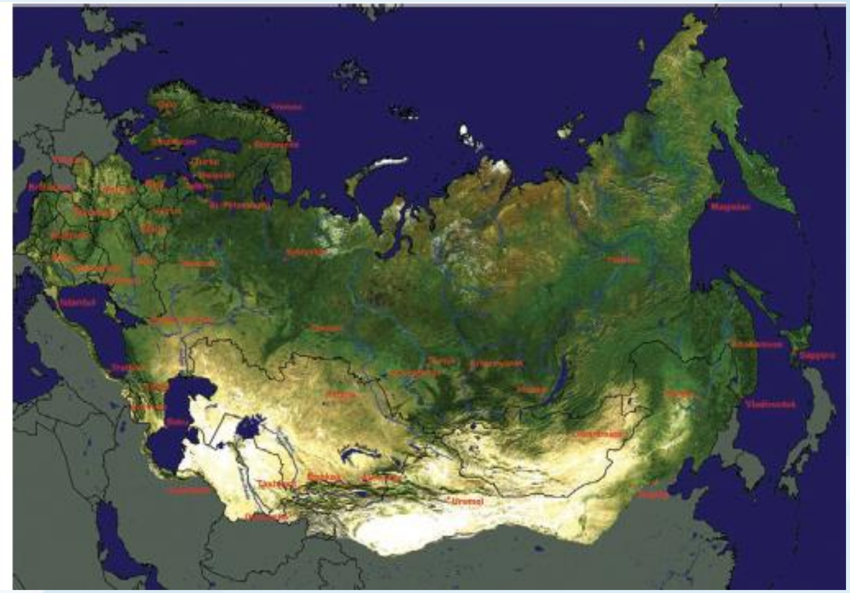

Full Verified Carbon Account as a Fuzzy System: An Attempt to Assess Uncertainty

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4th International Workshop on Uncertainty in Atmospheric Emissions, Cracow, Poland, Crakow, 7-11 October 2015

Major system requirements to carbon account of terrestrial ecosystems

- Full carbon account: ALL ecosystems, ALL processes, ALL carbon contained substances in a spatially and temporally explicit way (≥ 98%?)
- Proxy: Net Ecosystem Carbon Account

- 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

Backgrounds 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 phytomass, dead organic matter and soil organic matter,

and a flux-based approach

$$NECB = NPP – HR- ANT – FHYD - FLIT,$$

where 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

However

Terrestrial Vegetation Full Carbon Account (FCA) is a dynamic complicated open stochastic fuzzy system, with some features of a full complexity and wicked problems

Any individually used method of FCA is not able recognize structural uncertainty in a comprehensive way

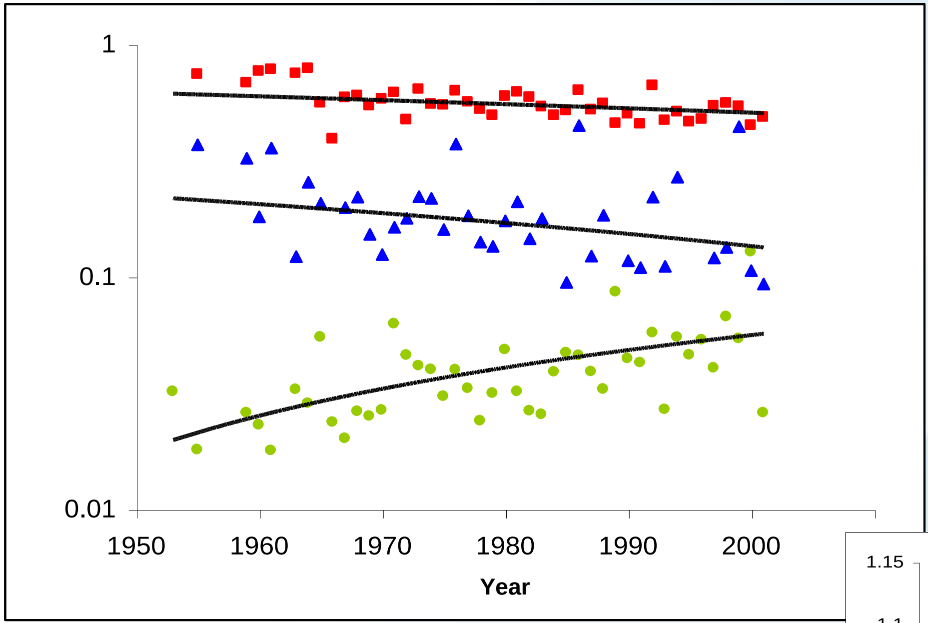
Major principle: integration, harmonizing and multiple constraints of independent methods and results

Landscape-ecosystem approach
Process-based models
Flux measurements
Multi-sensor remote sensing concept
Inverse modelling

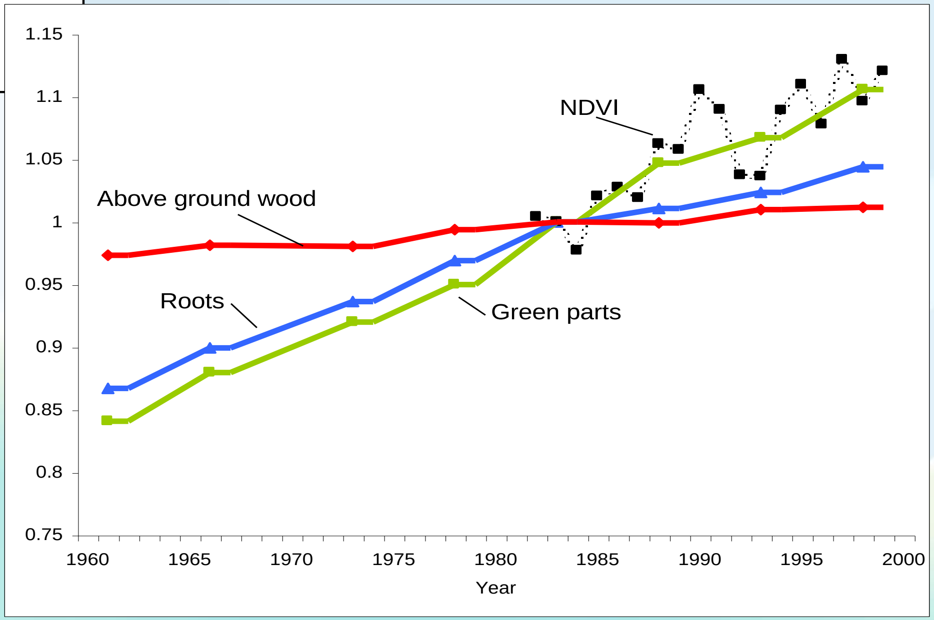
FCA: Complexity, uncertainty and conflict

- Fuzzy system: the membership function is stochastic
- Substantial features of a full complexity problem: 1) structurally, functionally and dynamically intricate; 2) non-separable from context, observation and interest; 3) multi-objective/ subjective; and 4) uncertain due to fragmentary knowledge and insufficient validation process (Schellngruber 2003)
- Some features of a wicked problem is a problem that is difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognize. According to Conkin (2006): 1) the problem is not understood until after the formulation of a solution; 2) wicked problems have no stopping rule; 3) solutions to wicked problems are not right or wrong; 4) every wicked problem is essentially novel and unique; 5) every solution to a wicked problem is a 'one shot operation‘; 6) wicked problems have no given alternative solutions.

Acclimation of Russian forests to Climate Change

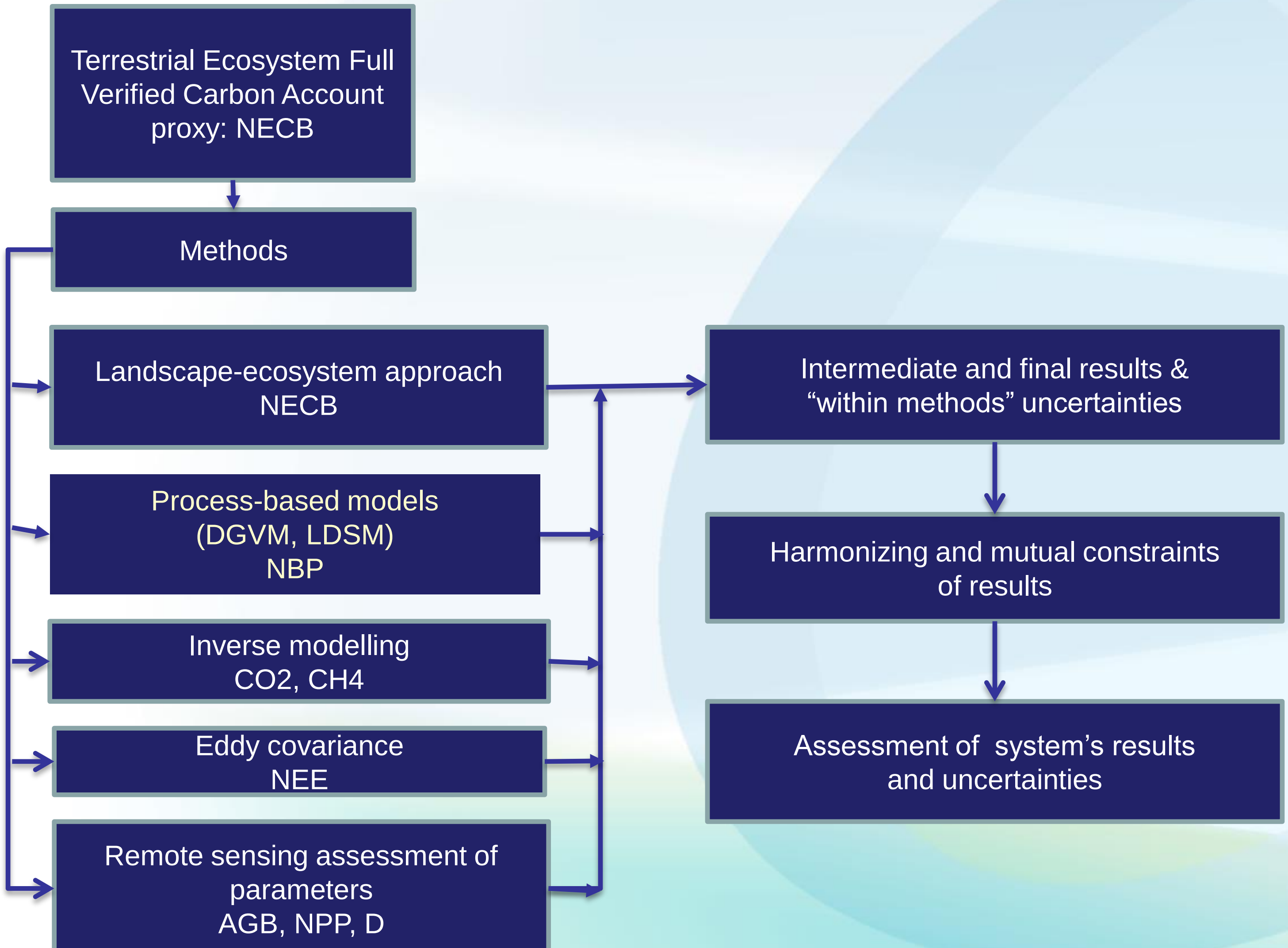


Temporal dynamics of BEF:
above ground wood (red)
roots (blue)
foliage (green)



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

Structure of FCA of forest ecosystems



Landscape-ecosystem approach: an empirical background of FCA

- As comprehensive as possible following the requirements of the applied systems analysis
- Relevant combination of flux- and pool-based approaches
- Strict mono-semantic definitions and proper classification schemes; harmonization of these with other approaches
- Explicit intra- and intersystem structuring: comprehensive and consistent information background; explicit algorithmic form of accounting schemes, models and assumptions
- Spatially and temporally explicit distribution of pools and fluxes
- Correction of many year 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
- Comparative analysis with independent sources, harmonizing and multiple constraints of the intermediate and final results

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

Information problems – some examples for Russia

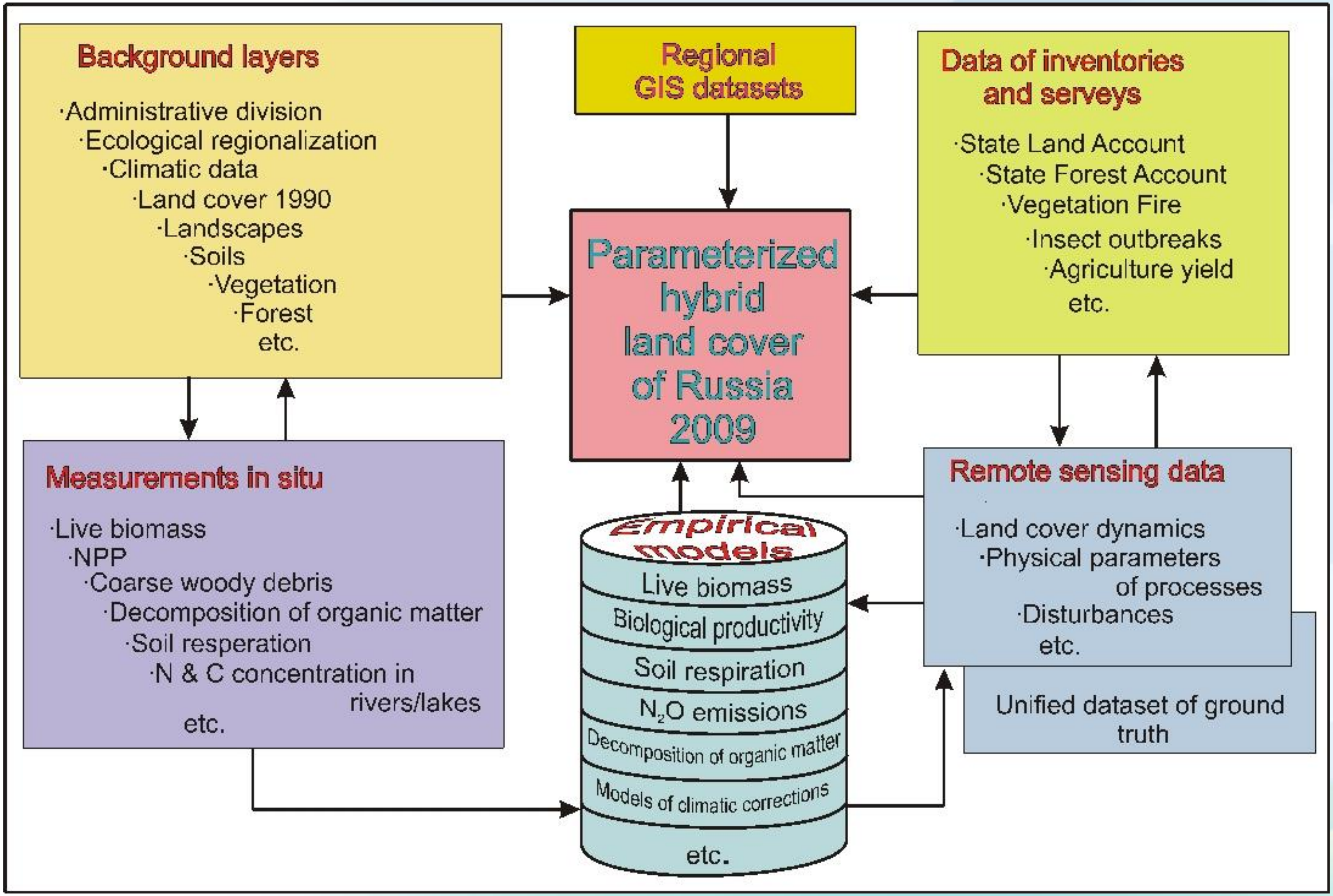
- There are large territories of rapid change in the boreal zone (Hansen et al. 2010, Schepaschenko et al. 2012)
- 63% of Russian forests have been inventoried more that 16 years ago, >50% - more than 25 years ago
- Current situation in Russian forest inventory does not allow to improve the situation in a short time
- Officially reported forest fire data differ from satellite assessment by 5-8 times
- State statistics are obsolete and often biased (e.g. estimates of abandoned arable land are in range from 16 to 75 mullion ha)
- Significant part of small and medium enterprises are out of account
- …

