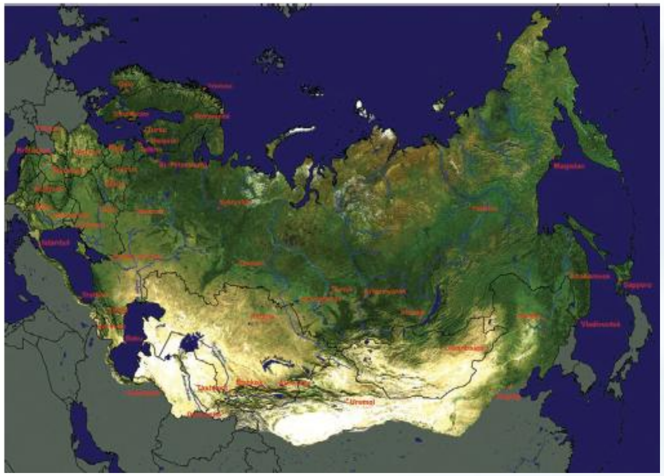

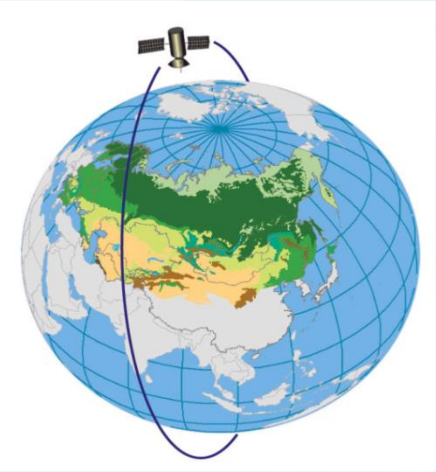

Biomass within the Paradigm of Full Verified Carbon Account of Forest Ecosystems

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1st User Workshop, ESA GlobBiomass Project, Laxenburg, 2-5 February 2015

Major system requirements to carbon accounting of forest ecosystems

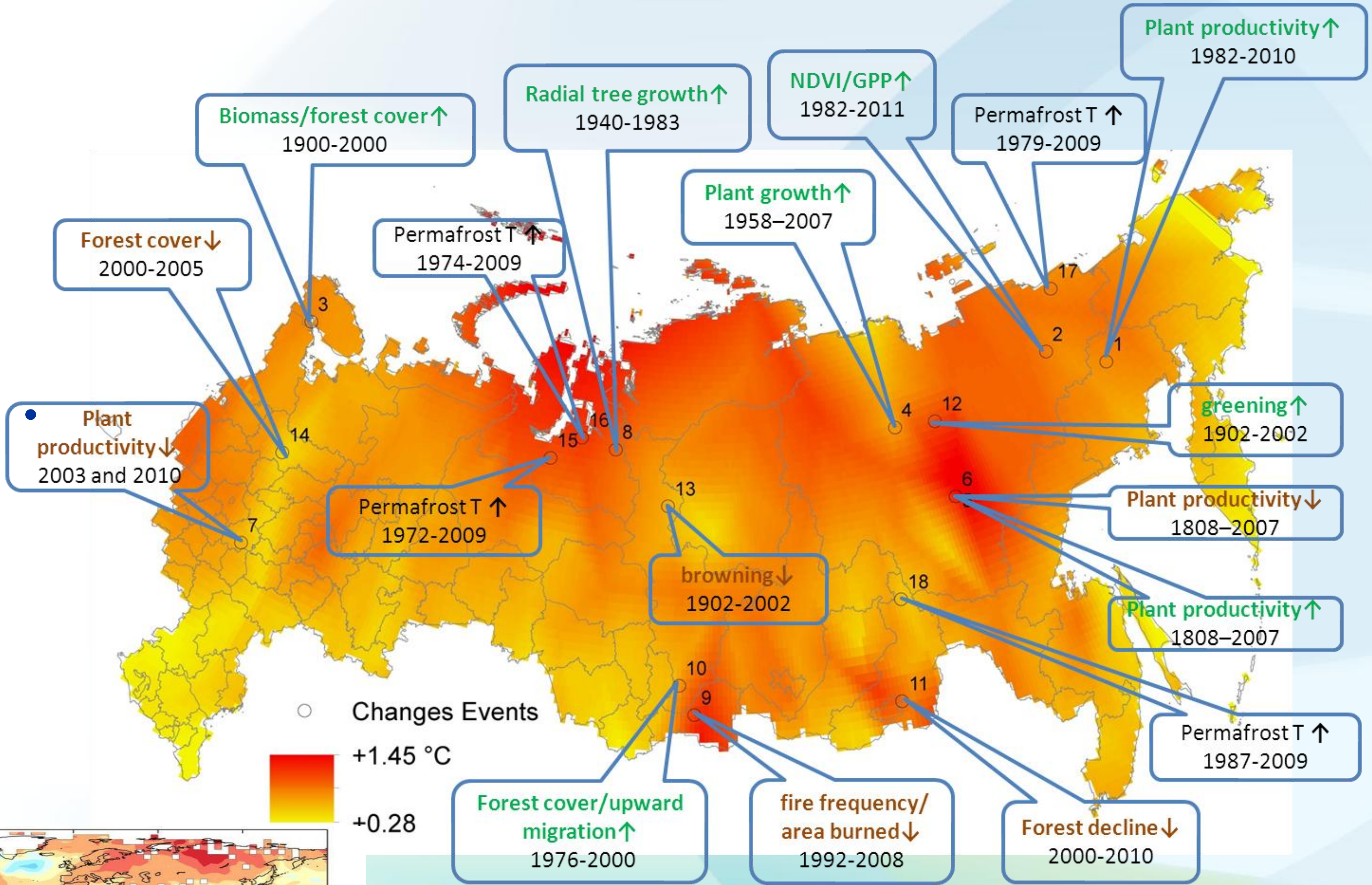
- Full carbon account: ALL ecosystems, ALL processes, ALL substances continuously in time
- Verified: (1) reliable and comprehensive assessment of uncertainties; (2) possibility to manage uncertainties
- Uncertainty is an aggregation of insufficiencies of outputs of the accounting system, regardless of whether those insufficiencies result from a lack of knowledge, intricacy of the system, or other causes

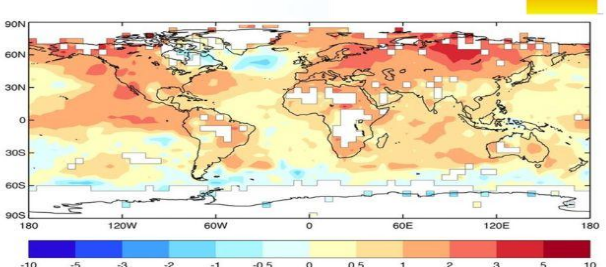
Recent estimates of carbon budget of Russia’s forests (C sink, Tg C/yr) – peer-reviewed publications

• **Baker et al. (2006)**	**332**
• **Balshi et al. (2007)**	**280**
• **Kudejarov, Kurganova (2008)**	**800**
• **Moiseev, Philipchuk (2010)**	**620**
• **Zamolodchikov et al. (2011)**	**205**
• **5th National Communication (2010)&**	**96**
• **Pan et al. (2011)**	**463±83**
• **Dolman et al. (2012)**	**680±246**
• **Shvidenko, Schepaschenko (2014)**	**560±117**

& For managed forests (about 70% of the country’s forests)

