based blocks as part of the multiple-constraints procedure.

The most important lessons learned from this regional case study are:

1. The study has supported the appropriateness of an ecosystem-landscape approach as the scientific background for the regional FCA.
2. The vegetation components of the FCA for individual polygons are estimated with high reliability. Hence, live biomass (phytomass) by polygons is defined with uncertainties ±7–15%, net primary production and heterotrophic soil respiration ±15–20% (confidence probability here and below 0.9). However, this aspect required the development of a number of special regional modeling systems based on a large number of sample plots (between several hundred and several thousand for each component) and the use of all available reference and normative information (e.g., yield tables and models of gross and net growth).
3. The uncertainty of estimates of soil carbon pools is high (in the range of ±10–15%) and contains a substantial share of expert elements and assumptions because of the coarse resolution of soil data (the basic soil map and reference databases are presented at a scale of 1:1 million), obsolete and unevenly distributed measurements, mapping at different time scales, and insufficiently documented history of vegetation fire during the last two decades. At the ecoregion level, uncertainties of major pools and fluxes (like NPP and HSR) are estimated to be in the range of 5–10% (each ecoregion contains 600–4,000 polygons), under the

assumption that the account has no significant bias (more information and typical examples are given in Box 2). Calculations provided by both pool-based and flux-based methods showed rather consistent results, although assessing the soil carbon dynamic is substantially less certain than for other carbon pools (phytomass, coarse woody debris).

4. Some problems with estimating uncertainties are generated by the aggregation of ecosystems in polygons taking into account the coarse scale of the accounting. To some extent these uncertainties are decreased by the implementation of "mixed classes" (e.g., polygons that contain more than one class). On the other hand, implementation of "virtual polygons" presents the additional possibility of decreasing uncertainties of this type. "Virtual polygons" comprise land classes that are represented by numerous plots of small areas and are not individually indicated at the GIS layer (roads, small rivers and water reservoirs, settlements, some classes of agricultural lands). As a rule, the total area of such land classes could be obtained from independent sources, and corresponding corrections of an area are provided at the ecoregion level. However, a substantial part of the aggregation is based on professional judgments, and estimating these uncertainties includes a substantial expert component.
5. Interannual variability of the FCA could be very high (up to 2–5 fold for NBP and up to 25–30% for NPP during a 10–15 year period) and is defined by the impacts of seasonal weather specifics and by the extent and severity of disturbances.
6. Uncertainties of an FCA estimated for an individual year could be very high. Thus, considering time series is the best strategy for reducing uncertainty.

Box 2 Monte Carlo estimation of uncertainties of phytomass, NPP, and net ecosystem production (NEP) at the regional level (SIBERIA-II) for a base year 2003.

The region of SIBERIA-II, a total area of 307.8 million ha, stretches for about 3,000 km from the Arctic Ocean to the boundary with the Tuva Republic in the south and includes the main vegetation zones of the northern hemisphere (polar desert, tundra, forest tundra, northern, sparse, middle and southern taiga, temperate forests, forest steppe, steppe and semidesert). The area of the region is divided in 23 ecological regions (ecoregions) and ~35,000 polygons of which 16,589 are covered by vegetation (ecosystem-landscape units). The FCA was provided by polygon. Phytomass by seven fractions was estimated as described in Box 1. Net Primary Production (NPP) was calculated based on a special method of modeling of the annual cycle of total production of phytomass (TPPh). The method, algorithm, and parameterization used are described in Shvidenko, Shepashenko, Nilsson, and Bouloui (2004). The estimation of the FCA was provided similarly to Eq. 1 with some technical modification. Monte Carlo simulations (15,000 runs per simulation) were provided for phytomass by fractions, NPP, and NEP at both polygon and ecoregion levels. Input uncertainties for simulation were estimated as follows: growing stock ±15–20% (requirements of forest inventory manual addressed to separate stand are ±12–15%), site index ±5%, age ±10–40 years, depending on the average age of stand and the dominant species, relative stocking ±15–20%. We present results of the simulations below.

Estimation of phytomass at the polygon level. For a typical ecoregion (no. 2,501 situated in middle taiga subzone of Irkutsk *oblast*), the uncertainty of the total phytomass varies between ±6% and ±14% (mean 12%). The range of uncertainty is similar for all forest fractions (±13–20%) apart from understory and green forest floor, which have lower mean uncertainties, and foliage, which has a higher upper limit (±21–25%). The size of the 90% confidence interval normalized by area ranges between 0.67 and 31.60 Mg C ha^{-1} (mean 13.44). The spatial distribution of the uncertainties is presented in Fig. 1. As a whole, there are no spatial trends of the magnitude of uncertainty. Confidence intervals are mainly influenced by the average density of total phytomass by unit area.