The situation in many other countries of the region is not better

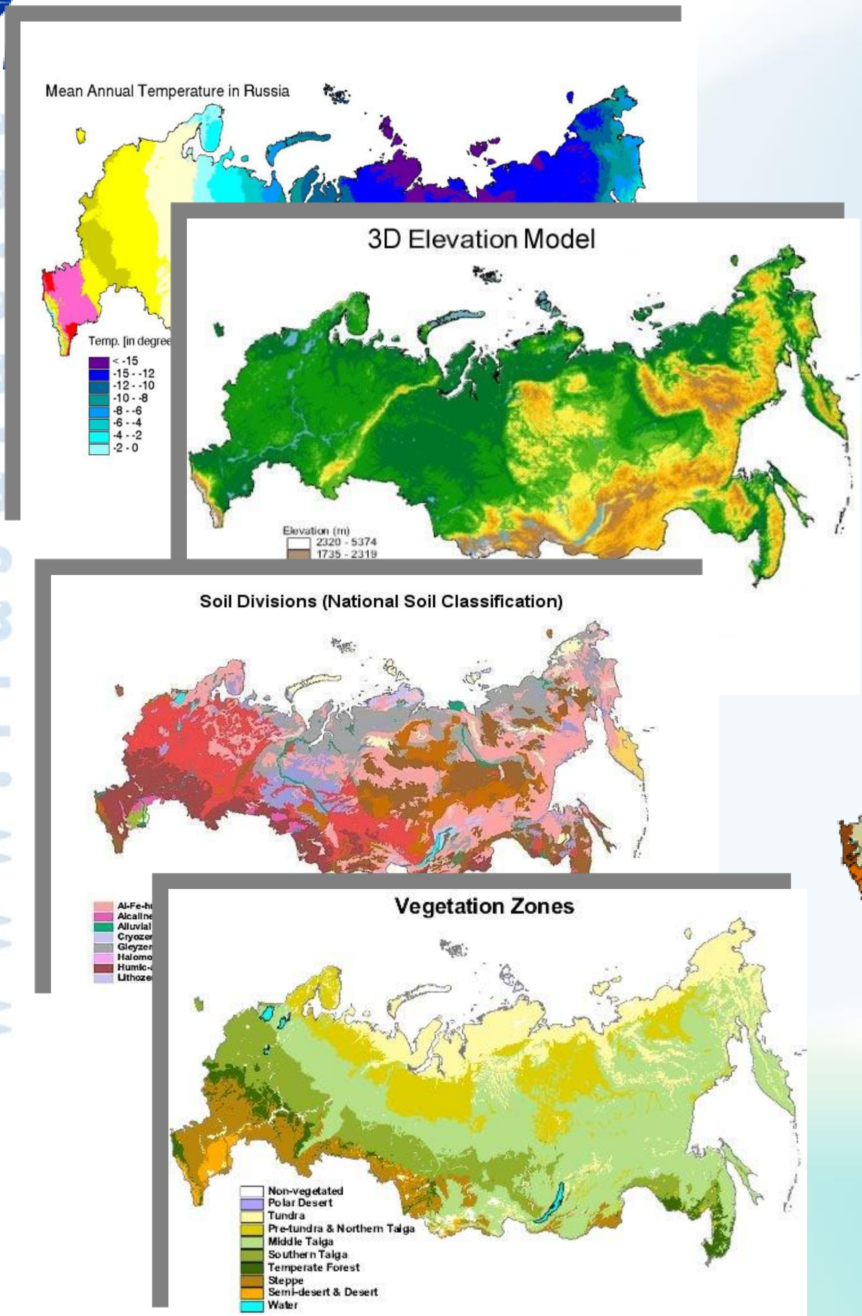
Way to operate: development of an Integrated Land Information System - major principles

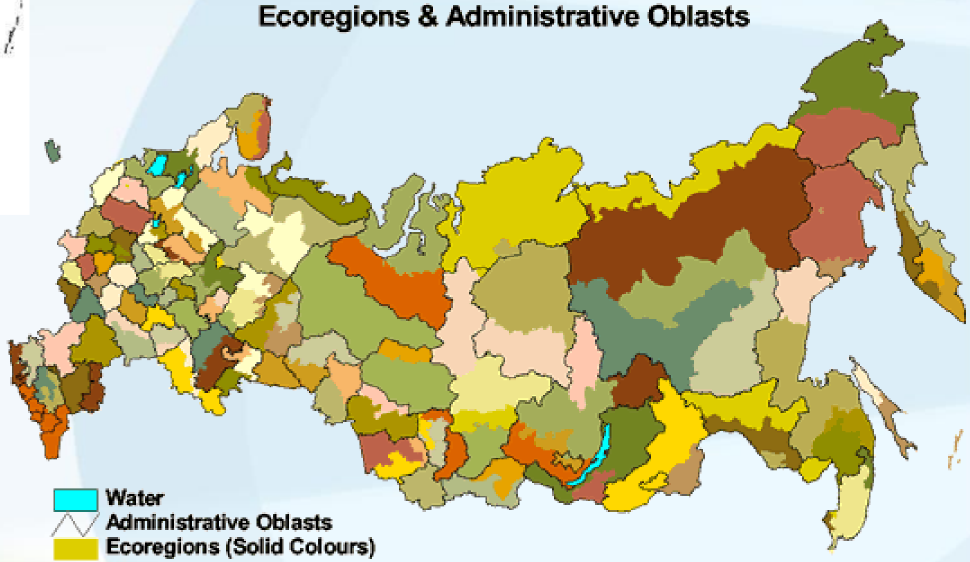
- Aggregation of all knowledge on land cover, ecosystems and landscapes
- A multi-layer and multi-scale GIS
- Basic resolution from 250m to 1km, finer resolution for regions of rapid changes
- As comprehensive as possible attributive databases
- Complimentary use of different relevant sources
- Particular role of “multi-RS” concept
- Certainty of data that are included in the ILIS should be known
- Relevant updating of information (every 3 years?)

Structure of the Integrated Land Information System of Russia (ILIS)



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





Major requirements to ecological regionalization

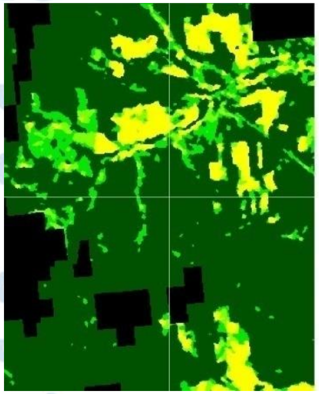
Ecoregions:

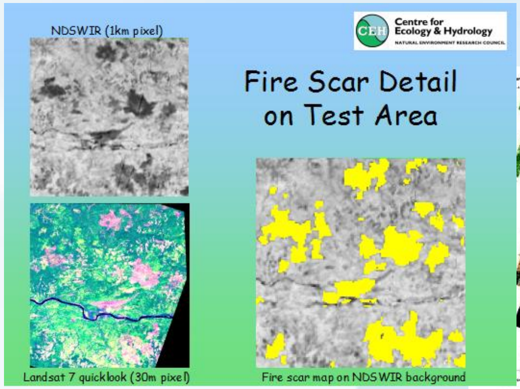
- Homogeneity of growth conditions (climate, soil, surface topography) and, consequently, similarity of vegetation cover – at level of bioclimatic zones (8 for Russia)
- Similar character and intensity of anthropogenic impacts on natural landscapes and ecosystems (systems of land management, air pollution, 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
- Boundary of ecoregions do not cross boundary of subjects of the RF

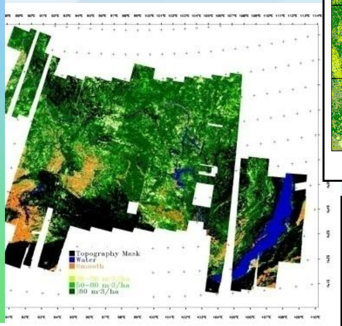
Subecoregions

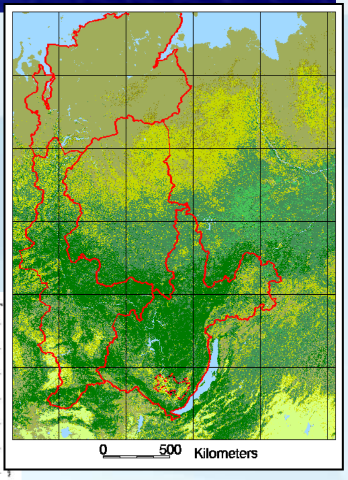
- To some extent an analog of the definition of landscape by N. Solntsev (1962)

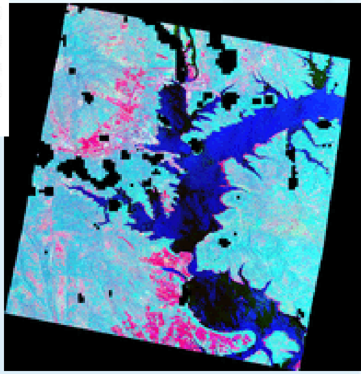
Multi-sensor & multi-temporal remote sensing concept



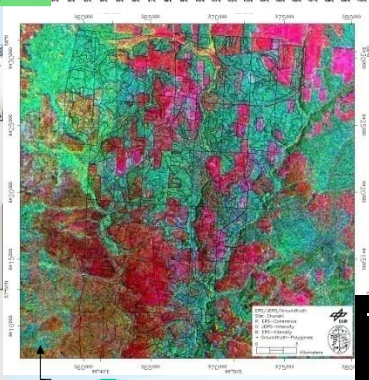


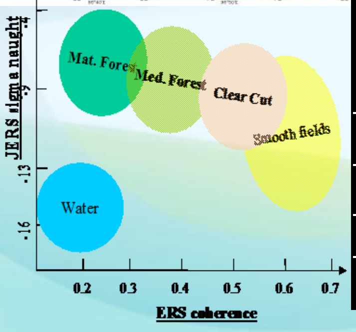


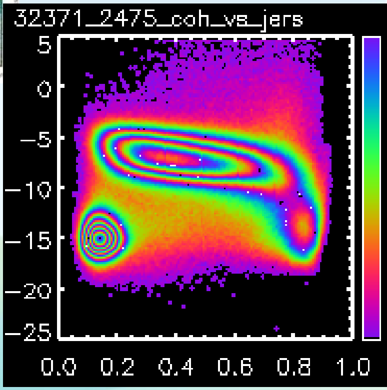




- NOAA AVHRR
- MODIS
- GLC-2000
- MODIS-VCF
- LANDSAT TM
- ENVISAT MERIS
- ENVISAT ASAR
- ERS-1 and ERS-2
- ALOS PALSAR
- etc.