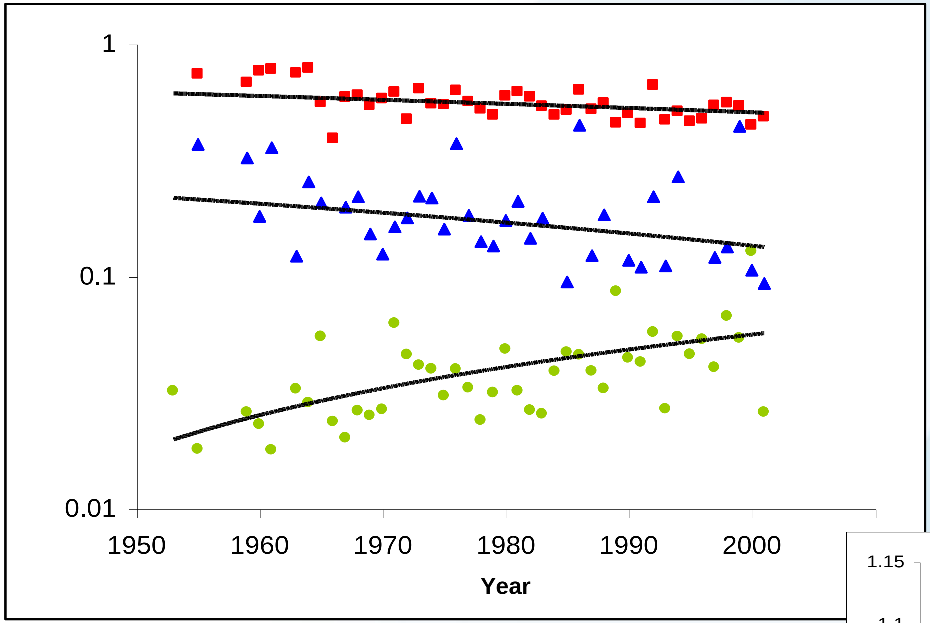
Climate change: Impacts on Russian forest



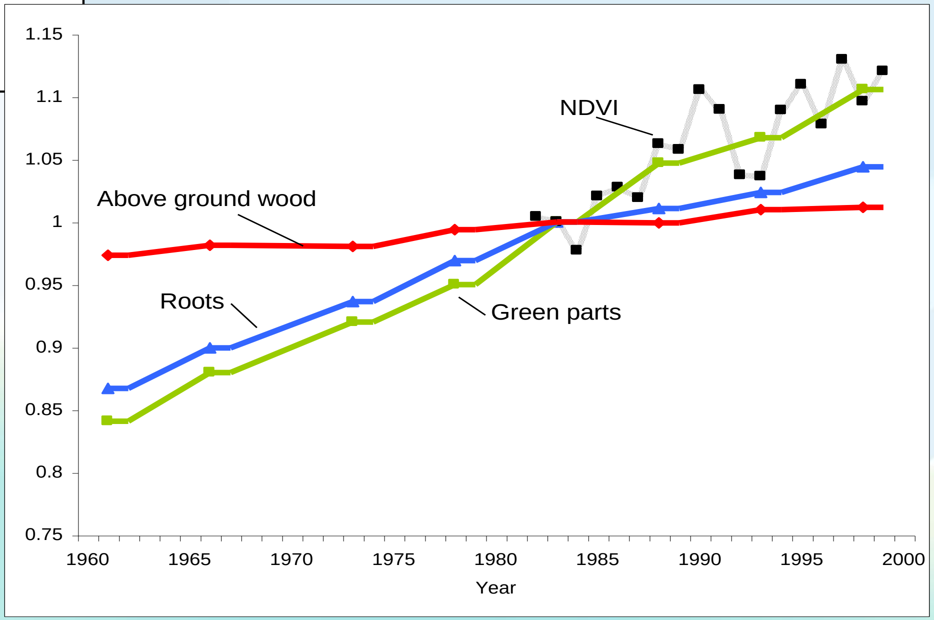


Source: Schaphoff et al.2016

Acclimation of Russian forests to Climate Change



Temporal dynamics of BEF:
above ground wood (red)
roots (blue)
foliage (green)



Dynamics of structure of live biomass of Russian forests in 1961- 2003 (normalized to 1983)

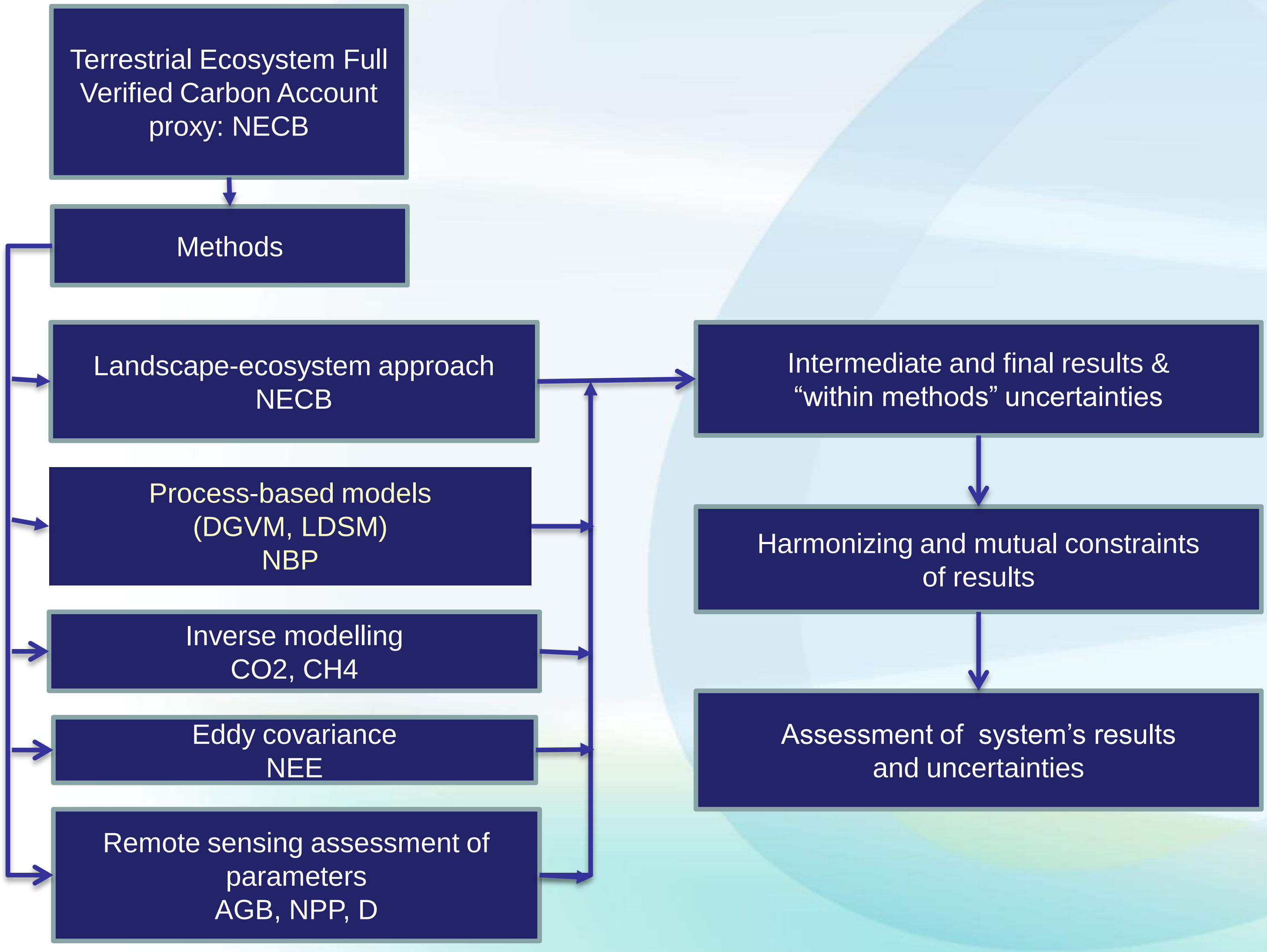
Diversity is inevitable

Forest Ecosystems Full Carbon Account is a dynamic complicated open stochastic fuzzy (underspecified) system (full complexity problem)

Membership function of fuzzy systems is stochastic

It defines incompleteness of both the accounting scheme and structural uncertainty of the results assessed by any individually used method of carbon accounting

