Understanding Carbon Cycling of Terrestrial Ecosystems as a Fuzzy System

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Abstract

We outline a methodology of a full and verified carbon account of terrestrial ecosystems (FCA) that supposes unbiased assessment of relevant proxy values (here: Net Ecosystem Carbon Budget) and reliable estimation of uncertainties, i.e. understanding "uncertainty of uncertainties". The FCA is considered a fuzzy (underspecified) system of which uncertainties obtained by any individual methods of carbon cycling studying are inevitably partial. Attempting at estimation of "full uncertainties" we combined the major methods of terrestrial ecosystems carbon account. "Within method" results and intermediate and final uncertainties of the individual methods are harmonized and mutually constrained based on the Bayesian approach. The above methodology have been applied to carbon account of Russian terrestrial ecosystems with a special emphasis to forests. The study highlights strengths and weaknesses of the approach; system requirements to different methods of the FCA; current and potential levels of uncertainties of the FCA; and unresolved problems of cognition of fuzzy systems in ecology.

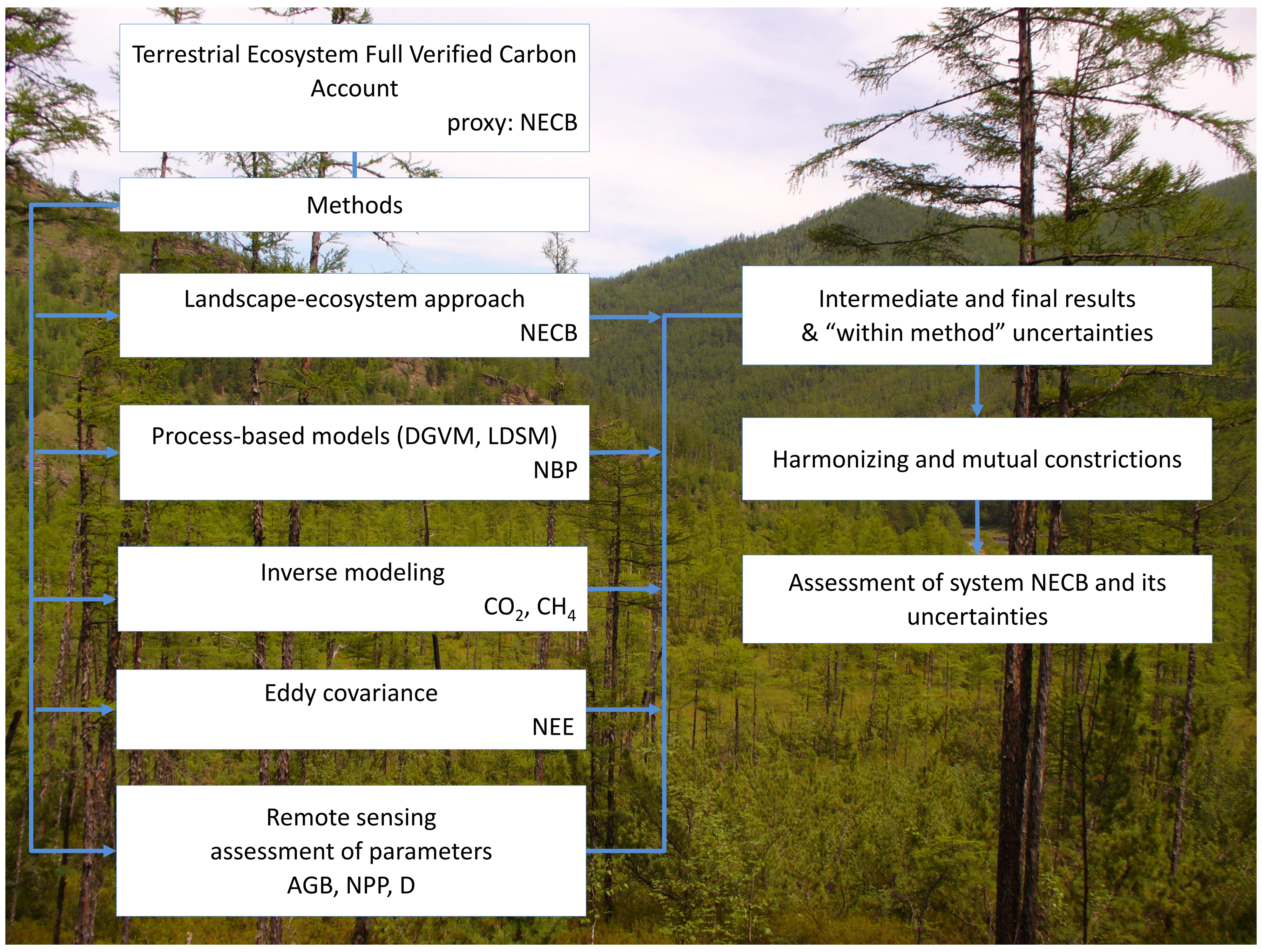
Major system requirements to the FCA

- **Full account:** ALL ecosystems, ALL processes, ALL carbon contained substances presented in a spatially and temporally explicit way (proxy: Net Ecosystem Carbon Budget)
- **Verified account:** reliable and comprehensive assessment of uncertainties. Uncertainty is an aggregation of insufficiencies of outputs of the accounting system, regardless of whether those insufficiencies result from a lack of knowledge, intricacy of the system, or other causes