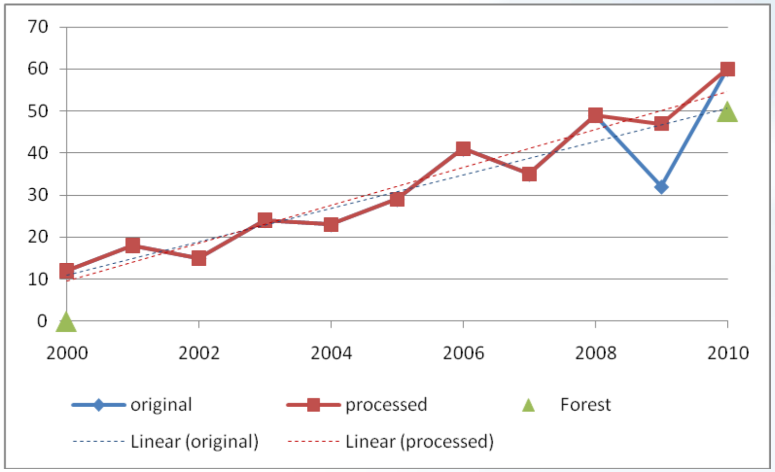


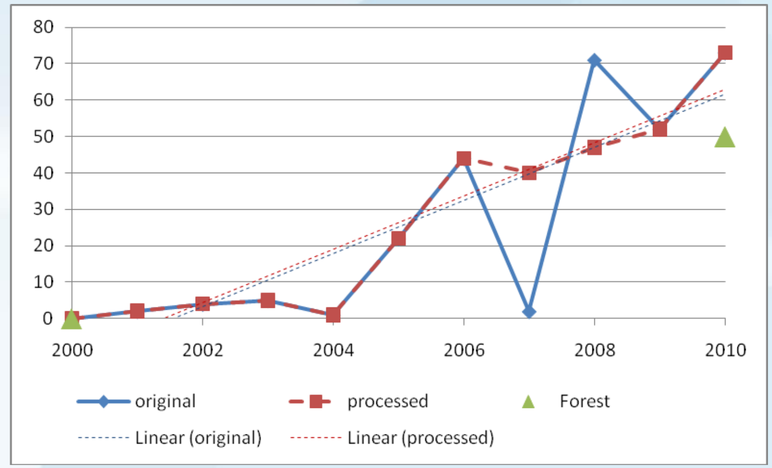


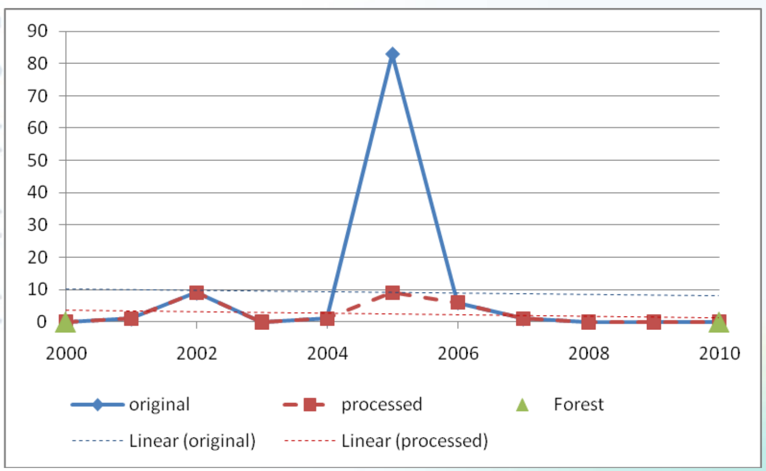


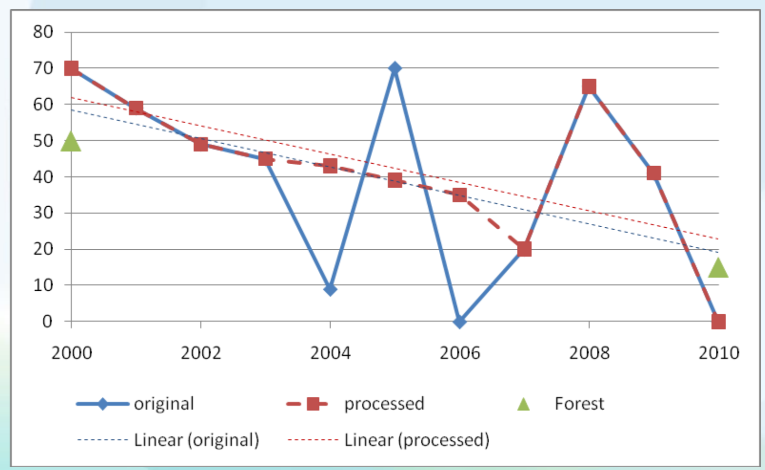
MODIS Vegetation Continuous Fields

(blue line – VCF original; red line - noise reduction)







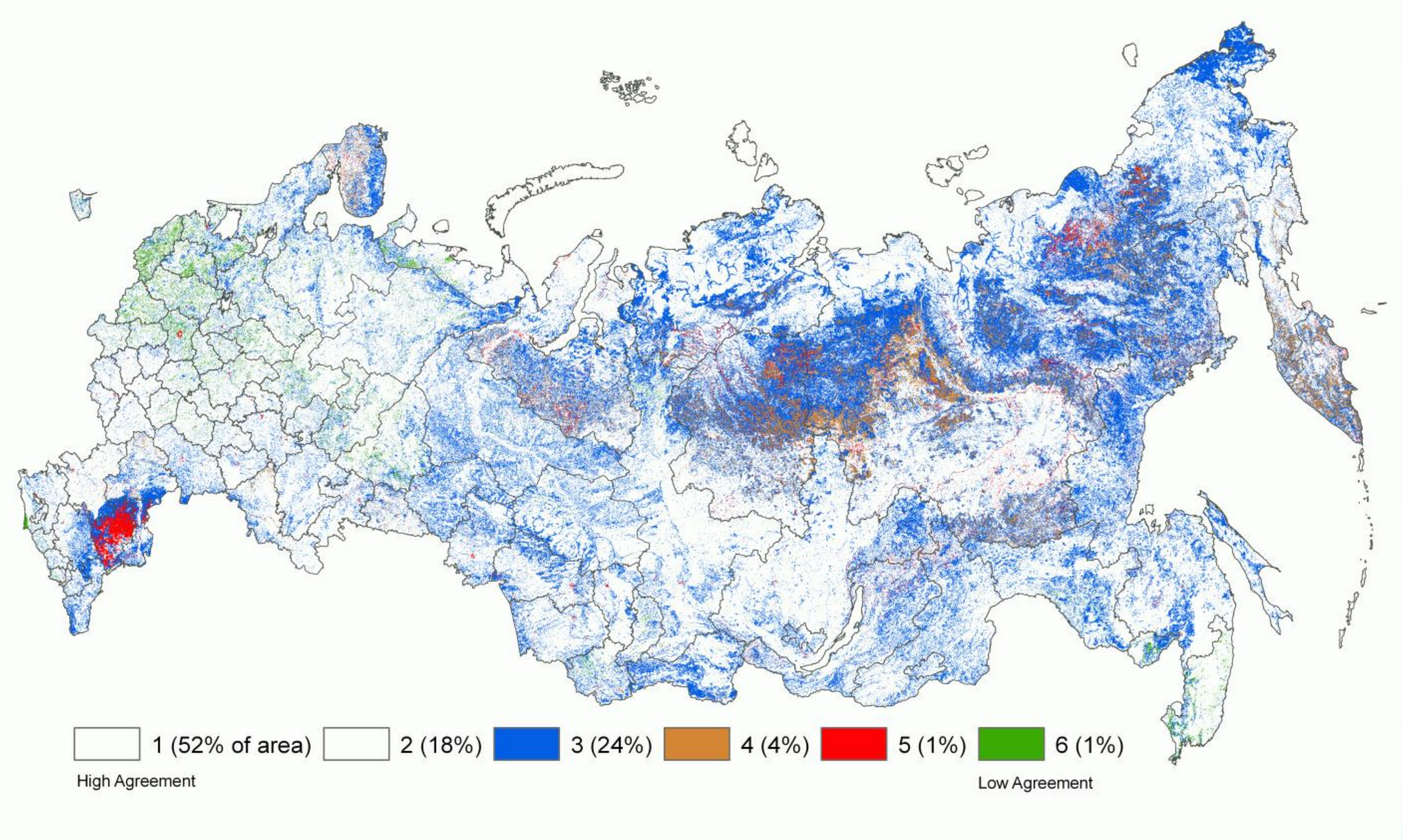


LP DAAC ftp://e4ftl01.cr.usgs.gov/MOLT/MOD44B.005/2010.03.06/

The Land Cover vegetation classes

- **Forest** (86613 units with detailed information about tree species, age class, growing stock, etc.)
- **Open woodland** (32 classes by main tree species and regions)
- **Agriculture** (arable land, hayfield, pasture, fallow, abandoned arable by 87 admin. units)
- **Wetland** (8 classes by 83 regions/zones)
- **Grass- & Shrubland** (about 50 classes)
- **Burnt area**
- **Water**
- **Unproductive**

Agreement/confidence classes of the hybrid land cover map (1 & 2 omitted for clarity)



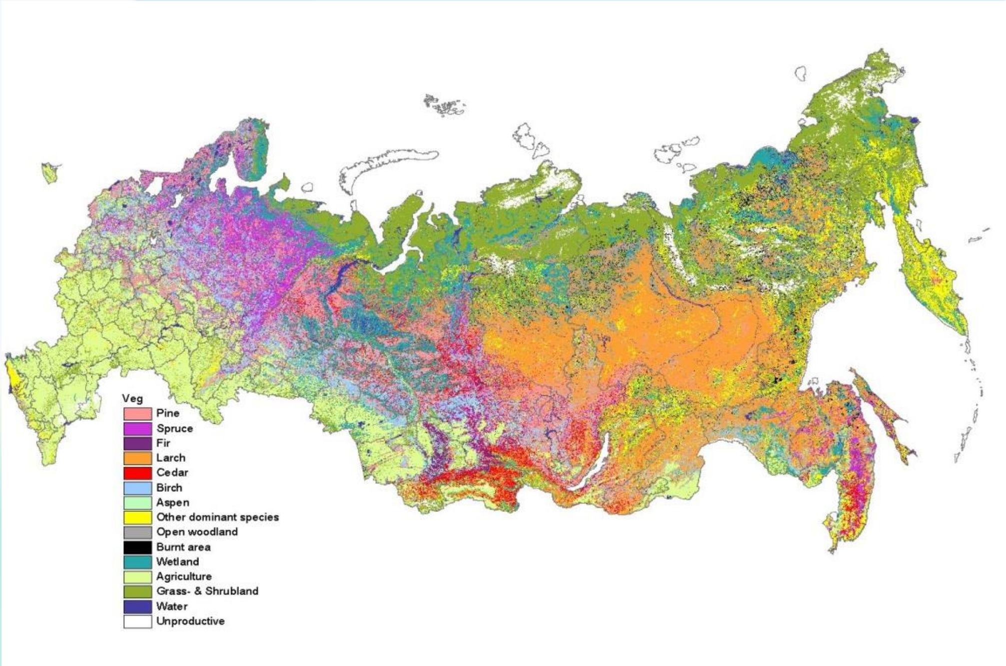
“Citizens science” as a way to improve knowledge of land cover: http://Geo-Wiki.org

- Geo-wiki makes GEO data easy to visualize and analyze.
- Volunteers from around the globe can classify Google Earth imagery, input their agreement/ disagreement with the existing data

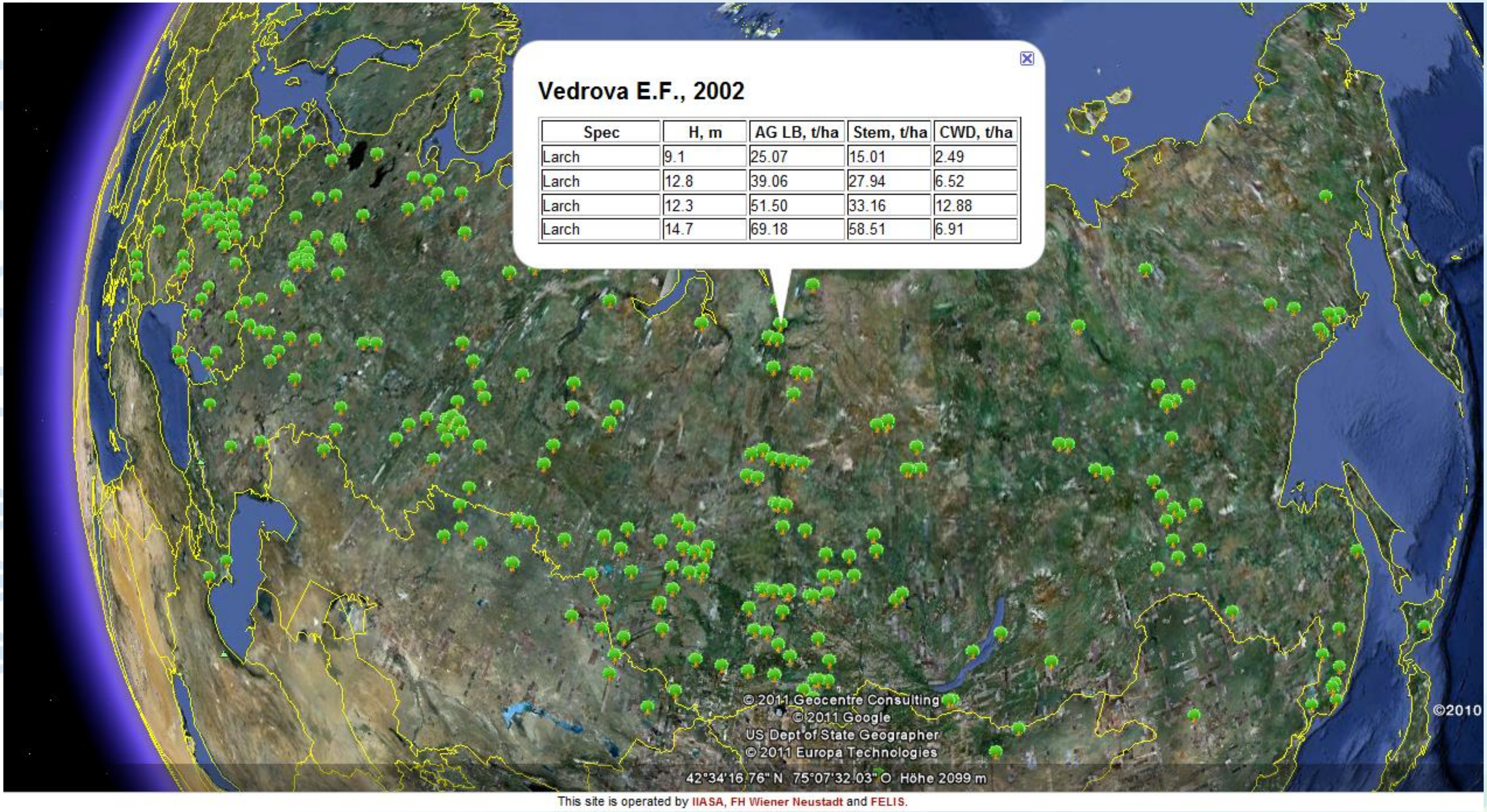
Major attributive databases

- Forest live biomass by components (~ 9100 sample plots)
- NPP of ecosystems (~2500 sample plots)
- Soil respiration (~810 studies, 2254 records)
- State forest account (~aggregated data by ~1700 forest enterprises), state land account
- Forest pathological surveys
- Disturbances
- …