Structure of FCA of forest ecosystems



Background of the methodology of FCA

The FCA is presented as a relevant combination of a pool-based approach

$$dC/dt = dPh/dt + dD/dt + dSOC/dt,$$

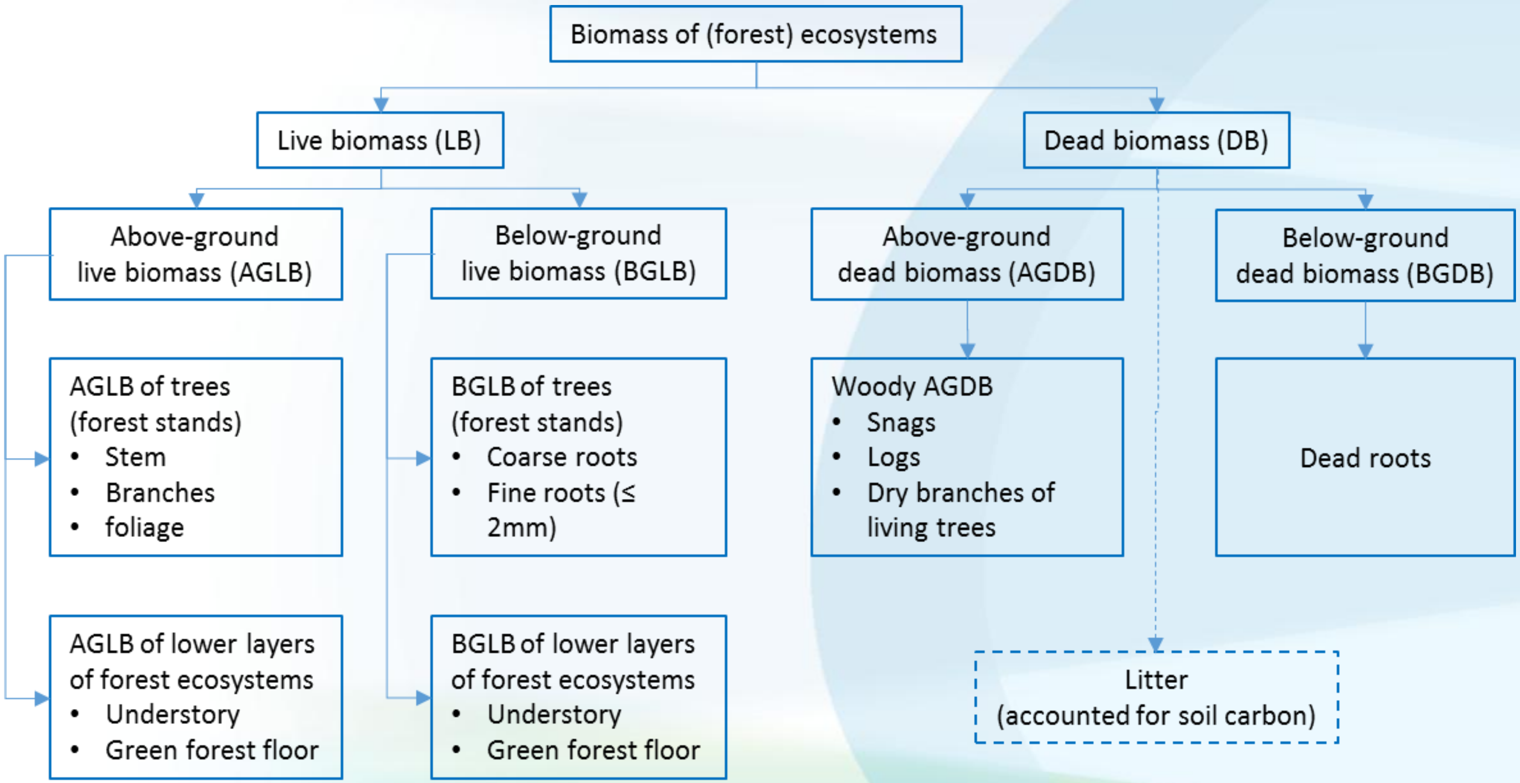
where Ph, D and SOC are pools of live biomass, dead organic matter and soil organic matter,

and a flux-based approach

$$NBP[NECB] = NPP – HR- ANT – FHYD - FLIT,$$

where NECB is net ecosystem carbon balance, NBP and NPP are net biome and net primary production, HR – heterotrophic respiration, ANT – flux caused by disturbances and consumption, FHYD and FLIT- fluxes to hydrosphere and lithosphere, respectively

Forest biomass which we have to know



Need of systems of multidimensional models of forest ecosystems: BEF as an example

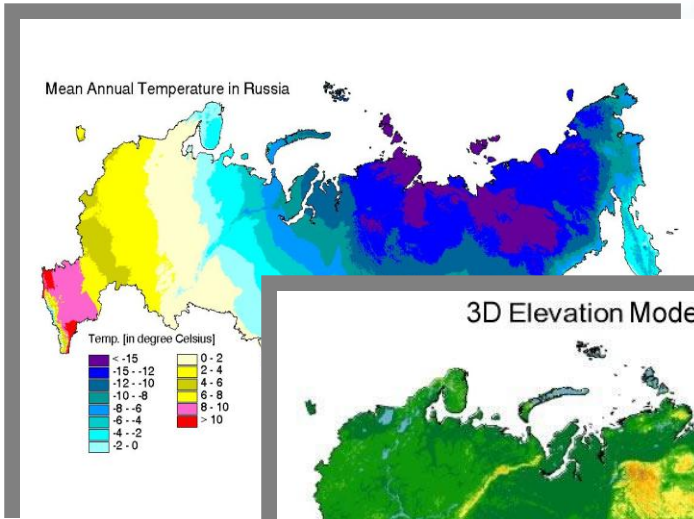
Minimal informative combination of Live Biomass components:

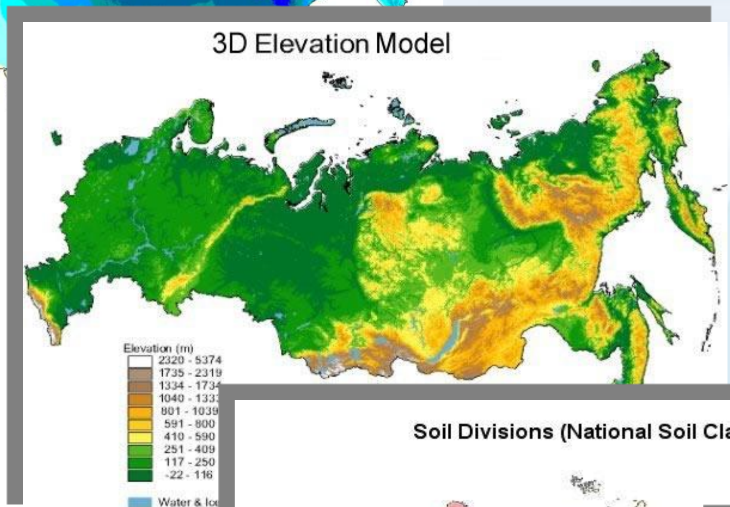
- stem wood over bark;
- bark;
- branches (over bark);
- foliage;
- roots;
- understory (shrubs and undergrowth);
- green forest floor.

