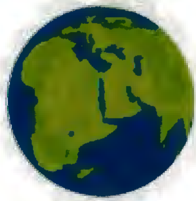

4th International Workshop
on Uncertainty in Atmospheric Emissions
7-9 October 2015, Krakow, Poland

PROCEEDINGS

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About the Workshop

The assessment of greenhouse gases and air pollutants (indirect GHGs) emitted to and removed from the atmosphere is high on the political and scientific agendas. Building on the UN climate process, the international community strives to address the long-term challenge of climate change collectively and comprehensively, and to take concrete and timely action that proves sustainable and robust in the future. Under the umbrella of the UN Framework Convention on Climate Change, mainly developed country parties to the Convention have, since the mid-1990s, published annual or periodic inventories of emissions and removals, and continued to do so after the Kyoto Protocol to the Convention ceased in 2012. Policymakers use these inventories to develop strategies and policies for emission reductions and to track the progress of those strategies and policies. Where formal commitments to limit emissions exist, regulatory agencies and corporations rely on emission inventories to establish compliance records.

However, as increasing international concern and cooperation aim at policy-oriented solutions to the climate change problem, a number of issues circulating around uncertainty have come to the fore, which were undervalued or left unmentioned at the time of the Kyoto Protocol but require adequate recognition under a workable and legislated successor agreement. Accounting and verification of emissions in space and time, compliance with emission reduction commitments, risk of exceeding future temperature targets, evaluating effects of mitigation versus adaptation versus intensity of induced impacts at home and elsewhere, and accounting of traded emission permits are to name but a few.

The *4th International Workshop on Uncertainty in Atmospheric Emissions* is jointly organized by the *Systems Research Institute of the Polish Academy of Sciences*, the Austrian-based *International Institute for Applied Systems Analysis*, and the *Lviv Polytechnic National University*. The 4th Uncertainty Workshop follows up and expands on the scope of the earlier Uncertainty Workshops – the *1st Workshop* in 2004 in Warsaw, Poland; the *2nd Workshop* in 2007 in Laxenburg, Austria; and the *3rd Workshop* in 2010 in Lviv, Ukraine.

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Full verified carbon account of forest ecosystems as a fuzzy system: An attempt to assess uncertainty

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Abstract

Carbon cycling of terrestrial ecosystems is a fuzzy (underspecified) system that imposes substantial constrains on possibility to get unbiased estimates of basic intermediate components (e.g., Net Primary Production, Heterotrophic Respiration) and final results (e.g., Net Ecosystem Carbon Budget) of the account within strictly defined confidential intervals based on any individually used carbon cycling method or model. We present a methodology attempting at minimizing possible biases and restricting the multivariate uncertainty's space. The methodology follows the principles of applied systems analysis and is based on integration of major independent methods of carbon cycling study (landscape-ecosystem approach, process-based models, eddy covariance and inverse modelling) with following harmonizing and mutual constraints of the results. Based on a case study for Russia's forests, we discuss strengths and limitations of the outlined methodology.

Keywords: Carbon cycle, uncertainty, fuzzy systems, Northern Eurasian forests

1. Introduction

Assessment of carbon budget of terrestrial ecosystems (FCA) requires obtaining two equally important outputs: 1) an unbiased proxy value, e.g. Net Ecosystem Carbon Budget (NECB) in a spatial and temporal explicit way and 2) uncertainties of NECB and its major components. A possible bias of the results depends upon the method used and completeness of the FCA. The latter is usually estimated based on expert estimates and professional judgements. Consideration of numerous interacting processes, which control NECB, in many models are often limited by a few such as climate change, impact of elevated CO_2, sometimes disturbances, nitrogen limitation and deposition [1]. Based on previous assessments of uncertainties' range of major components of the FCA, we consider the carbon account as full if the accounting schemes include $\geq 98\%$ of all recognized processes. A *verified* account of NECB supposes reliable and complete assessment of uncertainties, i.e. judgments about "uncertainty of uncertainties" would be possible [2]. However, the full carbon account of terrestrial ecosystems, particularly at large spatial scales is a typical fuzzy (underspecified) system, of which membership function is inherently stochastic, with some typical features of full complexity problems [3] and to some extent - wicked problems [e.g., 4]. This predetermines a principle impossibility of formally strict assessment of structural uncertainties within any method individually used. Thus "within method" uncertainty inevitably presents only part of "full" uncertainties. Posterior independent empirical validation of NECB is difficult to be realized in practice due to large resources required. This necessitates development of a methodology, which would be able to assess the "full uncertainties" of a studied system.