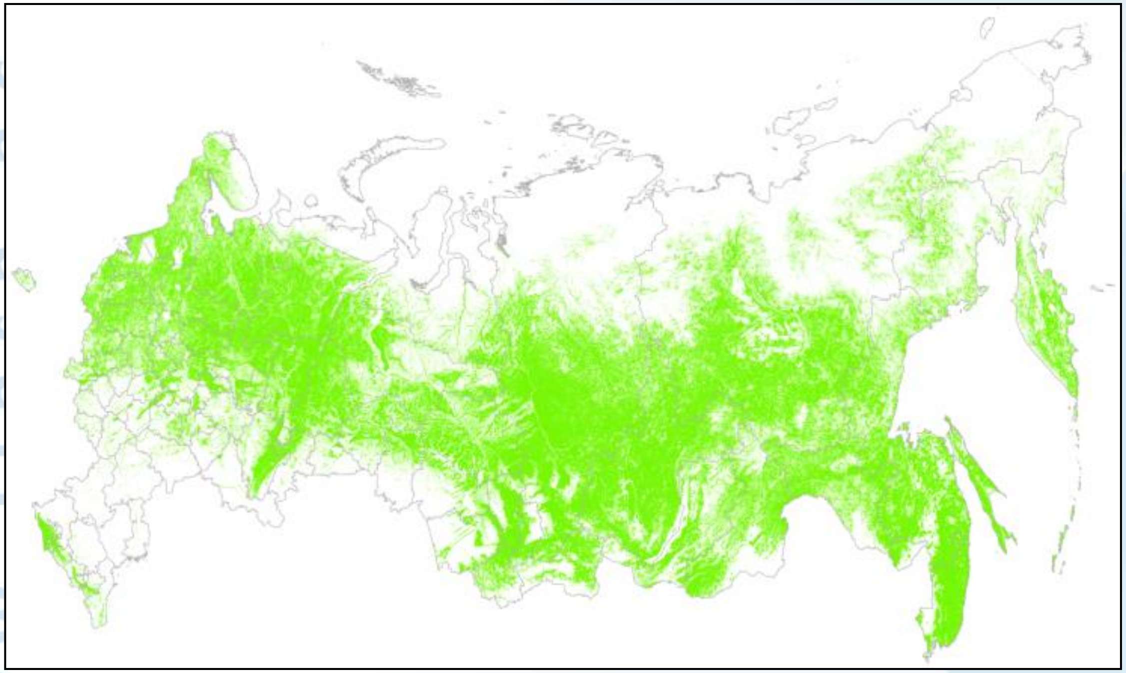
Hybrid land cover of Russia (2009) (1 km resolution)



Database of *in situ* biomass measurements (over 9100 records for Eurasia)



Hybrid land cover: forest mask



Forest area of Russia in 2010 is estimated at (Mha)

Total	782.0
Incl. on abond. agr. land	18.2

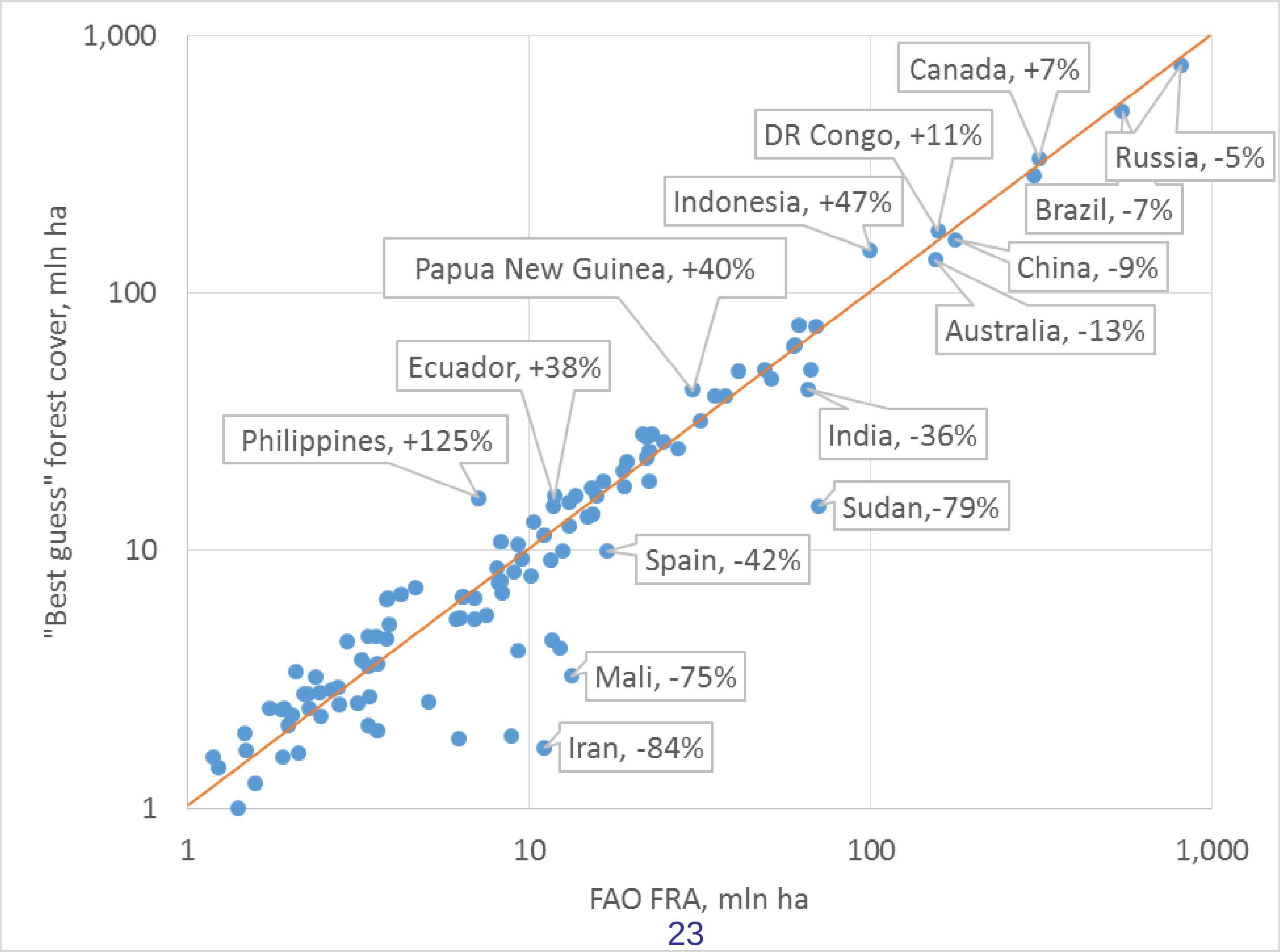
Satellite estimate of forested areas managed by SFA is at 45 M ha less than data of the State Forest Registry

European part	+8%
Asian part	-7%

The input RS products include land covers of 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 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**.**

Source: Schepaschenko et al. 2015

Comparison of forest area estimated by the model and FAO FRA national statistics (Schepaschenko et al. 2015)



Spatial parametrization of land cover

A suitability index (S_{ts}) is calculated for each pair: grid of territory (t) and different information sources (e.g. statistic records). The source is allocated to the most suitable place within the territory unit (forest enterprise, administrative region).

Suitability index (S_{ts}) is the quantitative correspondence of an information source (e.g. forest or land account) and spatial (remote sensing, GIS) data

$$S_{ts} = \frac{1}{q}\left(\sum_{j=1}^{q}(x_{tj}^{norm} - x_{sj}^{norm})^2\right)^{\frac{1}{2}}$$

$$x_j^{norm} = \frac{x_j - x_{j\min}}{x_{j\max} - x_{j\min}}$$

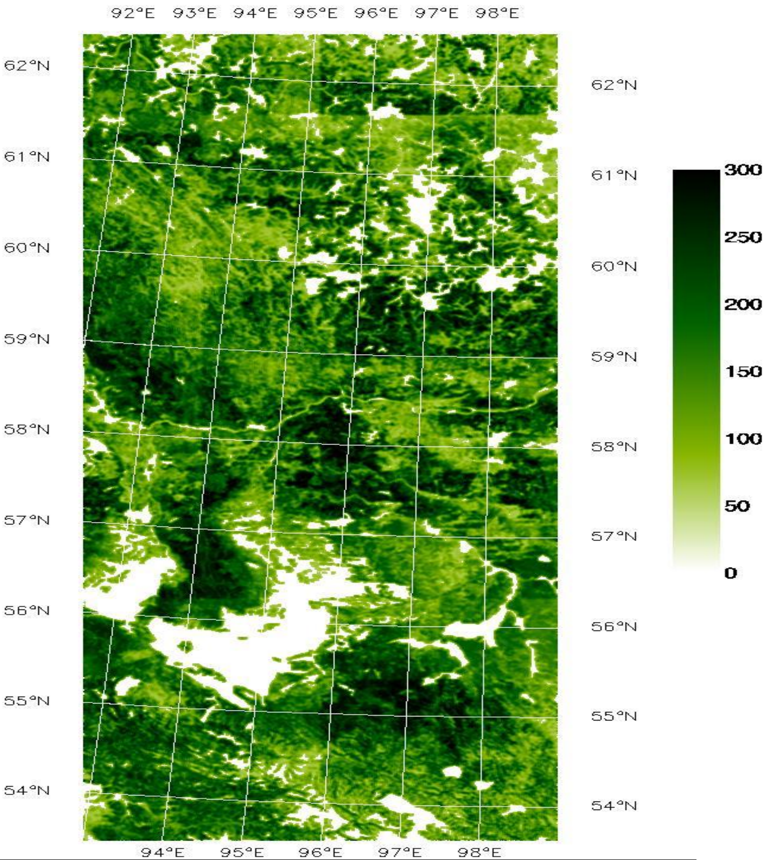
q - number of parameter;

X_{tj}^{norm}, X_{sj}^{norm} - normalized value of parameter j for territory pixel t and statistic record s;

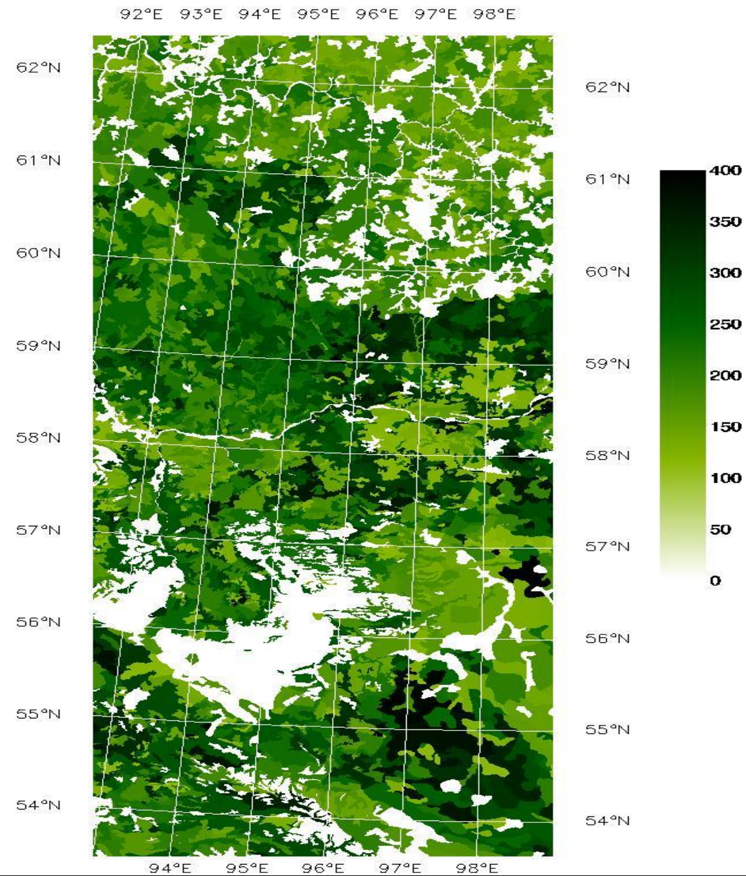
$X_{j\ max}$, $X_{j\ min}$ - maximum and minimum values of parameter j within the certain area (forest enterprise, administrative unit).

Parameter	Statistics	Remote sensing/ GIS
Land cover	Tree species	GLC2000; Modis
Stocking	Relative stocking	VCF trees
Site quality	Site index	Zone; Soil
NPP	Ground NPP	Modis NPP

Radars – a perspective tool for assessing GSV and LB of forests

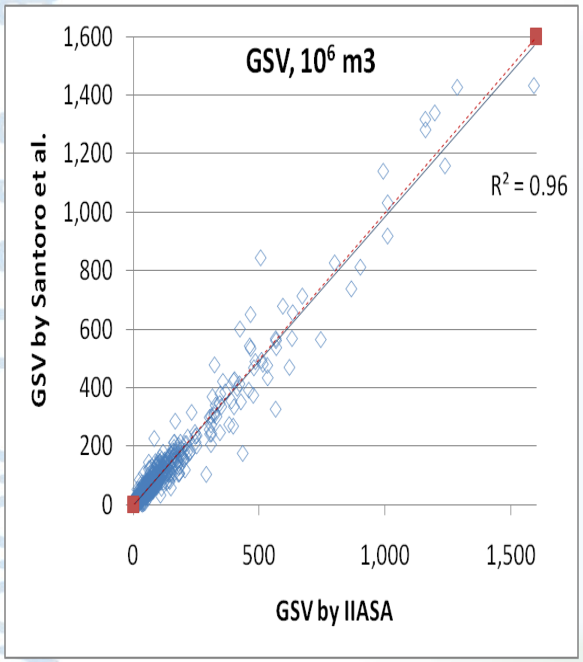


GSV (m3/ha) – ASAR WS

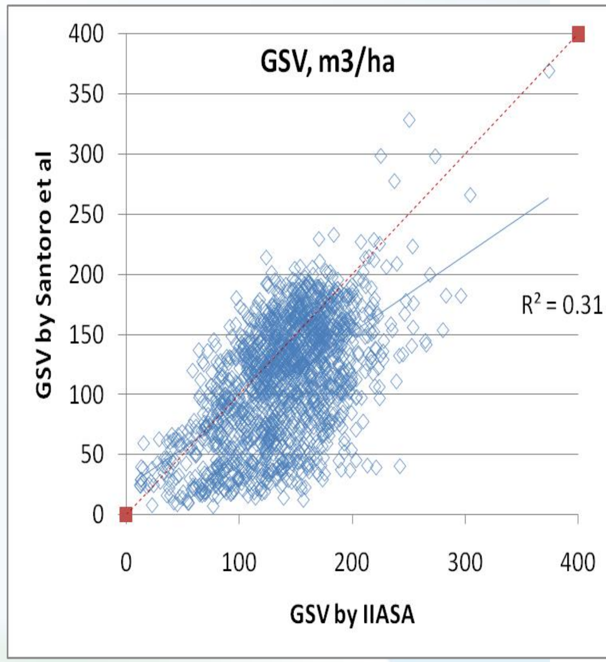


GSV (m3/ha) – forest inventory data

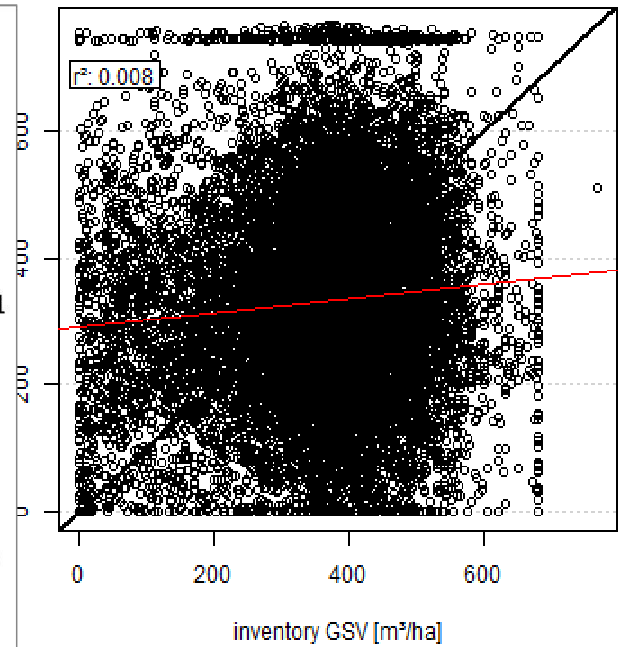
Comparison of Growing Stock Volume estimations IIASA – ground based vs. Santoro – radar based) at the different spatial resolution



forest unit level
(500’000 ha on average)