Specifics

- FCA is a fuzzy (underspecified) system, of which membership function is inherently stochastic
- Any individually used method of FCA is not able to estimate structural uncertainties, and "within method" uncertainties are inevitably partial
- Assessment of "full uncertainties" of the FCA requires integration of independent results of major methods of terrestrial ecosystems carbon account at all stages and for all modules (landscape-ecosystem method, LEA; process-based models; eddy covariance; and inverse modelling); formal assessment of uncertainties within each methods; and harmonizing and mutual constraints of major intermediate and final results.

Structure of FCA of forest ecosystems



Major principles of Landscape-ecosystem approach (LEA) – an empirical background of the FCA

- Comprehensive use of applied systems analysis
- Relevant combination of flux- and pool-based approaches
- Availability of a matrix of compatibility of definitions and classification schemes used by different methods of the FCA
- Explicit intra- and intersystem structuring of the account; strict algorithmic form of accounting schemes, models and assumptions; spatially and temporally explicit distribution of pools and fluxes
- Correction of historical average estimates for environmental and climatic indicators of individual years
- Assessment of uncertainties at all stages and for all modules of the account – intra-approach uncertainty
- Comprehensive and consistent information background in form of an Integrated Land Information System

Integration of existing knowledge on ecosystems and landscapes in form of an Integrated Land Information System (ILIS)

- A multi-layer and multi-scale GIS
- Basic resolution from 250m to 1km, finer resolution for regions of rapid changes
- As comprehensive as possible attributive databases, empirical aggregations and auxiliary models
- Complimentary use and comparative analysis of different relevant sources
- Particular role of the multi-RS concept
- Certainty of data that are included in the ILIS should be known
- Relevant updating of information

References

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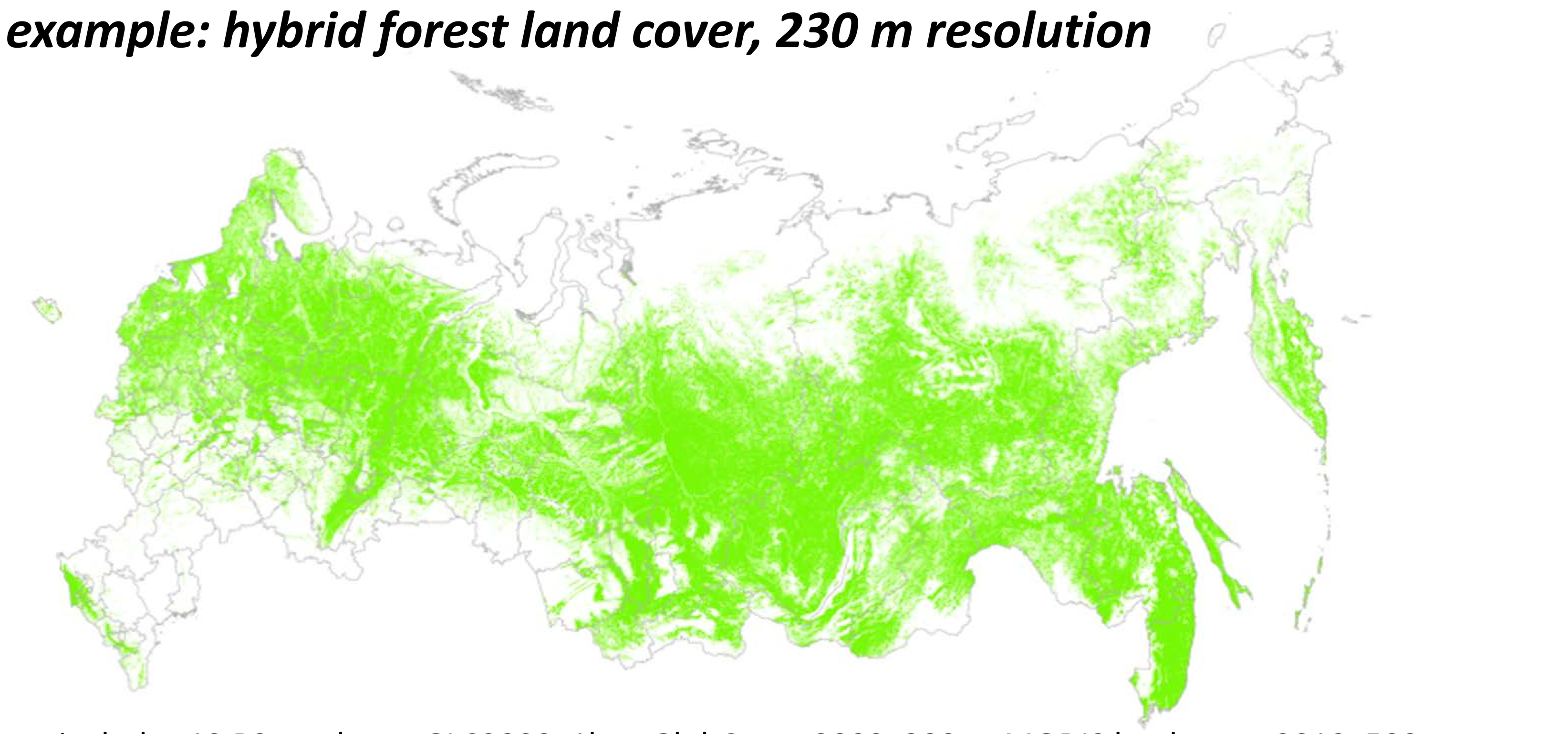
An example: hybrid forest land cover, 230 m resolution