We attempt to outline such a methodology based on major principles of applied systems analysis [2,5], considering combination of major methods of carbon cycling understanding: landscape-ecosystem approach (LEA), process-based models, inverse modeling, and eddy covariance. Use of remote sensing methods in the FCA is crucial and two-faced because those deliver important input data (such as land cover at its biophysical parameters like above-ground live biomass) for different methods, but also some components of FCA directly (e.g., NPP). The principle of integration is applied at all stages and for all modules of the account - from development of the information base to uncertainty assessment of final results. Some ideas of the considered approach have been presented in previous publications [5,6,7] but the descriptions of methods used were lacked a common system basis. The approach was applied to the FCA of Russian forests as the most complicated by structure and processes terrestrial ecosystem that allows to highlight the methodology's strengths, weaknesses and potential. We also discuss system requirements to different methods of FCA, relevant scales and required details, information and research needs, as well as obtained and potential levels of uncertainties.

2. Methods

Basic methods of studying the carbon cycling of terrestrial ecosystems differ by specifics of cognition of biogeochemical processes, amount of information required, spatial and temporal details of consideration, and possibility of uncertainties' assessments. In an ideal case, each method should satisfy a minimum of system requirements that would allow to reliably assess "within method" uncertainties including monosemantic (and potentially consistent) definitions and classification schemes; explicit structuring of the account including strict spatial, temporal and process boundaries; explicit algorithmic description of the FCA for all steps and modules including that of assumptions, expert estimates and other "soft knowledge"; matching the temporal dimensions of the FCA with characteristic times of processes considered. Effectiveness of potential integration of results obtained by different methods depends on compatibility and amount of information comprising by each method. Structure of the FCA is outlined in Figure.

2.1 Landscape-ecosystem approach as empirical background of FCA

Landscape-ecosystem approach (LEA) plays specific role in the FCA as its empirical basis. In essence, it combines two basic backgrounds of any carbon cycling study - pool-based and flux-based approaches in a possibly complimentary way. The LEA serves for strict designing the studied system, defining the inter- and intra- boundaries, and contains spatially distributed accumulated information about ecosystems and landscapes (data of measurements *in situ*, diverse empirical and semi-empirical aggregations, data of forest inventory and different surveys, empirical aggregations and models etc.). LEA's information background is presented in form of an Integrated Land Information System as multi-layer and multi-scale GIS by polygons of a hybrid land cover (HLC). The HLC uses a hierarchical classification of land cover with details, needed for carbon cycling assessment. Land cover is developed using diversity of relevant remote sensing products, geographically-weighted regression and validation by Geo-Wiki tool. For instance, the last version of forest mask for Russia (resolution 230 m) was based on 12 remote sensing products, 5300 control points for the algorithm training and 730 for validation points; this allowed to minimize the possible biases in assessment of the forest area and its distribution providing accuracy of the forest mask >95% [8]. By-pixel parametrization of forest cover is provided based on multi-sensor remote sensing data, data of forest inventory, soil and landscape characteristics and other diverse relevant sources using a special optimization algorithm [9].