Estimation of NPP at the polygon level. NPP of three aggregated fractions (above-ground wood, green parts, and below-ground wood) was considered. The range of uncertainty is similar for each forest fraction, from less than ±1% to between ±12 and 14%. The mean values are ±12% for the tree fractions and ±8–9% for understory and green forest floor. Percentiles of 5 and 95% boundaries are similar for the above-mentioned fractions, which are on average 0.92 and 1.08 of the mean, respectively.

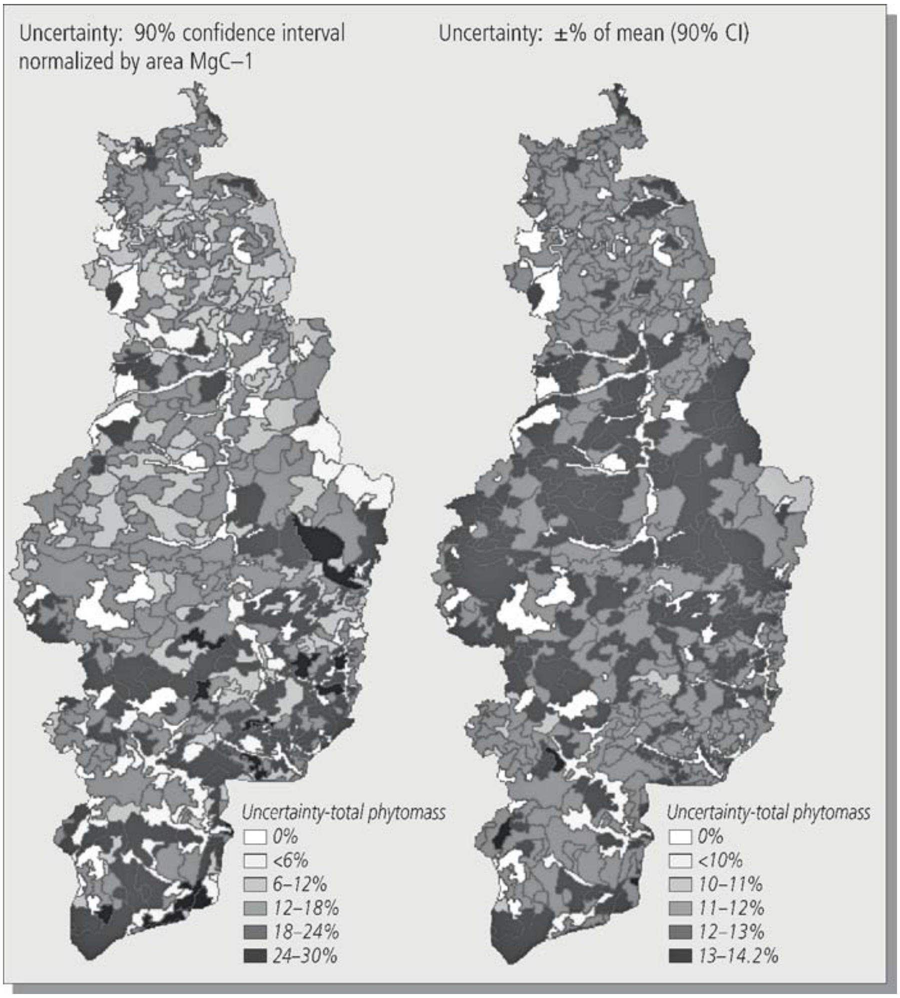

Fig. 1 Uncertainties of total phytomass by polygon for ecoregion 2501. The location of the ecoregion in the SIBERIA-II region is shown in Fig. 2

Estimation of NEP. An estimation of uncertainties of assessment of NEP has been carried out at the polygon level for each ecoregion and for the region of SIBERIA-II as a whole. The normalized range of NEP in ecoregion 2,501 varies between 0.17 and 0.85 Mg C ha^{-1} (mean of 0.67 Mg C ha^{-1}). The normalized range of NEP varies across the Siberia-II region between 0.01 and 2.64 Mg C ha^{-1} (mean of 0.51 Mg C ha^{-1}). There is a clear spatial trend in distribution of uncertainties across the region's area (Fig. 2) which is explained by the increasing human impact on ecosystems from north to south.