The input includes 12 RS products: GLC2000, 1km, GlobCover 2009, 300m, MODIS land cover 2010, 500m; Landsat-based forest masks: by Sexton 2000, 30m and by Hansen 2010, 30m; MODIS VCF 2010, 230m; FAO World's forest 2010, 250m; Radar-based datasets: PALSAR forest mask 2010, 50m, ASAR growing stock 2010, 1km. *Source*: *Schepaschenko et al. 2015*

Assessment of uncertainties

For LEA at each stage - standard errors of functional *Y = f (xi)* where variables *xi* are known with standard errors *mxi*

$$m_y = \sum_i \left(\frac{\partial y}{\partial x_i} m_{xi}\right)^2 + 2r_{ij} \sum_{ij} \left(\frac{\partial y}{\partial x_i}\right)\left(\frac{\partial y}{\partial x_j}\right) m_{xi} m_{xj}$$

For ensembles of models (inverse modeling, DGVMs) – standard deviation between models

For multiple constraints – the Bayesian approach, e.g.

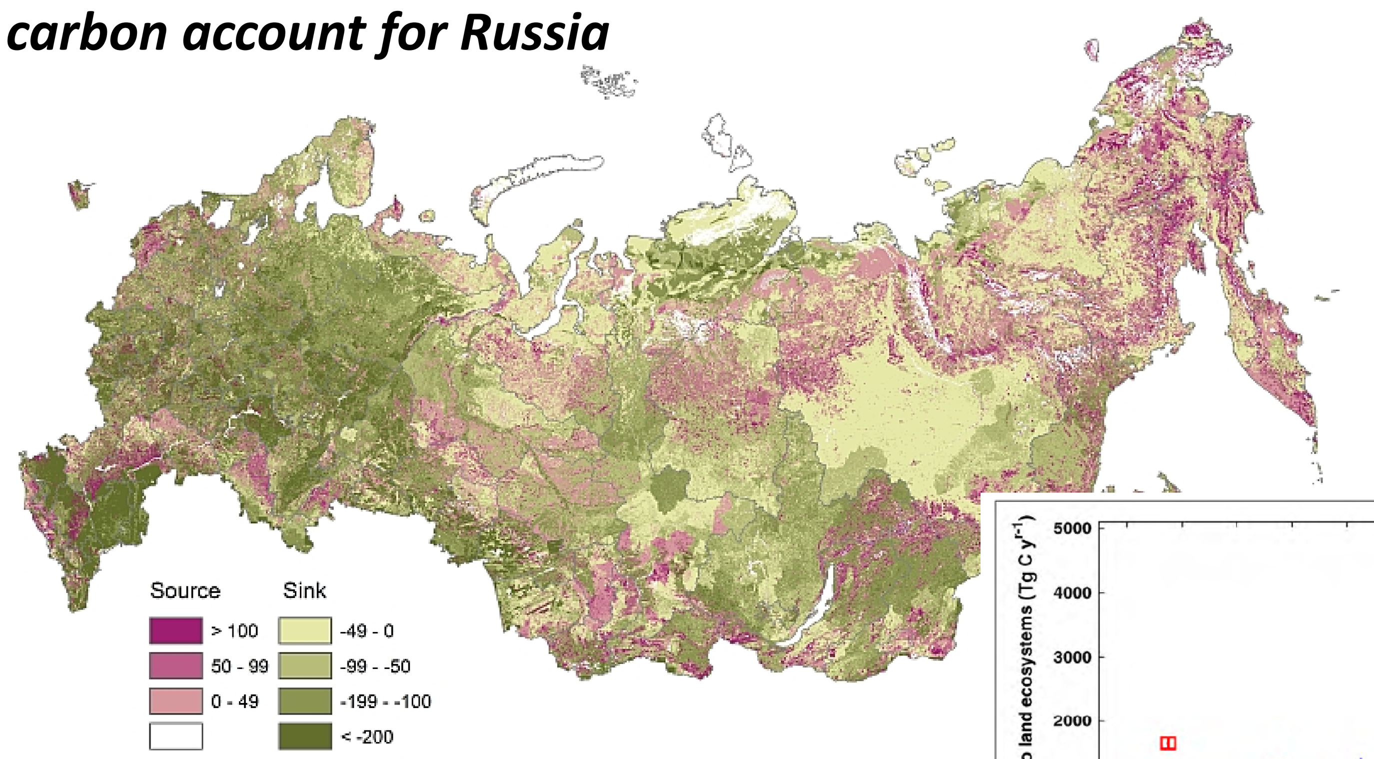
$$NECB_{Bayes} = \sum_i \frac{NECB_i}{V_i} / \sum_i \frac{1}{V_i}$$