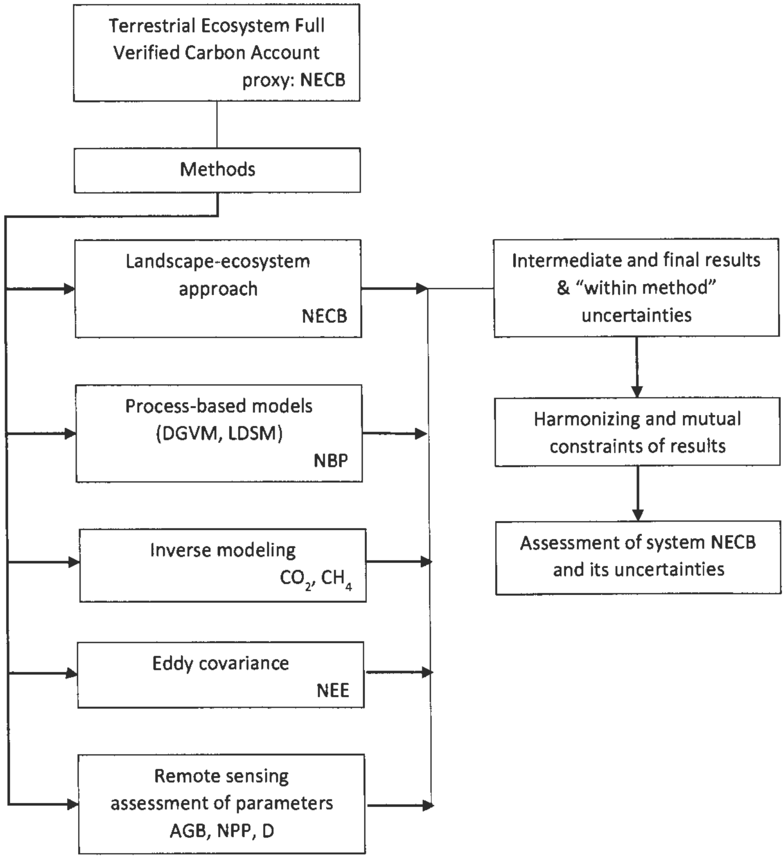

Figure 1. Structural scheme of full verified carbon account of forest ecosystems.

An important requirement is providing a system consistency between resolution (spatial scale of land cover and its parametrization) and certainty of attributive data. It could be shown that accuracy of major part of input data and empirically based models are logically consistent with resolution of 200-500 m at the country's scale. This provides a minimal level of uncertainty which presumably would be available for policy makers [10] but requires, e.g. for forests, by-pixel knowledge of dominant tree species, age, average height and diameter, site index, relative stocking, growing stock volume, and stock of dead wood. At the level of forest enterprises (of the total amount of ~1700 for Russia) the algorithm provides consistency of aggregated ILIS data with the most accurate available information sources (e.g., data of recent forest inventory). The assigned by-pixel parameters are presented by the most likely values based on indexes of suitability which are calculated based on ILIS data aggregating the system characteristics of site and growth conditions (such as elevation and exposure in mountains, soils, hydrological regimes etc.).

Pools of organic carbon include live biomass, dead wood, and soil carbon. Live biomass is calculated based on regionally distributed multi-dimensional regressions of Biomass Extension Factors which include region, aggregated forest type, dominant species, age, site index and relative stocking [10]. These regressions are based on ~7000 sample plots and allow to assess live biomass by 7 components (stem wood, branches, foliage, coarse roots, fine roots, understory (undergrowth + shrubs), and green forest floor). Coarse woody debris that includes logs, snags, stumps, and dry branches of living trees is assessed based on field measurements on sample plots and relevant data of forest inventory. Soil carbon is assessed for on-ground organic layer and 1m top layer of mineral soil based on soil map at scale at 1:2.5 M and corresponding database of typical soil profiles [11].

Major carbon fluxes that directly describe production process include Net Primary Production (NPP), Soil Heterotrophic Respiration (SHR), decomposition of coarse woody debris (DEC), fluxes due to disturbances (D), and lateral fluxes. By definition, NECB also includes other carbon contained substances like methane (CH_4), carbon oxide (CO), Volatile Organic Compounds (VOC) and particulates. NPP is assessed by a tentatively unbiased semi-empirical method which is based on modelling of full production of live biomass by components presented in models of bioproductivity [11]. A special empirically based modelling system was used for assessing SHR [11]. Decomposition of dead wood is described by kinetic models of the 1st order. Fluxes due to disturbances include fire, outbreaks of insects and deceases and impacts of unfavorable weather and environmental conditions [2,5]. Harvest and later fluxes of wood products (import, export) were assessed following Ciais et al. [13]. Fluxes to the hydrosphere are estimated based on measurements of DOC in water reservoirs including estimation of outgassing [14,15]. Emissions of methane and VOC were estimated based on dataset of field measurements and simplified models of dependences of emissions on different classes of forest cover.