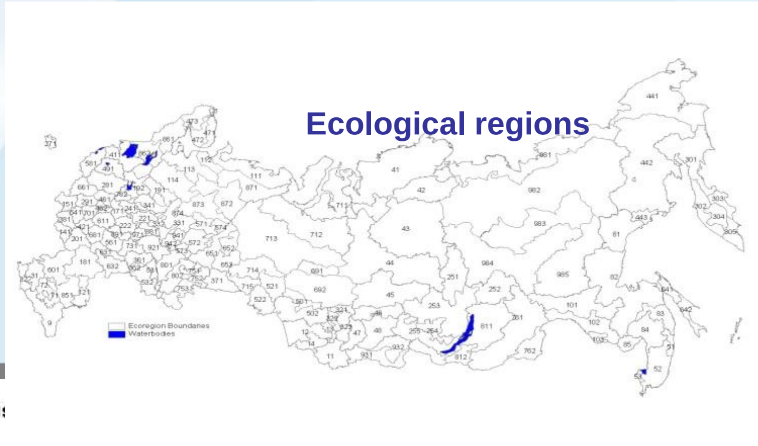
$$BEF_{fr} = M_{fr} / GS = c_0 \cdot A^{C_1} \cdot SI^{C_2} \cdot RS^{C_3} \cdot EXP(C_4 \cdot A + C_5 \cdot RS)$$

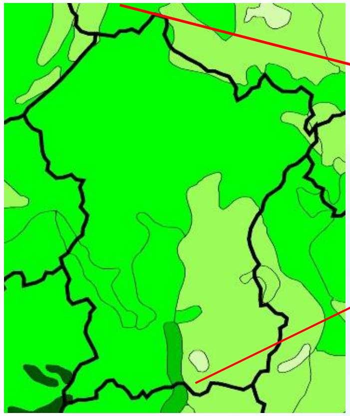
where BEF_{fr} – mass of phytomass by fractions, t ha^{-1};
GS – growing stock, m^3 ha^{-1};
A – average forest stand age, years;
SI – site index (correspond to average stand height at the age of 100);
RS – relative stocking;
$c_0, c_1, \ldots, c_5$ – model parameters.

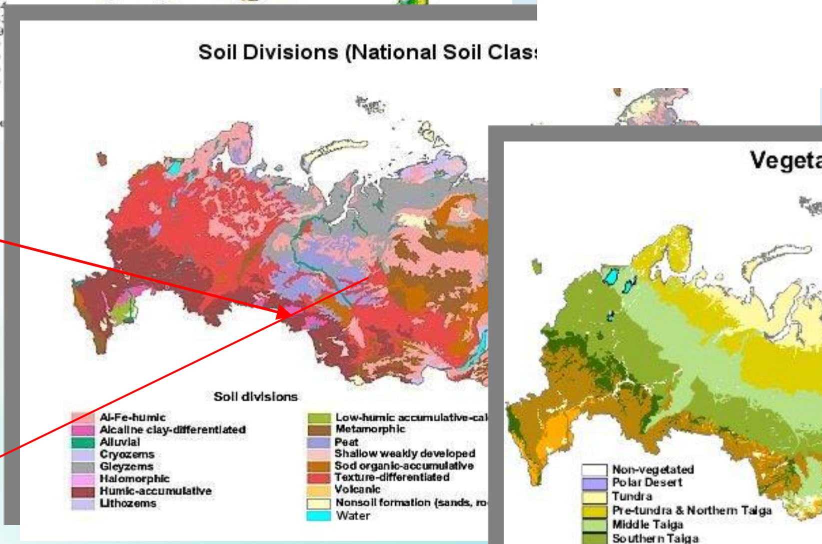
Hybrid Land Cover – an information basis of Integrated Land Information System











Major requirements to ecological regionalization

Ecoregions:

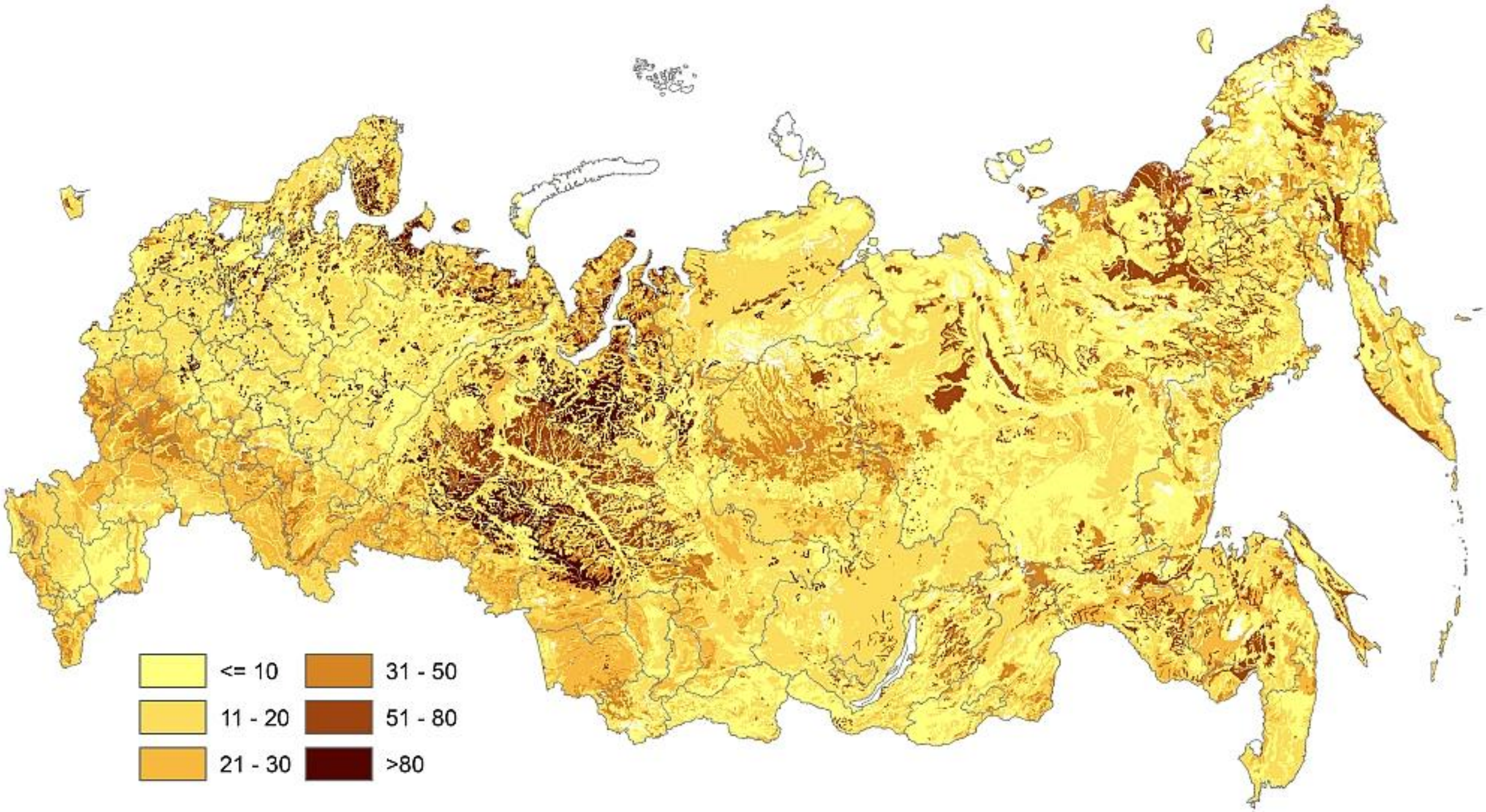
- Homogeneity of growth conditions (climate, soil, surface topography) and, consequently, similarity of vegetation cover
- Similar character and intensity of anthropogenic impacts on natural landscapes and ecosystems (systems of land management, air pollution, soil and water contamination etc.)
- Similarity of levels of transformation of indigenous vegetation, particularly forests
- Approximately similar impact of each ecoregion on major biogeochemical cycles

Subecoregions

- To some extent an analog of the definition of landscape by N. Solntsev (1962)