1km resolution



150m resolution

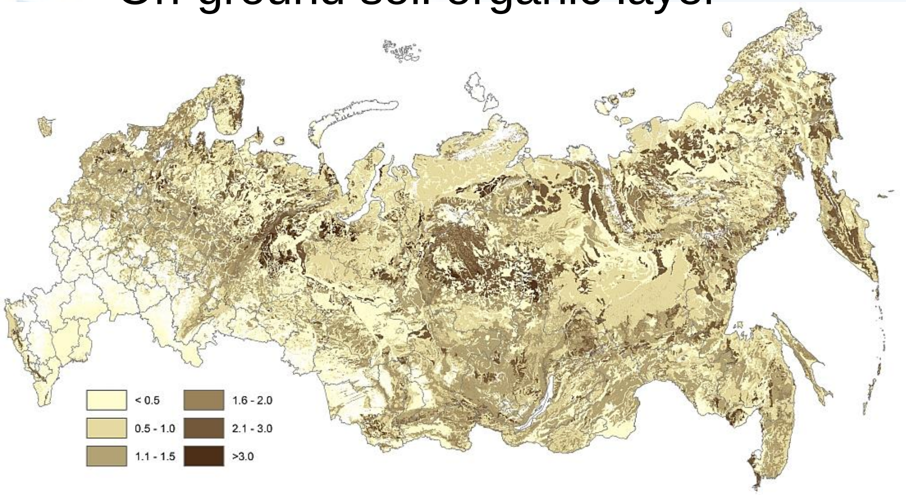
Carbon pools of ecosystems of Russia

Live biomass of all ecosystems

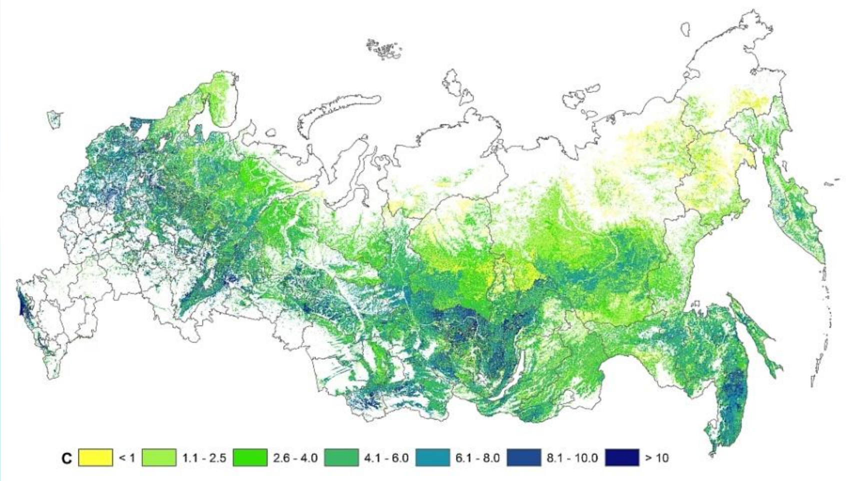
Forest carbon pools (Pg C), 2009

Live biomass	37.5
Coarse woody debris	7.0
Litter carbon	8.3
Soil carbon	136.2
Total	193.4

On-ground soil organic layer



Forest live biomass



An example: Estimating the biomass extension factors

Live biomass (phytomass) fractions were considered:

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

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

where F_{fr} – mass of phytomass by fractions, t ha^{-1};

GS – growing stock, m^3 ha^{-1};

A – average forest stand age, years;

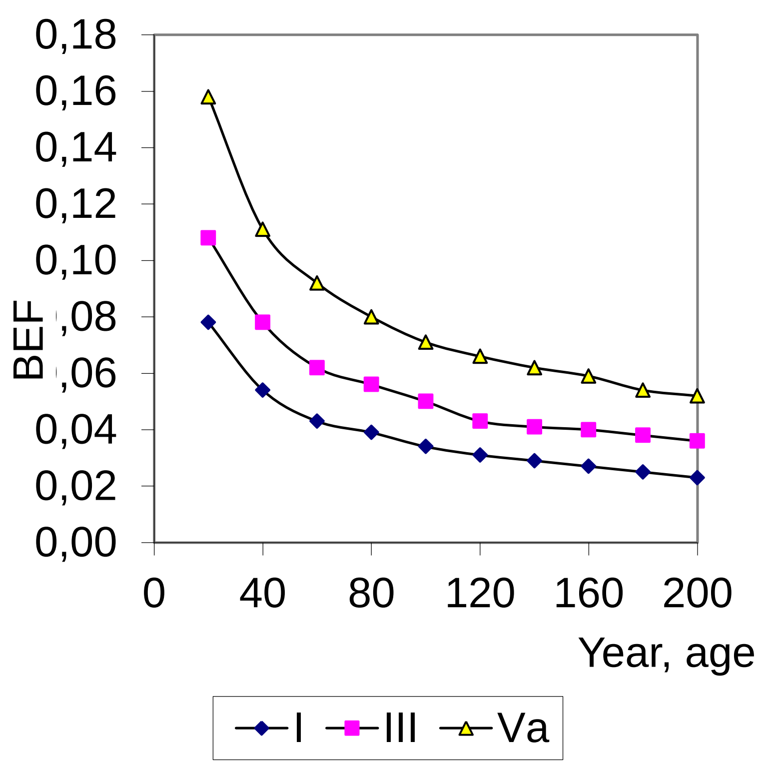
SI – site index (correspond to average stand height at the age of 100);

RS – relative stocking;

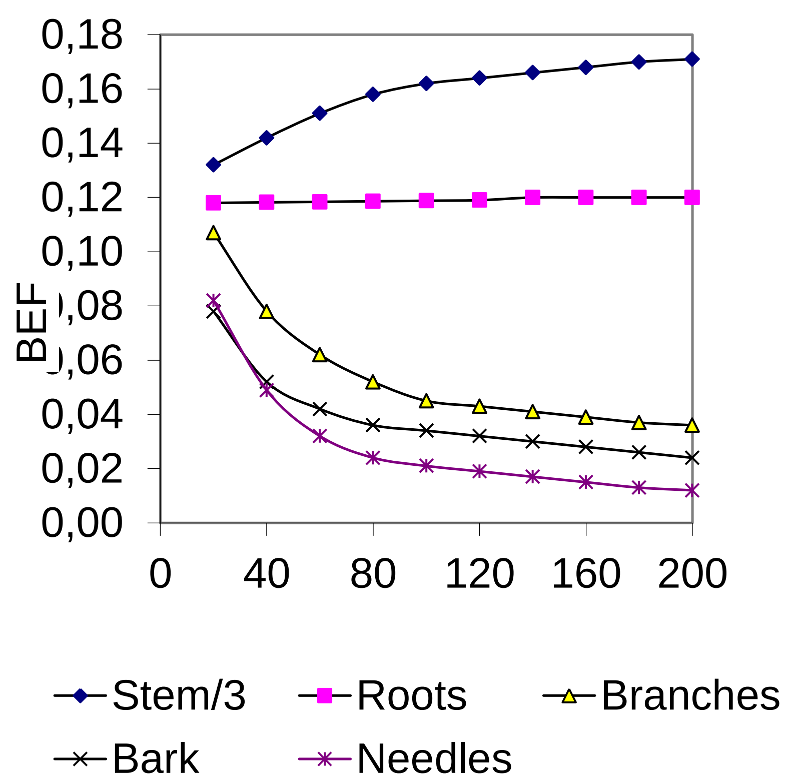
c_0, c_1, …, c_5 – model parameters.

Biomass extension factors for *Pinus sylvestris* (examples for RS 1.0)

Branches as a function of SI

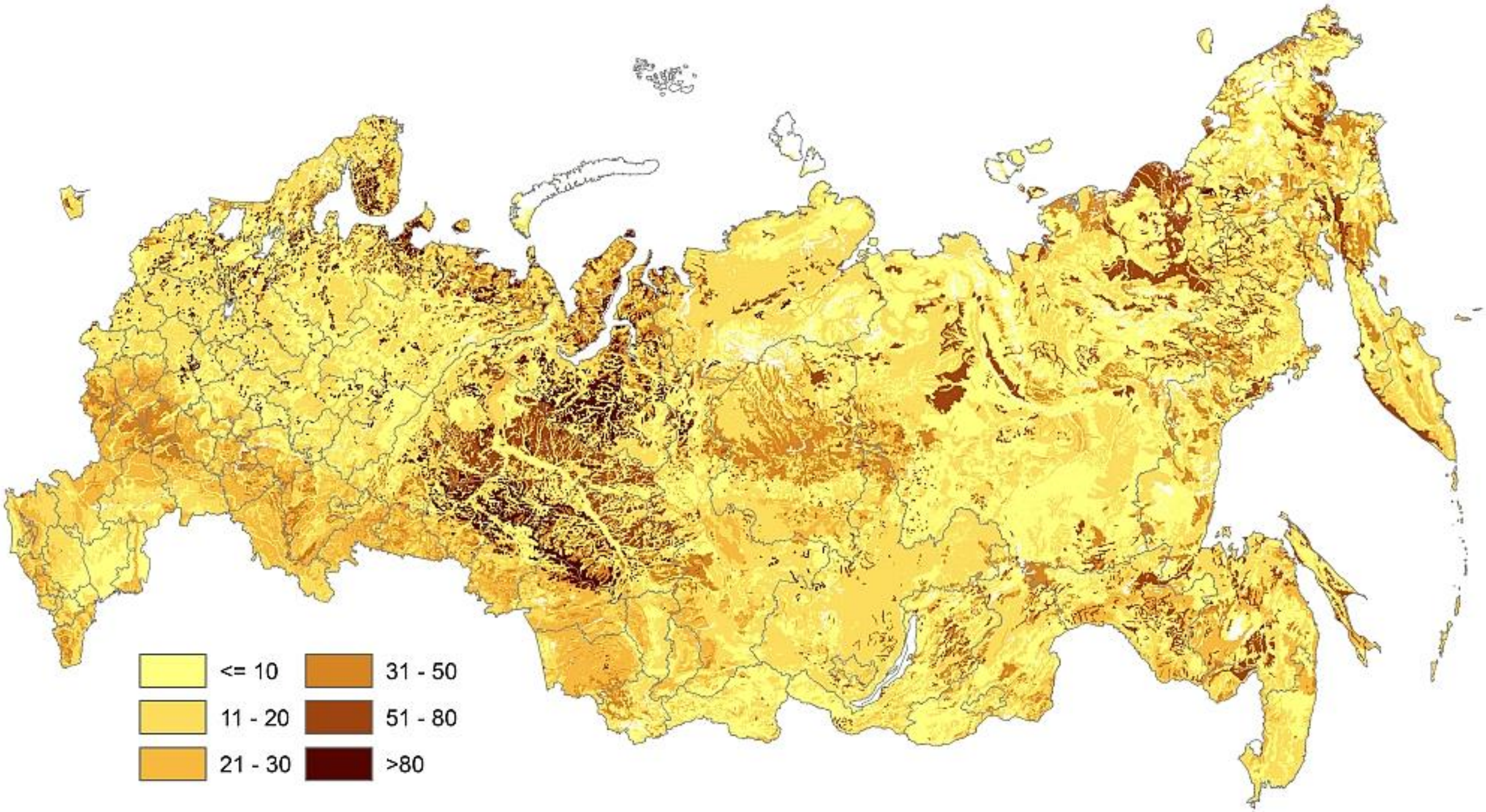


BEF for different biomass components(fractions)