There are different ways of managing uncertainties based on additional information. There are many ways of evaluating the value of information, most of which rely on determining the benefit of making a decision based on current knowledge versus spending more resources to improve the knowledge base that could be used in Bayesian decision analysis (Berger, 1985), or referring to the more familiar expected value of perfect information (Morgan & Henrion, 1990). Effective ways of reducing carbon flux uncertainties strictly depend on the structure and specifics of the accounting schemes; the most appropriate ways of reducing their uncertainties differ from those used to reduce uncertainties in the inventories of carbon pools. As a rule, an optimal way of reducing uncertainty requires a systems approach and lies in the attempt to utilize the synergism of combining heterogeneous information sources. For example, to substantially reduce the uncertainties of emissions caused by vegetation fires, more appropriate classifications (for example, types of fires, types of combustibles) are required than are used in many countries; also required are more accurate vegetation

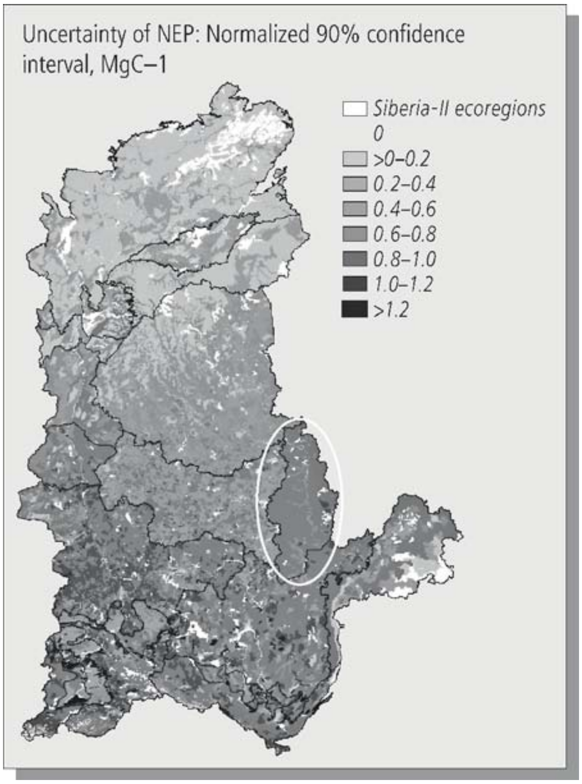

Fig. 2 Uncertainty of NEP for all vegetation classes across the Siberia-II region (uncertainty is shown as the 90% confidence interval normalized by polygon area). The red ellipse identifies ecoregion 2501 depicted in Fig. 1

fuel maps, new or modified RS sensors (which enable types of fires and their severity to be identified), and improved empirical models (e.g., to assess the amount of consumed combustibles of definite forest types depending on such factors as environmental indicators, and fuel storage). In addition, it must be kept in mind that some uncertainties cannot be reduced, given current knowledge and economic conditions.

7 Conclusion

The development of global integrated observing systems is a major strategy that aims to establish verified regional terrestrial biota full carbon accounts in the future. The integrated observation system is understood as a permanent tool for combining all the relevant information sources (on-ground measurements, remotely sensed data and empirical knowledge) and models of different types linked to primary polygons relevant to the FCA. Some prototypes for components of such systems and possible decisions are outlined above. Presumably, such an approach would allow the uncertainties of annual NBP at regional and national scales to be decreased to a range of 7–10%. However, any proper development and implementation of such a system will require not only advanced theoretical and technical improvements but also the development of new elements and subsystems. These improvements mostly deal with remote sensing, the study of some poorly understood basic processes, and the development of new types of regional model. Remotely sensed data are vitally important for the FCA. However, (1) only a multisensor remote sensing concept will be able to satisfy the major requirements of the accounting; and (2) there is an obvious need for the development of new sensors that would specifically address the assessment of the basic components of the FCA. One of the main bottlenecks of the FCA is insufficient knowledge of ecosystem below-ground processes. From the modeling point of view, it is clear that results produced by dynamic global vegetation models (DGVMs) for individual countries and continents have little in common with reality and that their uncertainties still cannot be estimated in any formal way. Inventory-based modeling schemes are able to present only average data for a rather uncertain period. Recent developments show that the “regionalizing” of DGVMs is one way of introducing such models into the verified FCA (Beer, Lucht, Schmullius, & Shvidenko, 2006). In addition, there are promising results from the introduction of process-based elements in inventory-based approaches and the ways in which this was carried out under the SIBERIA-II project. These can be considered as steps toward developing new types of hybrid regional model which would keep the strengths and minimize the weaknesses of both inventory- and process-based approaches.

One important unresolved question is the setting of the thresholds of relevant uncertainties that should be provided by verified regional and national FCAs. There is little progress in this field to date.

In the foreseeable future, the FCA will remain a fuzzy system in the sense discussed above. This implies that judgments about the reliability of the FCA will be based on a combination of strict formal methods as well as expert conclusions. In February 2005 the Kyoto Protocol entered into force and the technical task of assessing uncertainties gained political and economic importance. The theoretical and practical aspects of the problem will thus need to be elaborated, and the special institutions that would be responsible for certifying FCAs to be developed.

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