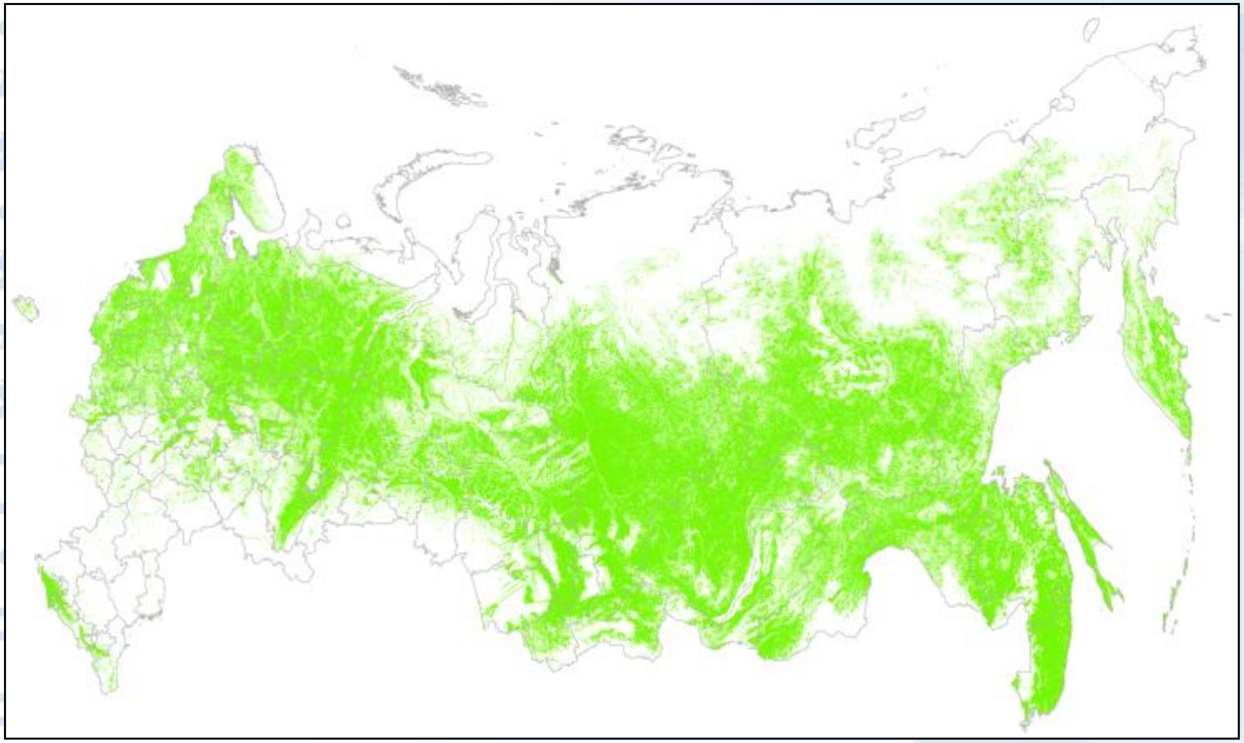
Soil organic matter

(on-ground organic layer + 1 m of soil under OOL, kg C m^{-2})



317 Pg C or 19.2 kg C m^{-2}

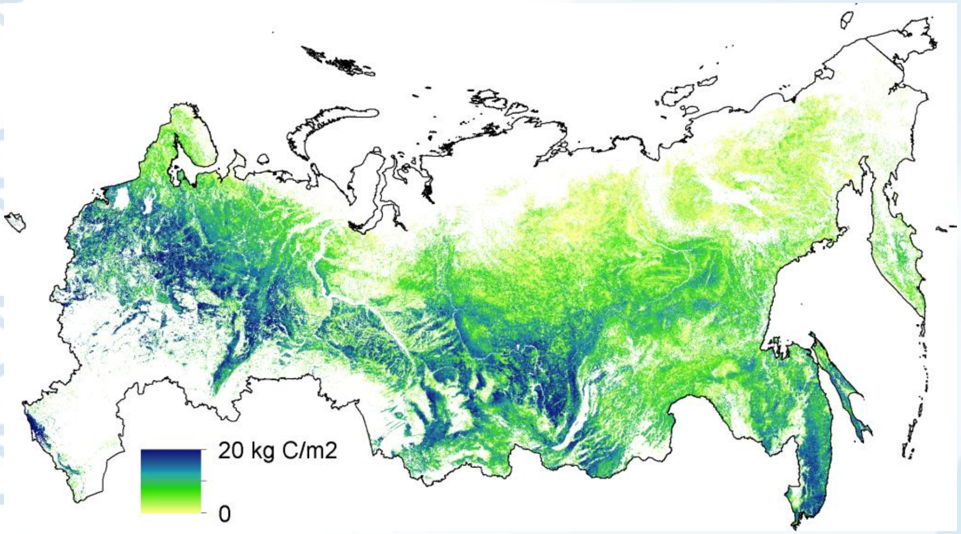
Forest mask: 12 RS products, resolution 230 m

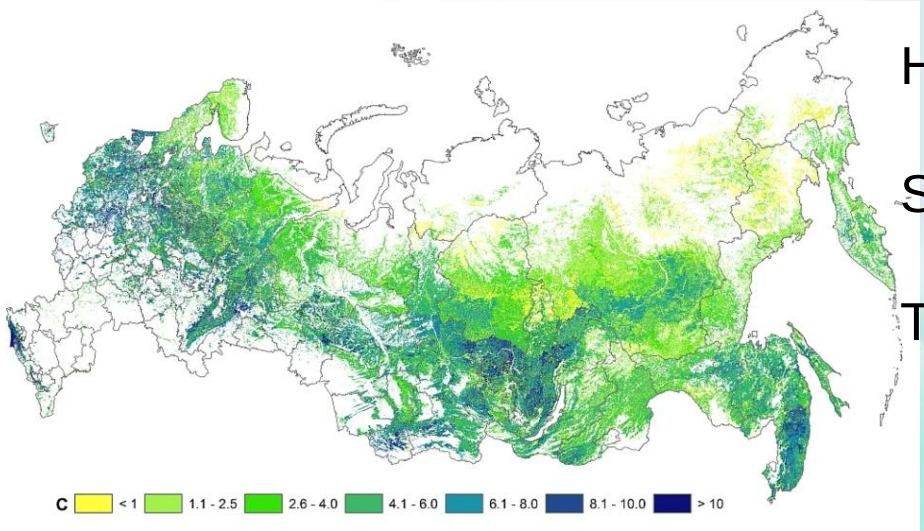


The input RS products include land covers: GLC2000, 1km, GlobCover 2009, 300m, MODIS land cover 2010, 500m; Landsat based forest masks: by Sexton 2000, 30m and by Hansen 2010, 30m; MODIS Vegetation Continuous Fields 2010, 230m; FAO World's forest 2010, 250m; Radar based datasets: PALSAR forest mask 2010, 50m, ASAR growing stock 2010, 1km. All datasets were converted to 230m resolution.