Soil organic matter

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

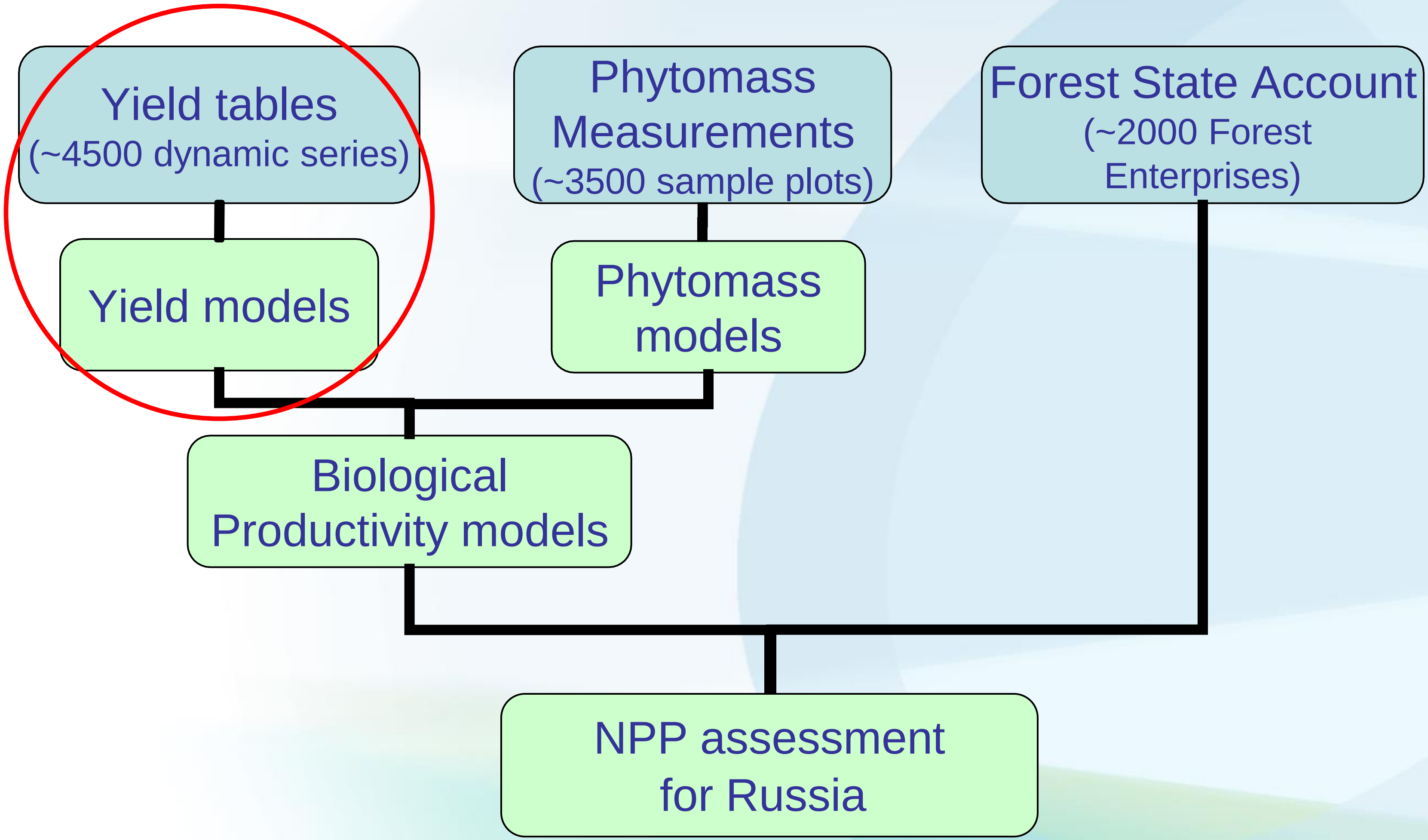


317 Pg C or 19.2 kg C m^{-2}

Reanalysis of empirical forest NPP

- Forest NPP assessment were provided by variety of methods : different destructive methods on sample plots; process-based models including remote sensing applications; methods based on chlorophyll index; rhyzotrons technique; indirect methods (carbon fluxes approaches, nitrogen budgeting); different empirical ratios, etc.
- Destructive measurements of forest NPP in Russia (methods almost exclusively used by the International Biological Program) are very labor consuming and their results underestimate NPP at 20-30% due to the lack of measurements of some components (e.g. underestimation of below ground components, root exudates, Volatile Organic Compounds etc.)
- Accuracy of all indirect methods at regional scale are very low and mostly unknown
- New measurement techniques (e.g. rhizotrons) are practically not available in Russia
- Major part of results reported for Russian forests do not correspond to the current definition of NPP
- Reported estimates of average NPP for Russian forests vary from 204 to 614 g C m^{-2} yr^{-1}

Modeling forest NPP



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

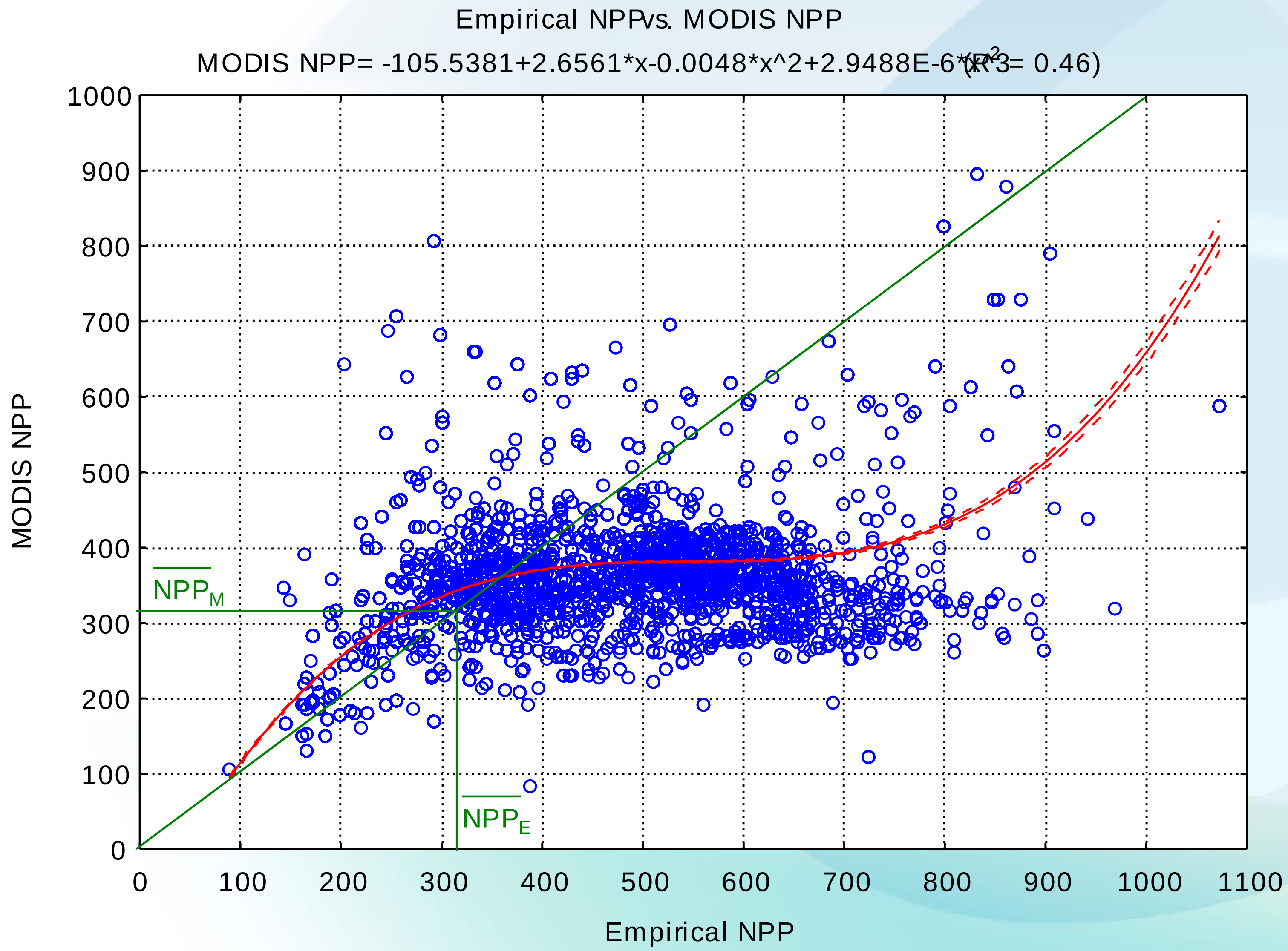
- Total production for stem wood

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

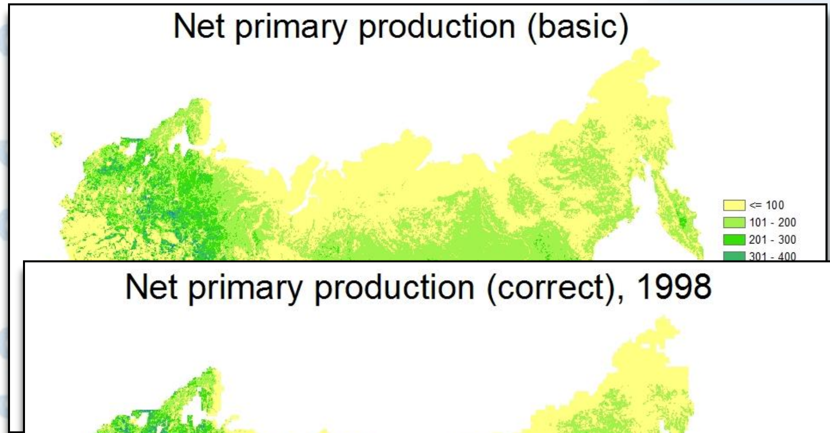
- Total production for foliage

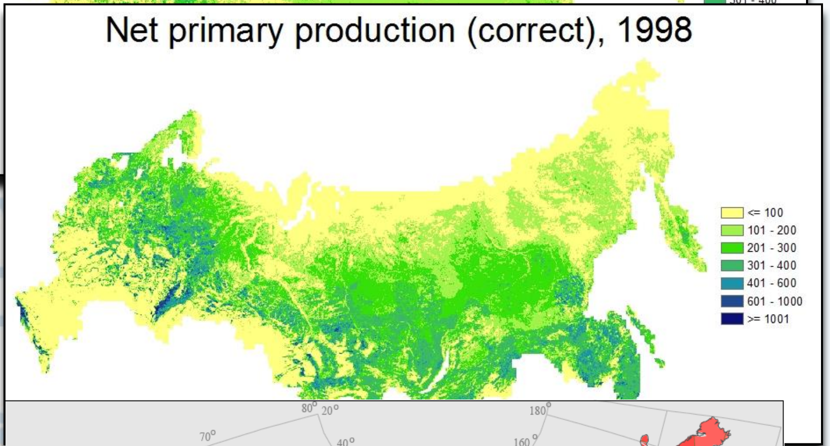
$$\mathrm{TP}F_A^{fol} = \sum_{A=1}^{A} \left[\begin{array}{l} \left(F_A^{fol} - F_{A-1}^{fol} \right) + \left(TPF_{A-l}^{fol} - TPF_{A-l-1}^{fol} \right) + \left(1 + \dfrac{\upsilon}{q} \right) F_{A-1}^{fol} + \\ \dfrac{\eta}{2k} \left[\left(TV_A - GS_A \right) - \left(TV_{A-1} - GS_{A-1} \right) \right]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

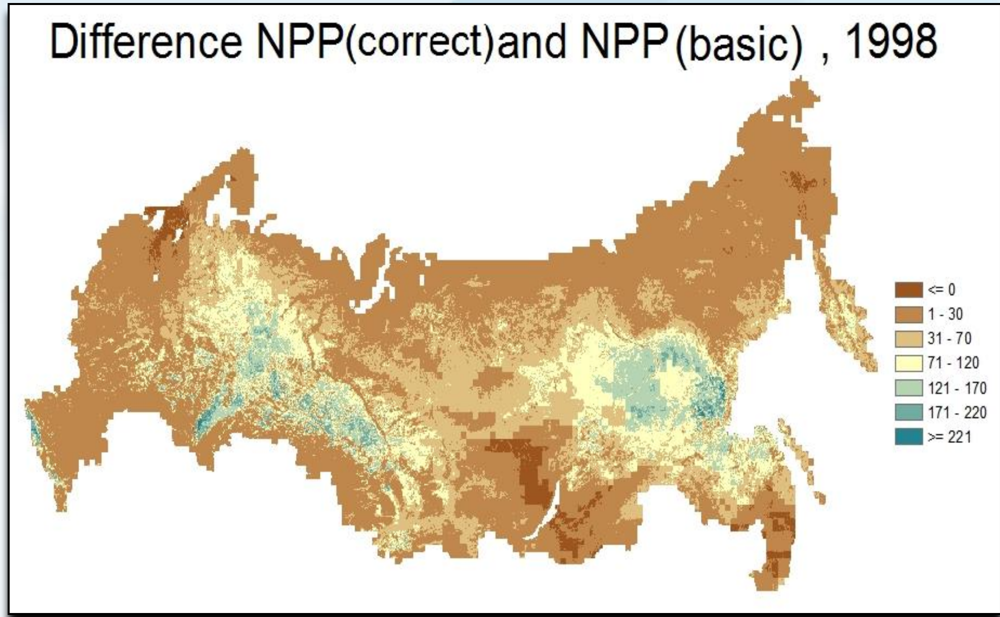
NPP by forest enterprises of Russia: LEA vs MODIS

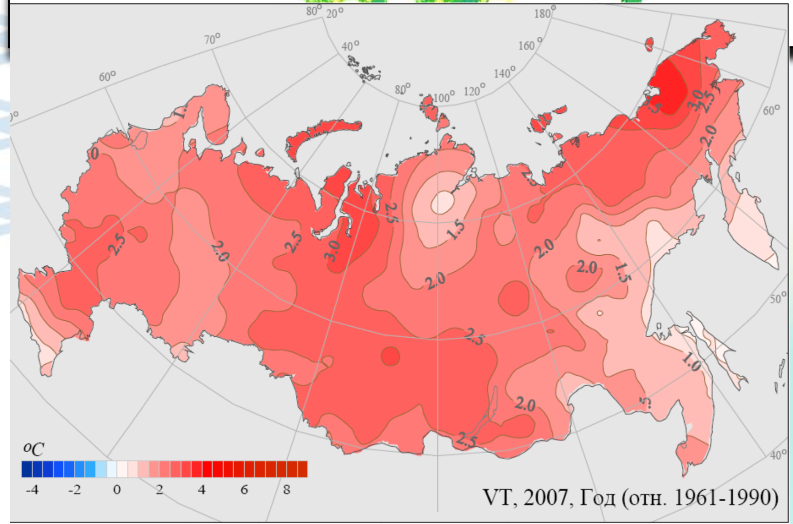


Correction of many year empirical averages for actual climate of individual seasons: Temperature impact on forest NPP