A disputable and not finally solved question is relevance of the account of impacts of elevated concentration of CO_2 and deposition of nitrogen on vast and to a substantial impact unmanaged forests of Russia. The data on this topic for Russian forests are scarce and not consistent. At this stage, we used an aggregated approach which combined recognized but not accounted impacts on forest health and productivety. Observation on permanent sample plots [e.g. 16] and analysis of data of forest inventory [17,18] indicated that during the last 4 decades the increase of productivity (expressed in terms of growing stock volume) was 0.2-0.4% yr^{-1}. Such corrections were implemented when updating forest inventory data for input them in the ILIS was provided.

All fluxes which depend on climatic or environmental conditions and are calculated based on databases of measurement *in situ* are corrected for seasonal weather and environment conditions.

2.2 Assessment of uncertainty

Uncertainties within LEA were calculated in the following way: 1) analysis and numerical attribution of accuracy of input data; 2) calculation of precision of intermediate and final results; 3) use of error propgation theory (assuming the Gaussian distribution) and/or numerical differentiation for assessing the precision of intermediate and final results; 4) expert estimation of completness of the account and „transformation" of precision in uncertainty using the sensitivity analysis. Note that in practice basically „summarized errors" of input data, i.e. a mixture of random and systematic errors are available.Two end points of the assessment were considered: assessment of the unknown „fixed true value"and unknown true distribution.

The situation with assessment of uncertainties of parameters obtained by other methods is more diverse. Such results are usually derived from different studies which are not coordinated each other in any way. While *process-based models* (e.g., DGVMs) remain practically a sole method for explanation of processes and prediction, they have a number of specific features which should be taken into account: 1) as a proxy, DGVMs present only part of NECB (either Net Biome Production or Net Ecosystem Production); 2) they use a very simplified land cover classification with a limited number of plant functional types; part of these classification do not consider such important land classes as wetland or agricultural land; 3) substantial part of DGVMs is based on modelling „potential" vegetation and consider in very simplified way (or not consider) disturbances; 4) as global models, they are not able to properly describe some important regional features, e.g., specifics of impacts of processes on permafrost on forests of high latitudes [19]. *Eddy covariance method* presents a direct „bottom-up" estimate the Net Ecosystem Exchange (NEE) is widely used for parametrization of different models but at this stage cannot be used for upscaling for forests of the entire country due to very small amount of measurements (totally only in 17 different sites of which 13 were in forests). *Inverse modelling* is an inly methods of a „top-down" control of NEE. Uncertainty of measurements of some components of the FCA by remote sensing (e.g., NPP) substantially depends on completeness of regional validation and reliability of the models used at the regional level. Very often, the proper assessment of this type of uncertainties requires additional regional validation.

Harmonizing and mutual constraints of the results obtained by different methods have some specifics. First, the methods estimate different final indicators of carbon cyclimg: LEA – NECB, DGVMs – NBP, eddy covariance and inverse modeling - NEE. Second, the estimated uncertainties for DGVMs and inverse modelling differ from those of LEA and eddy covariance because they are usually calculated as standard deviation between different models of the ensembles used. This impacts the essence of the final (system) results constrainted by the Bayesian approach, particularly in the judgment about confidential intervals.

3. Results and discussion

Application of the LEA to Russian forests for 2007-2009 gave the following major results. NECB was estimated as the net sink of 546±120 Tg C yr^{-1} with substantial spatial variability: significat areas on permafrost and in disturbed forests serve as a carbon source. Uncertainties of major carbon pools were estimated (CI is equal 0.9, here and below) : live biomss ±5.0% and dead wood ±9.7%. Soil carbon pool could be estimated only very approximately (at level of 7-10%) that – taken into account a high size of this pool - limits the potential use of pool-based methods in the FCA. Uncertainties of major fluxes were estimated: NPP ±6%, HSR ±8%, DEC ±12%, fire ±23%, biotic factors ±25%, forest harvest and use of forest products ±25%, flux to the hydrosphere and hydrosphere ±33%. These data were obtained assuming that the estimates do not have significant systemstic errors.