Schepaschenko et al. 2014

Biomass of Russian forests

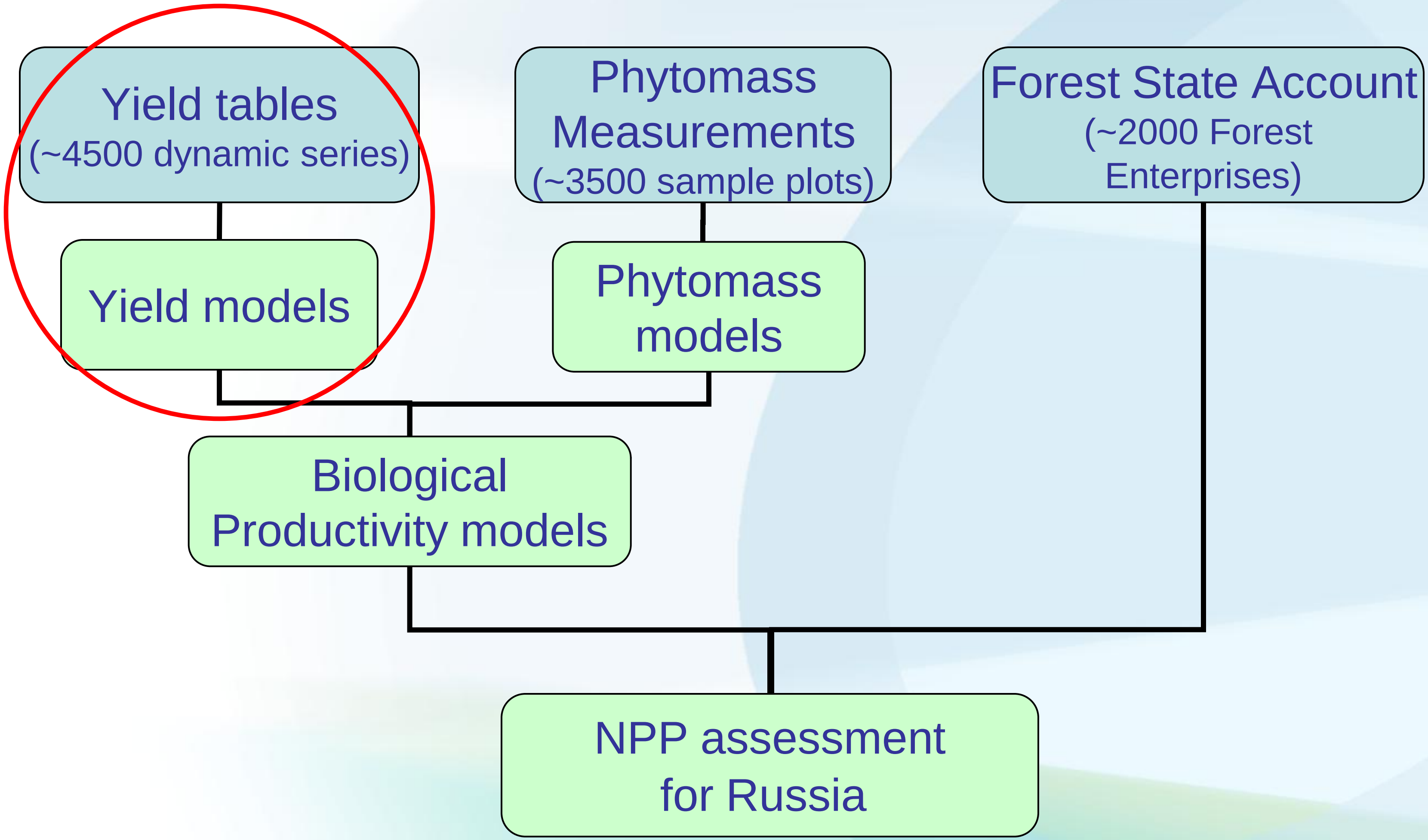




Estimates (Mg C/ha)

Alexeyev & Birdsey (1998)	28.7
Houghton et al. (2007) (1)	43.0
Houghton et al. (2007) (2)	39.5
Shvidenko et al. (2009)	37.5
Turner et al. (2013)	49.7

NPP as function of live biomass – a method



Total production of forest by live biomass (phytomas by year A (TPF_A) – accumulated value of all LB produced by an ecosystem during its life span up to year A

$TPF_A = TPF_A^{st} + TPF_A^{br} + TPF_A^{fol} + TPF_A^{root} + TPF_A^{under} + TPF_A^{gff}$

$NPP = TPF_A – TPF_{A-1}$

TPF_A – total production, kg C m^{-2} or Mg C ha^{-1}

A – forest stand age ;

st – stem;

br – branches;

fol – foliage;

root – roots;

under – shrubs and undergrowth;

gff – green forest floor.

Examples of the models of total forest production by fractions

- Total production for stem wood

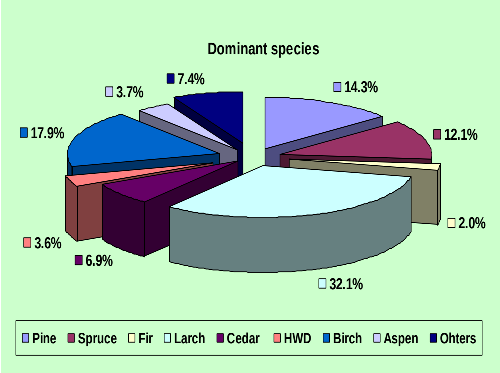
$$TPF_A^{st} = \sum_{A=1}^{A} \left[\left(TV_A - TV_{A-1} \right) R^{st} \right]$$

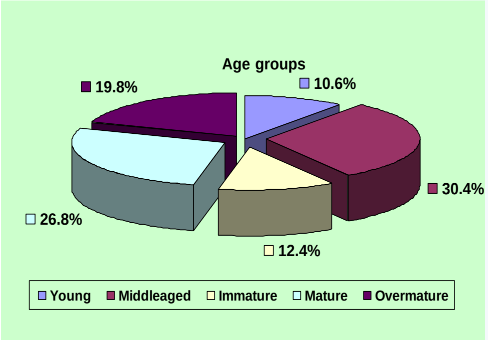
- Total production for foliage

$$\mathrm{TP}F_A^{fol} = \sum_{A=1}^{A} \left[\begin{array}{l} \left(F_A^{fol} - F_{A-1}^{fol} \right) + \left(TPF_{A-l}^{fol} - TPF_{A-l-1}^{fol} \right) + \left(1 + \frac{\upsilon}{q} \right) F_{A-1}^{fol} + \\ \frac{\eta}{2k} \left[\left(TV_A - GS_A \right) - \left(TV_{A-1} - GS_{A-1} \right) \right] R_{A-1}^{fol} \end{array} \right]$$

NPP as a function of live biomass - results

Net Primary Production (2009) 2.61±0.20 Pg C $year^{-1}$





Other methods

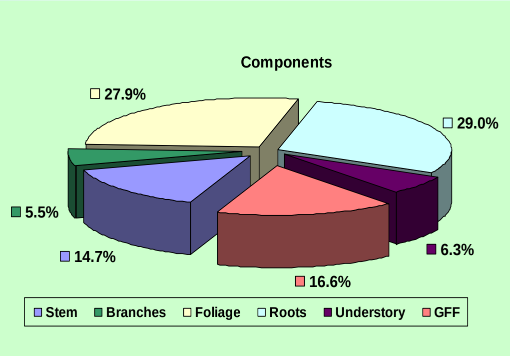
DGVMs (ensemble of 17 models, Cramer et al. 1999) +6.3%

DGVMs (ensemble of

Chlorophyll index by Voronin (Zavarzin 2007) +1.5%

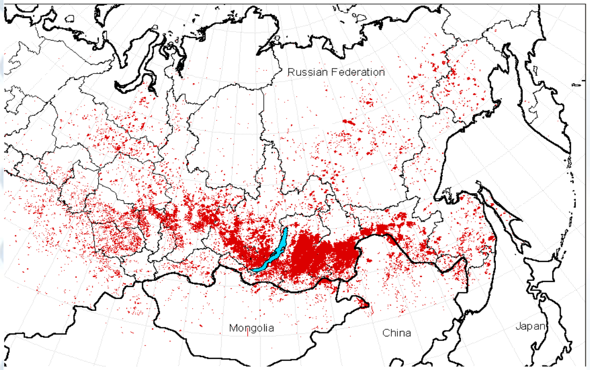
MODIS +0.0%

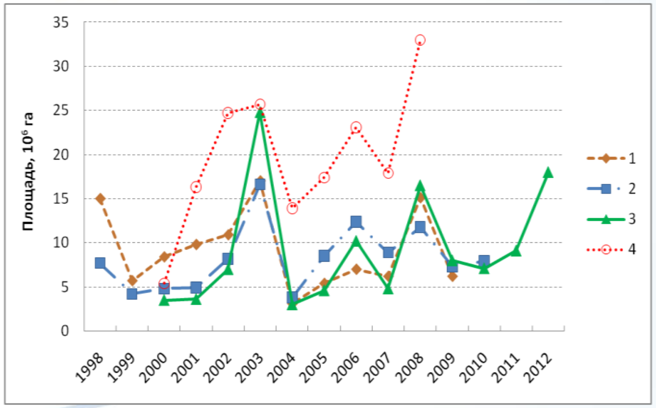
Different inventories from -36% to +93%



Fluxes due to natural and human-induced disturbances

April - November of 2003 year. The total hot spots distribution in Siberia and Far East . NOAA/AVHRR 12,15,16
Center of Remote Sensing. Institute of solar-terrestrial physics SB RAS.