Examination of different regression models

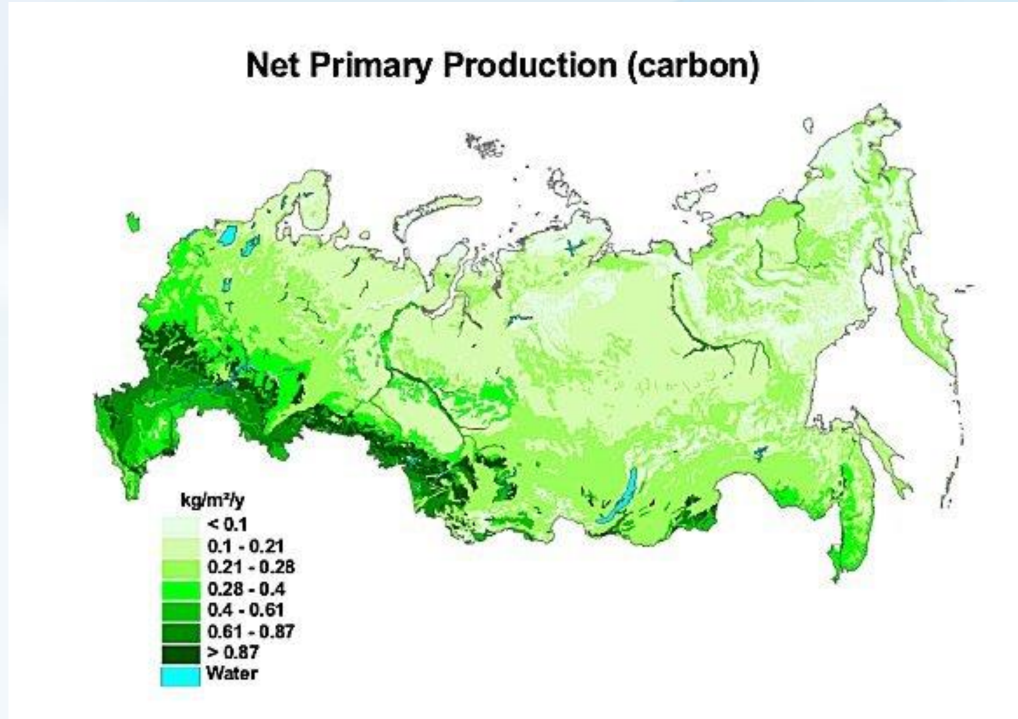
$\Delta NPP = F(\Delta DD>5^oC, \Delta P>5^oC, \Delta[CO_2])$

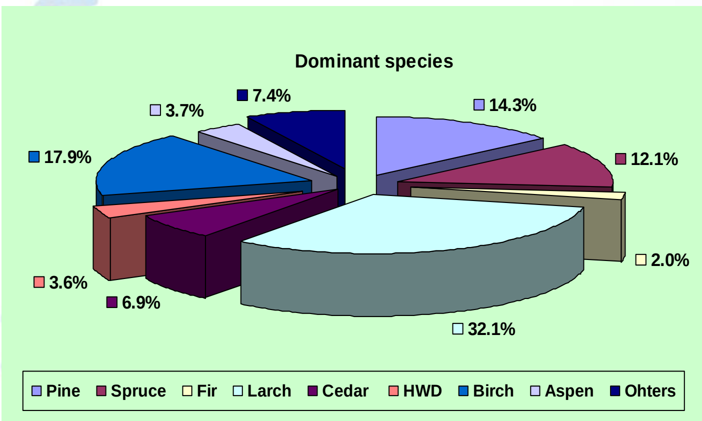
$\Delta HR = \Phi(N>0^oC, P>0^oC, \Delta T>0oC, W)$

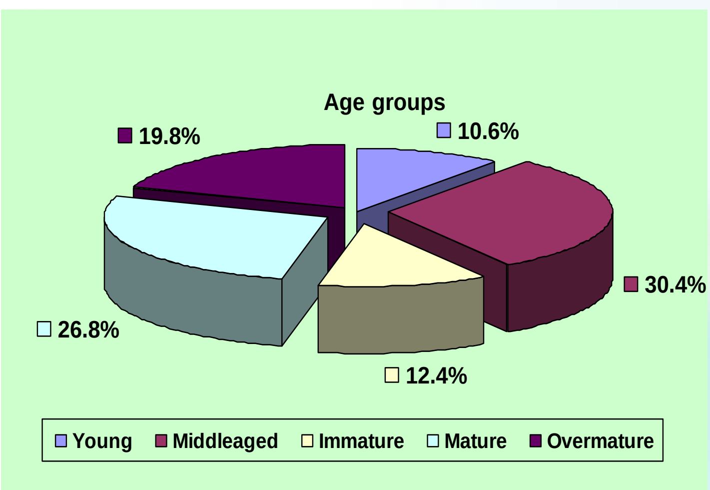
$\Delta HR = \varphi$ (11 seasonal climatic indicators)

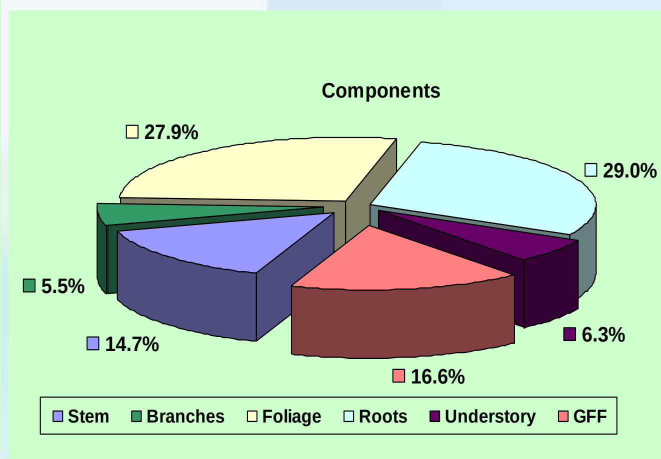
Inter-seasonal variability of NPP can reach 15-30%, dependently of size of area

Net Primary Production of Russian Forests (2009)









NPP of forests 2.62 Pg C yr^{-1} or 319 g C ha^{-1} yr^{-1} (55% of the total NPP of terrestrial ecosystems) Uncertainty 7% (CI 0.9)

Heterotrophic soil respiration: Initial data

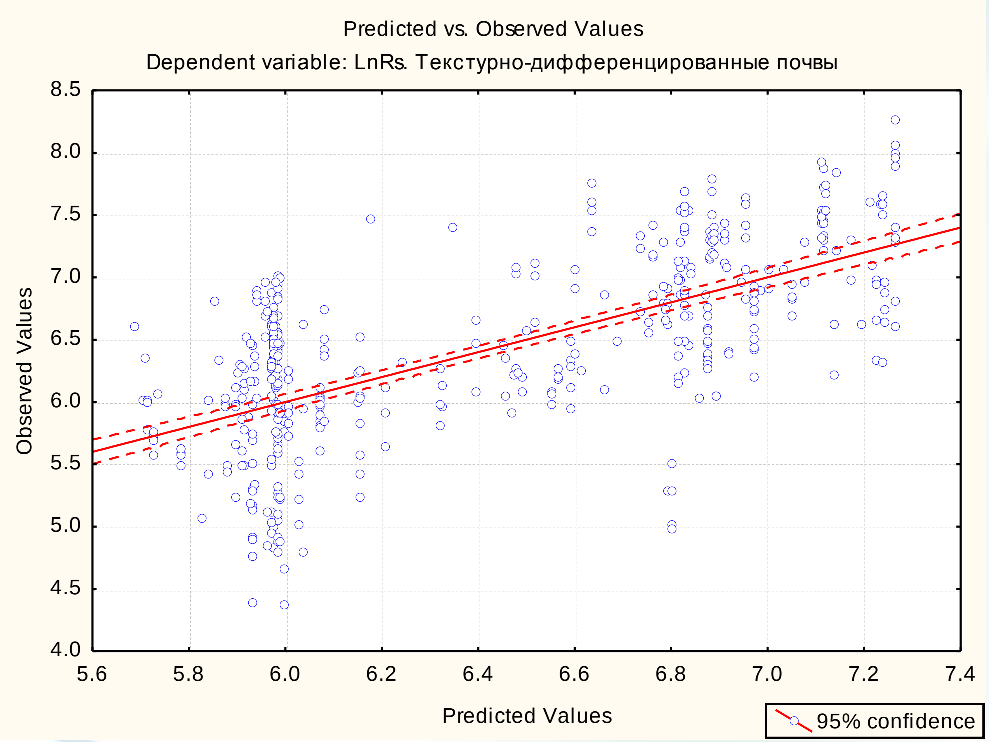
- Soil map of the Russian Federation 1:2.5 Mio (Fridland, 1988)
- Hybrid land cover (Schepaschenko et al., 2010)
- Database of measurements of organic carbon in soils of Russia (1068 records-Kurganova, Mukhortova, Schepaschenko)
- Global database of soil respiration (3592 records)
- Map of bioclimatic zones (Stolbovoi, McCallum, 2002)
- Administrative map

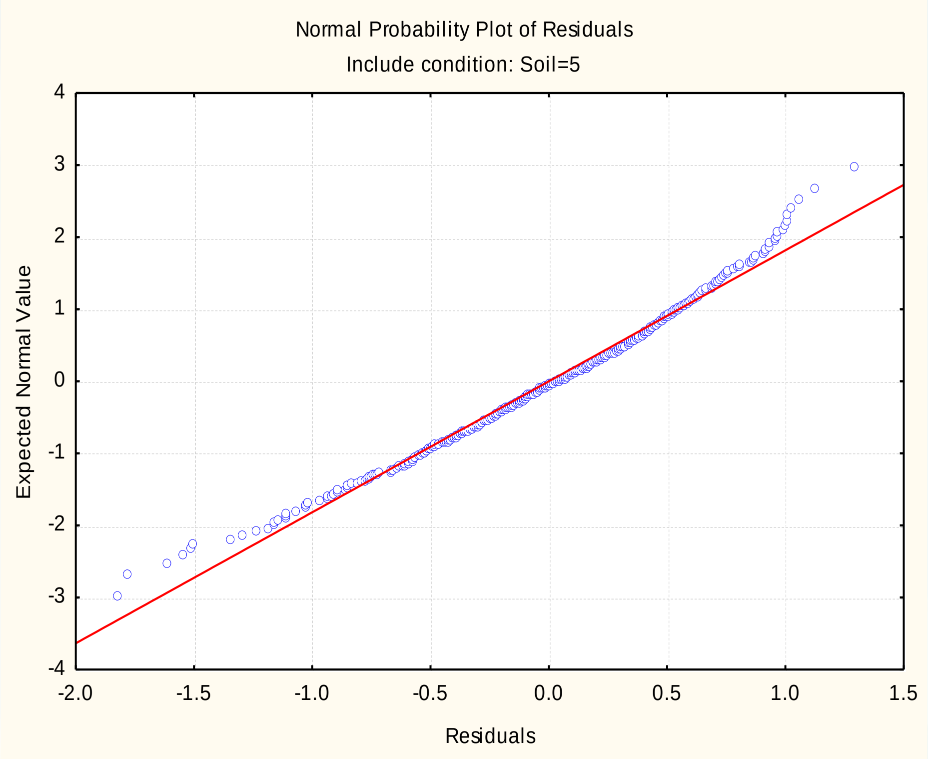
Method of estimation of HSR

- Regression models of total soil respiration (SR) on climate by soil types
- Modification of models by region/bioclimatic zone, vegetation type and disturbance
- Model of share of autotrophic respiration in total SR by soil types
- Regression correction of SR by level of Net Primary Production

Details – in Mukhortova et al. 2014

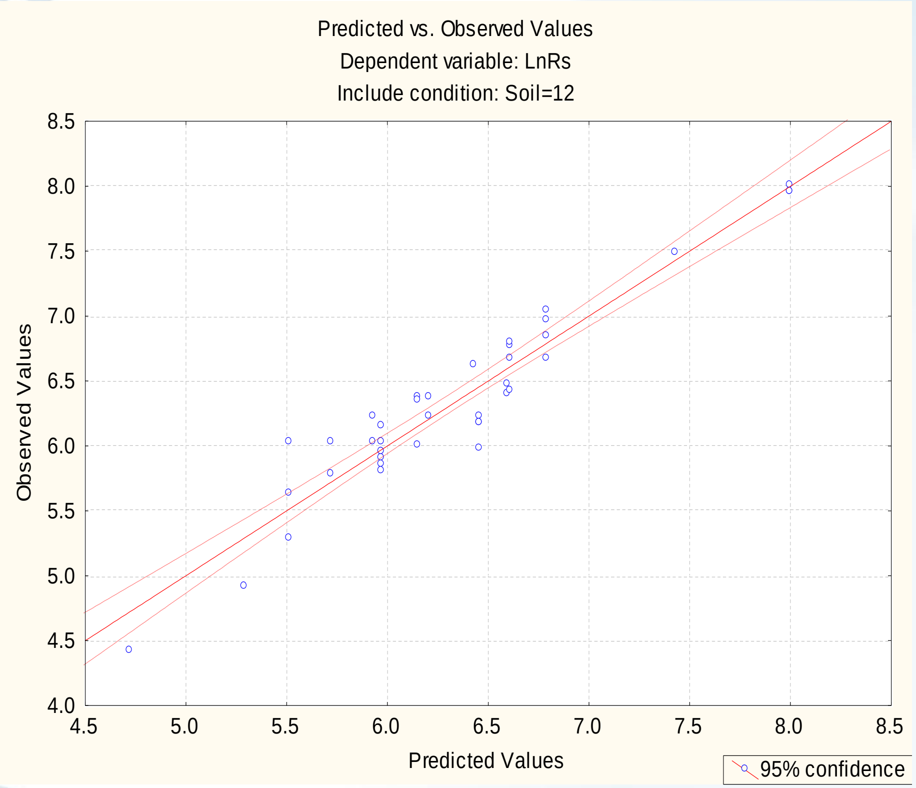
Example: Dependence of total SR upon climate parameters for texture-differentiated soil