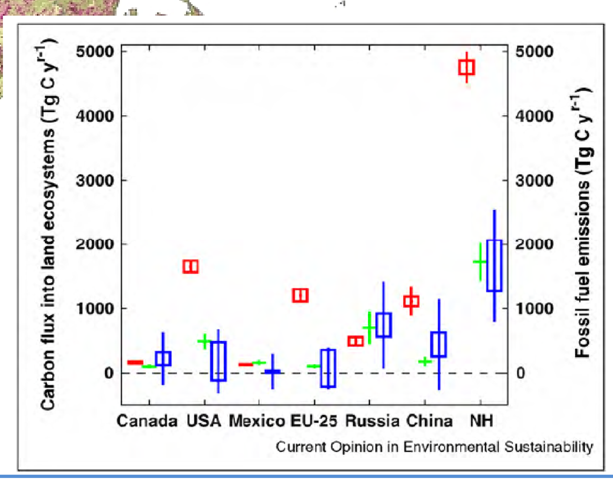
where NECB is assumed to be unbiased and Gaussian-distributed with variance Vi, i =1, …, n

NECB of terrestrial ecosystems of Russia in 2003-2008 (LEA approach)

Land classes and components	Flux, Tg C yr^{-1}
Forest	-563±88
Open woodland	-28±8
Shrubs	-22±5
Natural grassland	-58±10
Agriculture land	-32±10
Wetland (undisturbed)	-47±10
Disturbed wetland	+36±7
Wood products	+48±7
Food products (import-export)	+18±6
Flux to hydro- and lithosphere	+81±13
NECB	-567±92

Full carbon account for Russia





All ecosystems of Russia in 2000-2010 served as a net carbon sink at 0.5-0.7 Pg per year.
Of this sink ~95% was provided by forests
Source: Shvidenko et al. 2011

Comparison of results obtained by different methods, Pg C yr^{-1}

Method	Reference	Result
LEA	Shvidenko, Schepaschenko, 2014*	-0.55±0.12
Pool-based methods	Pan et al. 2011 (2000-2007)	-0.52±0.10
Inverse modelling	Ciais et al., 2010 (2000-2005), 4 dif. inv.	-0.65±0.12
	Dolman et al., 2012 (1988-2008), 12 dif. inv.	-0.69±0.25
DGVM	Dolman et al., 2012 (1988-2008)	-0.20±0.16
Eddy covariance	Dolman et al., 2012 (2000-2010)	-1.03 (-0.76-1.10)
Bayesian constraints	Shvidenko, Schepaschenko, 2014**	-0.55±0.12

* Average estimate for 2007-2009

** Dependently on the method final results are presented either NECB, NBP or NEE

Lessons – the realized approach:

- allows minimize the bias and uncertainties of the FCA and increase formal strictness of the results; however a number of expert estimates and unrecognized biases remains
- presents evidences for exclusion of outliers from intermediate results and point out questionable estimates from other studies (e.g. assessment of NBP by DGVM on permafrost)
- illustrates relevance of using the ILIS as a background of integrated observing systems
- evidences the ways for potential improvements of different methods of carbon accounting
- empaasizes a need for development of relevant theory and tools for harmonizing and mutual constraints of results obtained by different methods