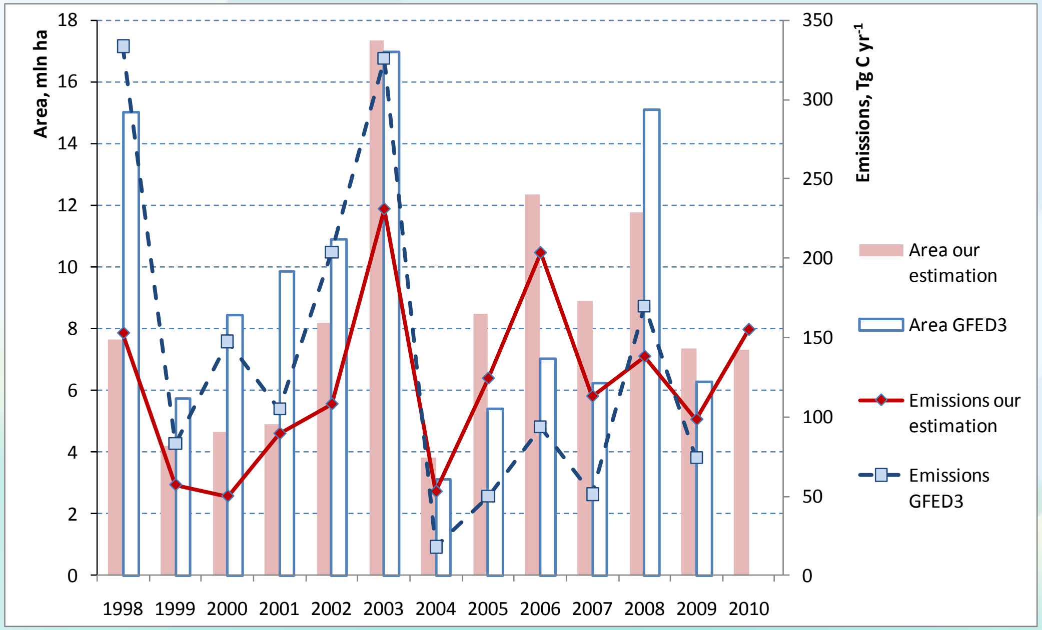
▲ the average area of wild fires in Russia in 1998 - 2010 exceeded 9 million ha including 5 million ha of forests

▲fires in 2011 – 16 million ha, 2012 – 32 million ha

▲ fires of the last decade produced direct carbon emissions at ~130 million ton C per year

▲an outbreak of Siberian moth in Russia in 2001 covered ~10 million ha

▲the total direct C emissions due to disturbances are from 250-300 million t per year

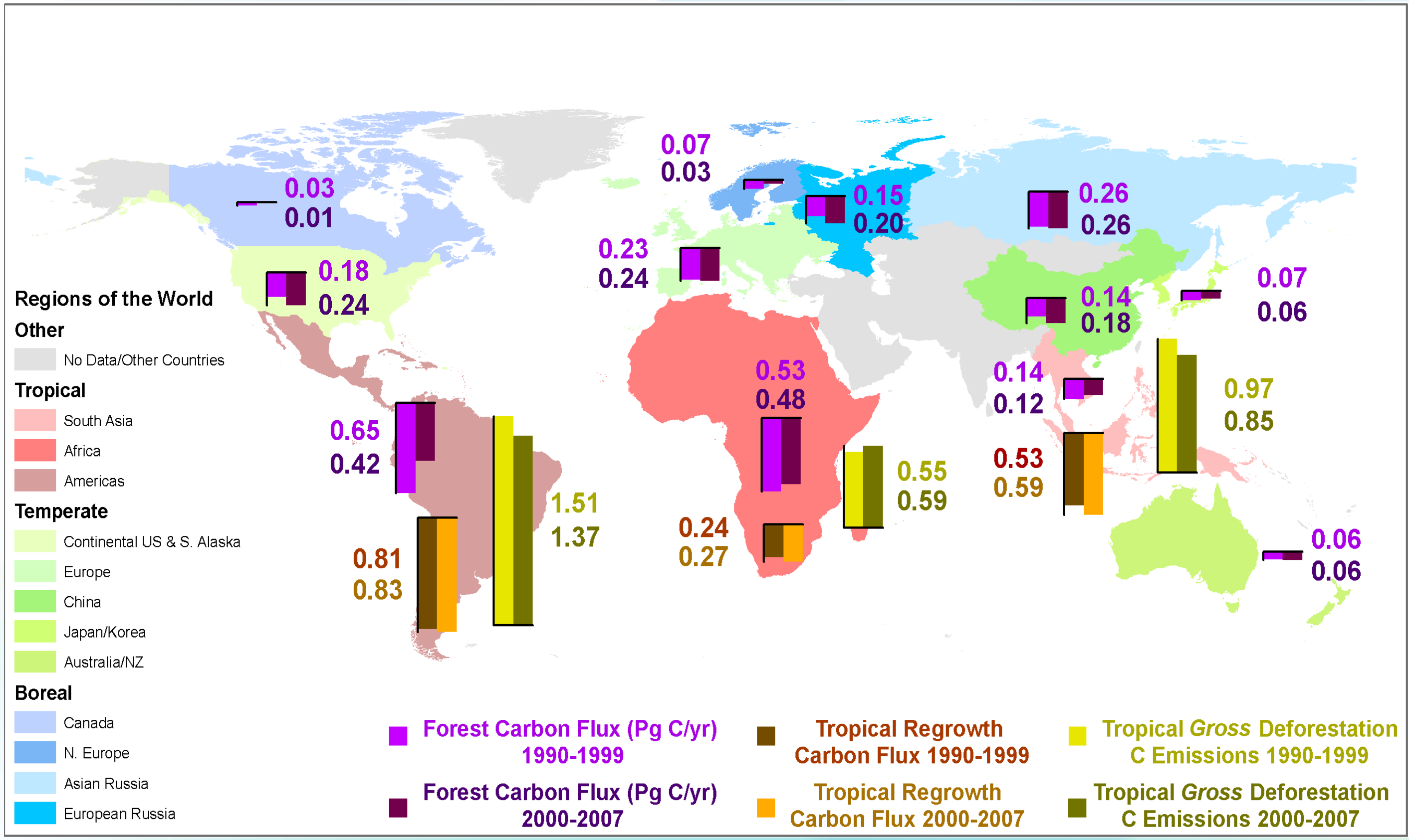


Change of carbon stock in boreal ecosystems in 1990-2007: net sink at 0.5 Pg C year^{-1} or 21% of established forests (Pan et al. 2011)