Other published results of carbon budget of Russian forests are diverse. Using the pool-based method and the FAO definition of forest (the LEA used the Russian national definition) Pan et al. [20] defined the sink of Russian forests at 463±116 Tg C yr^{-1} during 1990-2007. Transition to the Russian definition of forests gives the forest sink at ~530 Tg C yr^{-1}, i.e. very close to the above flux-based estimates by the LEA. However, this publication calculated change of soil carbon by usin models based on of one-shot measurements of estimated indicators that allows to assume that uncertainty of this result is underestimated. There are a number of other „inventory" based estimates of the carbon sink for different years. These estimates reported NBP in the range from 200-800 TgC yr^{-1}. However these studies do not report any uncertainties and often contain simplified approaches.

Based on inverse modeling, carbon sink estimates for Russia (all land classes) are rather consistent. Within the Global Carbon Project Dolman et al. [7] used 12 different inversion schemes for different periods between 1992 and 2008 and reported the average sink at -690 Tg C yr^{-1} although the inter-model variation is high – the standard deviation was ±246 Tg C yr^{-1}. Sink for 2000-2004 that was received for vegetative land of Russia by four different inversion models on average reported –0.65±0.12 Pg C yr^{-1} (P.Ciais, personal communication). These results are in line with a majority of previous studies for large Russian regions like Boreal Asia or Central Siberia [21,22,6].

Results presented by DGVMs are less consistent. While NPP estimates by ensembles of DGVMs is very close to major part of "semi-empirical" assessments (e.g., about 7% of the LEA resuls), the NBP differs for about 50% [5,6,7,23]. The reason of this may be found in a balance between NPP and HR that to a significant extent is prescribed by DGVM approaches. However, this is not a case for high latitudes with their low intensive rates of decomposition of dead organic where fire is an important regulator. In addition, some substantial components of the FCA are omitted in current generations of DGVMs [1].

Upscaling the direct measurements of NEE by eddy covariance is very uncertain. One of a very fea attempts realized in [7] gave the estimate in range from -760 to -1097 Tg C yr^{-1}. However, the certainty of this conclusion is basically in field of expert judgemwnt.

Application of the Biasian approach to results received by the LEA, pool-based methods from [20] and inverse modelling from different publications resulted in 560±117 Tg C yr^{-1}. Note that confidential interval of such an estimate, like and possible bias, could be estimated only in a very approximate way.

Taking into account the estimates of uncertainties obtained in this study, the following overall conclusions could be done: 1) with a high probability Russian forests served as a net carbon sink with NECB at 550-650 Tg C yr^{-1} during the last decade; uncertainty of this average is in limits of 15-20%; forests provide at 90-95% of net sink of the total land flux; 2) temporal and spatial variability of the carbon sink is high, particularly for individual region of the country; this variability is basically explained by interannual variability of seasonal weather and connected to this natural disturbances like fire and insect outbreaks; 3) in spite of the high average sink, there are vast areas (mostly in disturbed forests and in forest on permafrost) which serve as a carbon source or are close to the neutral state; 4) the last decade demonstrate a weak trend of decreasing the NECB.

In spite of substantial decrease of uncertainties of the FCA and increase of formal strictness of the results in this study for Russian forests, a number of expert estimates and unrecognized biases remain. Evidently, this is inevitably at this stage of cognition of impacts of terrestrial ecosystems on global biogeochemical cycles. However, the approach used allows to exclude the clear outliers from intermediate results or to stress a need to pay a special attention to questionable results of other studies. At the same time, this study highlighted a number of system requirements to major methods of studying the carbon cycle. The initial important consideration is a relevance of development of an integrated information base which could be used by all the major methods developed for understanding emissions to, and removels out, greenhouse gases by the terrestrial biosphere. An experience of development of the Integrated Land Information System seems very promising for that. Using such a system might substantially improve information capacity of process-based models and generate a solid basis for upscaling of „point" measurements, e.g. in eddy covariance applications. Another lesson is a clear evidence and need of a system improvements of practically all methods of study of the biospheric role of terrestrial vegetation if an integrated analysis would be used. Finally, an important and unresolved question is a search of relevant tools for harmonizing and mutual constraints of indepedently obtained results. In curremt applications, the Biasian methods is limited by the normal theory but experiences show that empirical distributions, which are usual in the considered system, might be very far from any normal regularities.

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