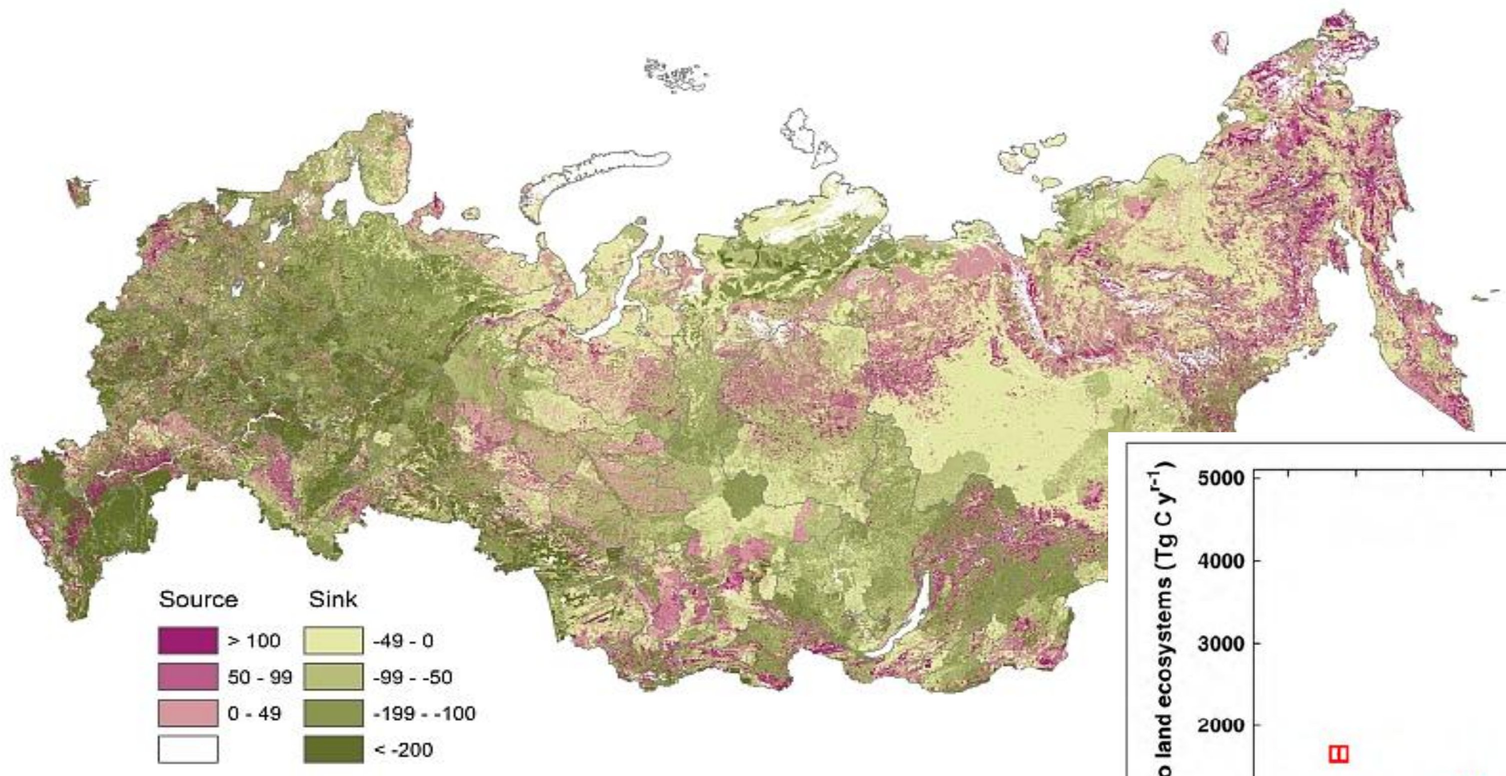
including (Tg C yr^{-1})

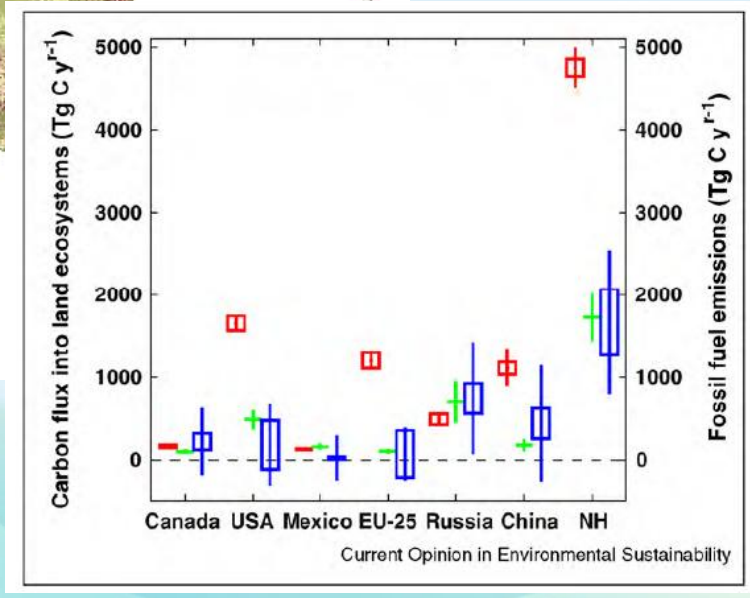
Asian Russia	259
European Russia	170
Boreal Europe	48
Canada	19
Total	496

Gudale et al. (2002) – ~500 Tg C yr-1



Full carbon account for Russia in 2009 – flux-based approach





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

Source: Ciais et al. 2010

DGVM results for Russia (Tg C yr^{-1})

Carbon fluxes from DGVMs	Mean	IAV (σ_{year})
	1921–2008	
GPP	8401	2612
NPP	4076	2186
NBP	91	110
	1990–2008	
GPP	9239	2857
NPP	4712	1780
NBP	199	160

Average of 8 DGVMs (CLM4, ORCIDEE, HYLAND, LPJGuess, LPJ, OCN, SDGVM, TRIFFID)
Source: Sitch et al. 2008, Dolman et al. 2012

Forest NPP: 19 DGVMs (Cramer et al. 1999) 2690±530
Forest NPP: LEA (this study) 2620±110

Eddy covariance approach (all ecosystems)

Land Cover	GLC Area in 10^{12} m	LEA	Observed NEE gC m^{-2} yr^{-1}	Corrected NEE gC m^{-2} yr^{-1}	NEP TgC yr^{-1}
Tundra	3.9	2.3	-58	-30	-119
Wetlands	0.5	1.5	-52	-63	-31
Grasslands	1.1	0.7	-107	-74	-80
Agriculture	1.6	2.2	0	0	-0
Larch	3	2.8	-200	-151	-448 (-296 -475)
Pine	1.4	1.3	-197	-149	-207 (-98 -157)
Spruce	0.9	1.1	1	1	-1
Fir	0.2	0.2	-279	-198	-37 (-25 -39)
Mixed/other	2.9	4.3	-119	-38	-111 –(73 -118)
Area weighted mean	17.1	16.1		-60	-1033 (-760 -1097)

Source: Dolman et al. 2012

Results of inverse modeling

Inverse system	Time period	Average NBP (Tg C yr^{-1})	IAV (σ_{year}) (Tg C yr^{-1})
C13 CCAM	1992-2008	-820	210
CSU	2003-2006	-630	408
CARBONTRACKER-EU	2000-2007	-907	199
CARBONTRACKER-US	2000-2007	-872	242
GEOSTAT	1997-2001	27	76
JMA_2010	1985-2008	-1305	237
LSCE_PEYLIN	1996-2004	-587	97
LSCE_4DVAR	1988-2008	-895	360
NICAM_NIWA	1988-2007	-390	260
NIES_PRABIR	1993-2006	-992	259
PSU	2001-2003	-906	288
MATCH	1992-2005	-1.14	4.75
Average		**-690**	**246**

Source: Gourney et al. 2013

Assessment of uncertainties: mutual constraints

- For LEA at each stage - standard error 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 is used*

- *For multiple constraints – the Bayesian approach, i.e.*

$$NBP_{Bayes} = \sum_i \frac{NBP_i}{V_i} / \sum_i \frac{1}{V_i}$$

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

Thinking about future

- Acceptable level of uncertainties of FCA at yearly basis (20-25%, CI 0.9) could be provided only based on fusion of remote sensing and ground data presented as regionally distributed multidimensional models of forest ecosystems. Lack of ground-based knowledge becomes a major limitation factor of the FCA
- Optimal resolution for assessing major biogeochemical cycles of forests at continental/ national scale is 100-300 m
- Major lesson of application of methodology of the FCA is a need of system comparison and modification of all major methods of studying carbon cycling
- How much promising is a system application of different radar bands under existing the appropriate models of forest ecosystems?
- There is a need for modification of methodology of mutual constraints of results obtained by independent methods for underspecified (fuzzy) systems

Thank you