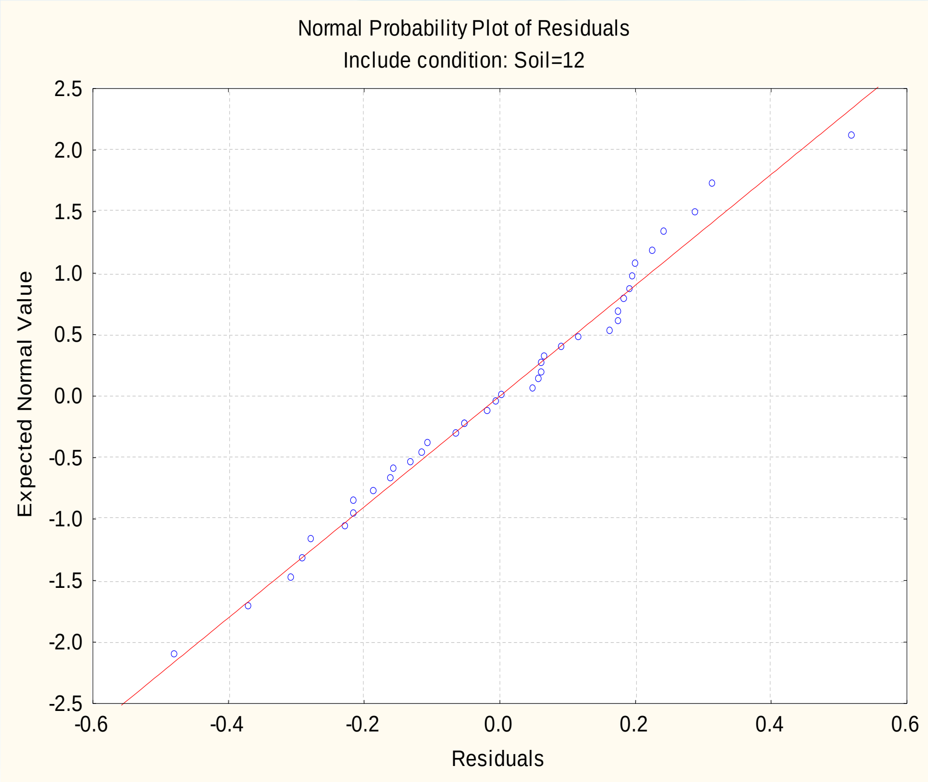




$Ln(Rs)= c_0+c_1*(SUM\_T_0)+c_2*(SUM\_T_{10})$ $R^2=0.45, p<0.01, N=454$

Dependence of total SR upon climate parameters for alluvial soils





$$Ln(Rs)=C_0+C_1*T_{av}+C_2*P_{av}+C_3*(D_0)+C_4*(SUM\_T_5)+C_5*(GTK_5)+C_6*(GTK_{10})$$

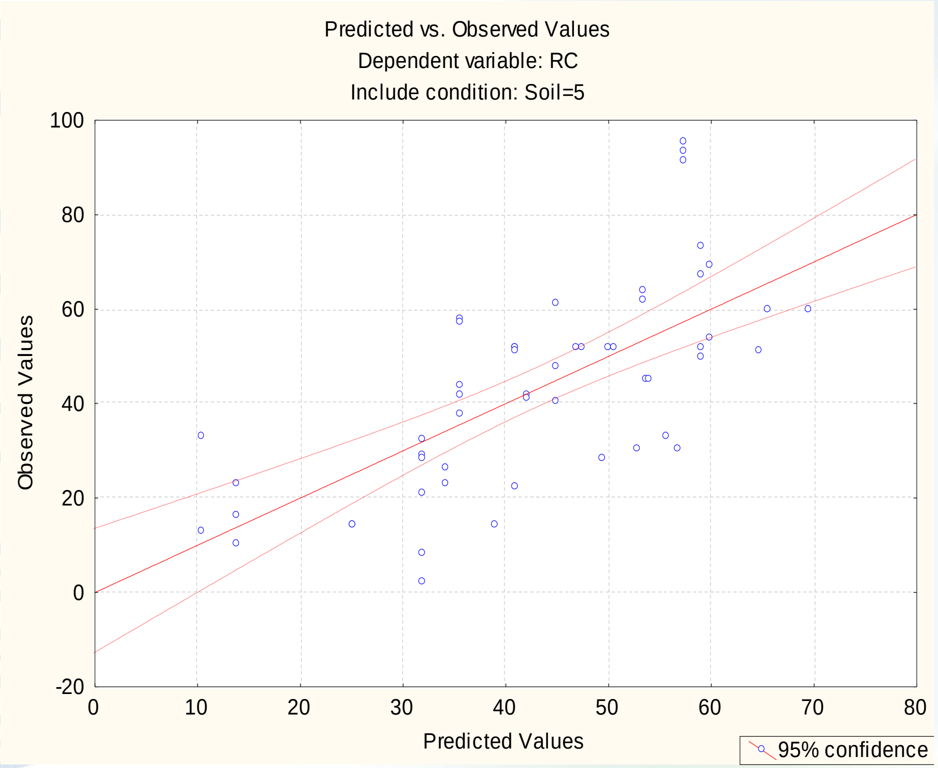
$R^2=0.91$, $p<0.01$, $N=39$

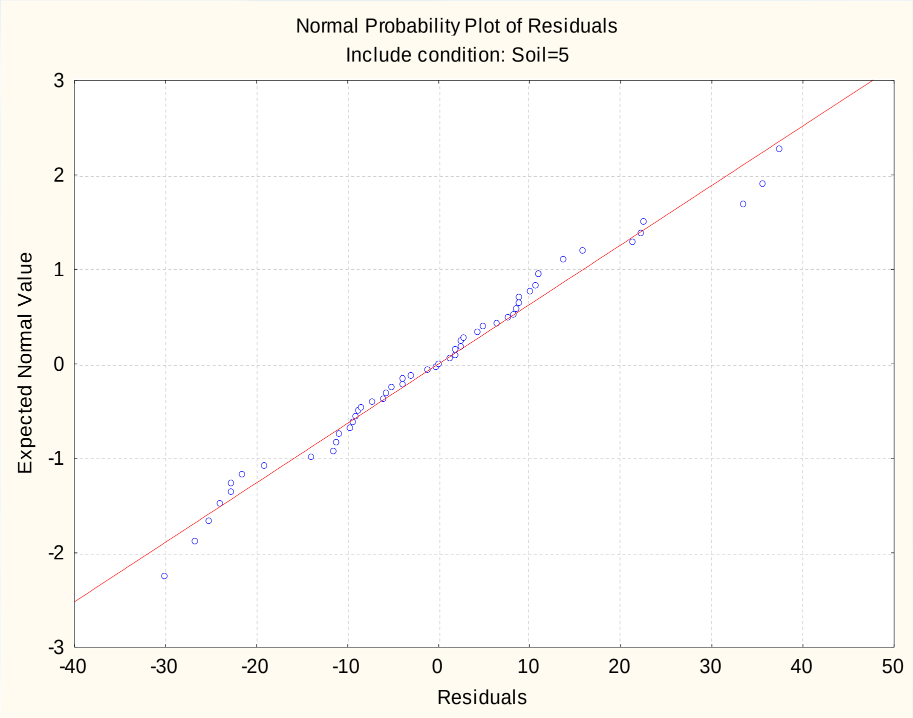
Modification of SHR dependently on region, bioclimatic zone, vegetation type, land use and disturbances

$$C_i = \frac{\bar{R}_{S\,i}^{measured}}{\bar{R}_{S\,i}^{mod}}$$

Corrections are provided by ratio of average measured SHR ($R^{measured}$) to SHR which is calculated by climatic model (R^{mod}) for each region, zone, vegetation type, land use and disturbances

Share of autotrophic respiration for texture-differentiated soils





$AR = C_0 + C_1*D_0 + C_2*D_5 + C_3*GTK_{10} + C_4*IndW$

$R^2=0.47$, $p<0.01$, $N=55$

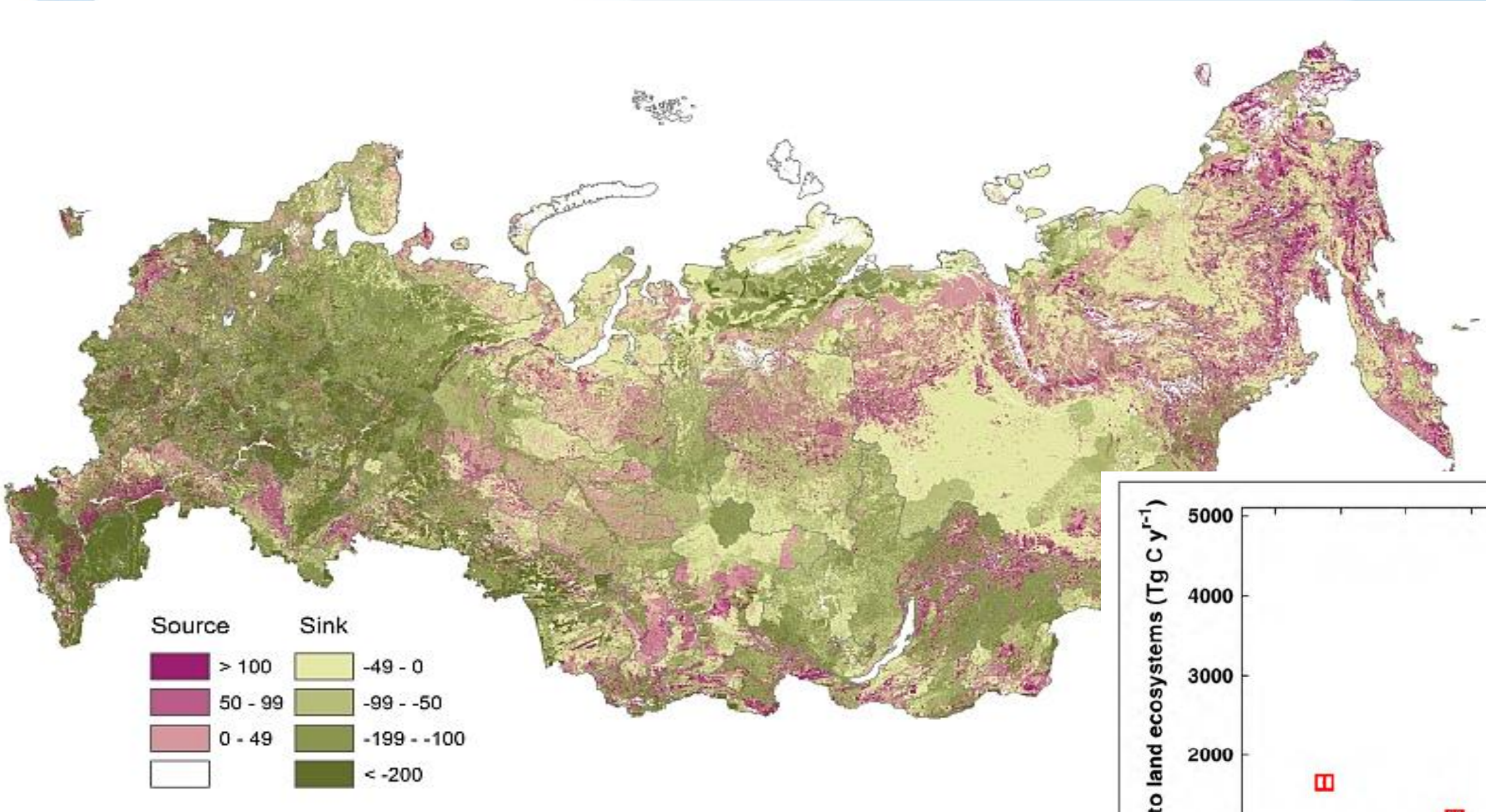
Heterotrophic soil rspiration

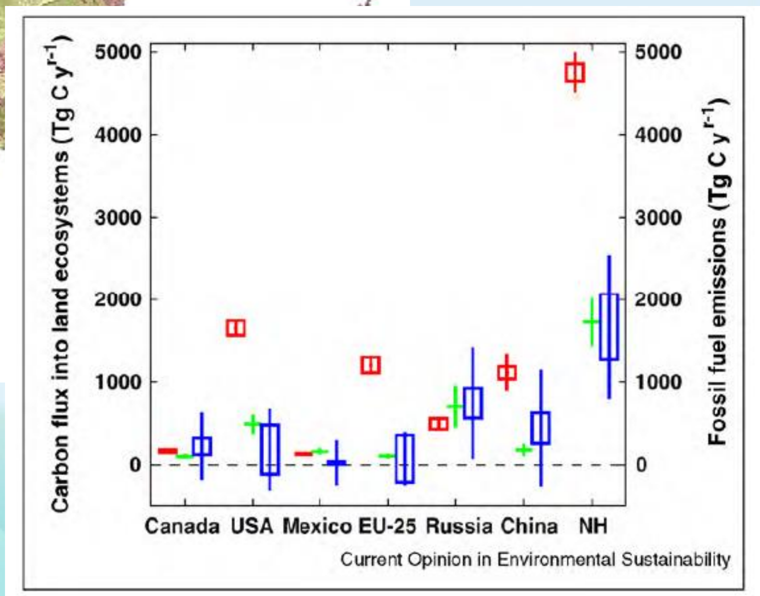
(g C m^{-2})

Need of NECB for all terrestrial vegetation of Russia (average for 2003-2010)

Land classes and components	Flux, Tg C yr-1
Forest	-563±250
Open woodland	-28±21
Shrubs	-22±12
Natural grassland	-58±26
Agriculture land	-32±28
Wetland (undisturbed)	-47±26
Disturbed wetland	+36±20
Wood products	+48±20
Food products (import-export)	+18±16
Flux to hydro- and lithosphere	+81±36
NECB	-567±259

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, ~90% was provided by forests

Source: Shvidenko et al. 2011

Source: Ciais et al. 2010

Uncertainty of the landscape-ecosystem approach (%): average for the period

Carbon pools

- Live biomass ±5
- Dead wood ±10
- Soil ±7-10

Carbon fluxes

- Net Primary Production ±6
- Heterotrophic soil respiration ±8
- Decomposition of dead wood ±12
- Disturbances: fire ± 23, biotic ± 25, wood products ± 25
- Lateral fluxes ±33
- NECB ±23

Inverse modeling

- Estimates for Eurasia, Pg C year^{-1}

Fan *et al*.,1999, *Science*	+0.1±0.7
Bousquet *et al*., 1999, *JGR*	-1.8±1.0
Rodenback *et al*., 2003, *AChPh*	+0.2±0.3
Gurney *et al*., 2004, *GChB*	-0.7±1.0

- Estimates for boreal Asia, Pg C year^{-1}

Maksyutov et al., 2003 (1992-1996)	-0.63±0.36
Gurney et al.,2003 (1992-1996)	-0.58±0.56
Baker et al. (1988-2003)	-0.37±0.24
Patra et al., 2006 (1999-2001)	-0.33±0.78

- Estimates for Russia, Pg C year^{-1}

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
Shvidenko et al., 2010 (2003-2010), LEA	-0.57±0.26

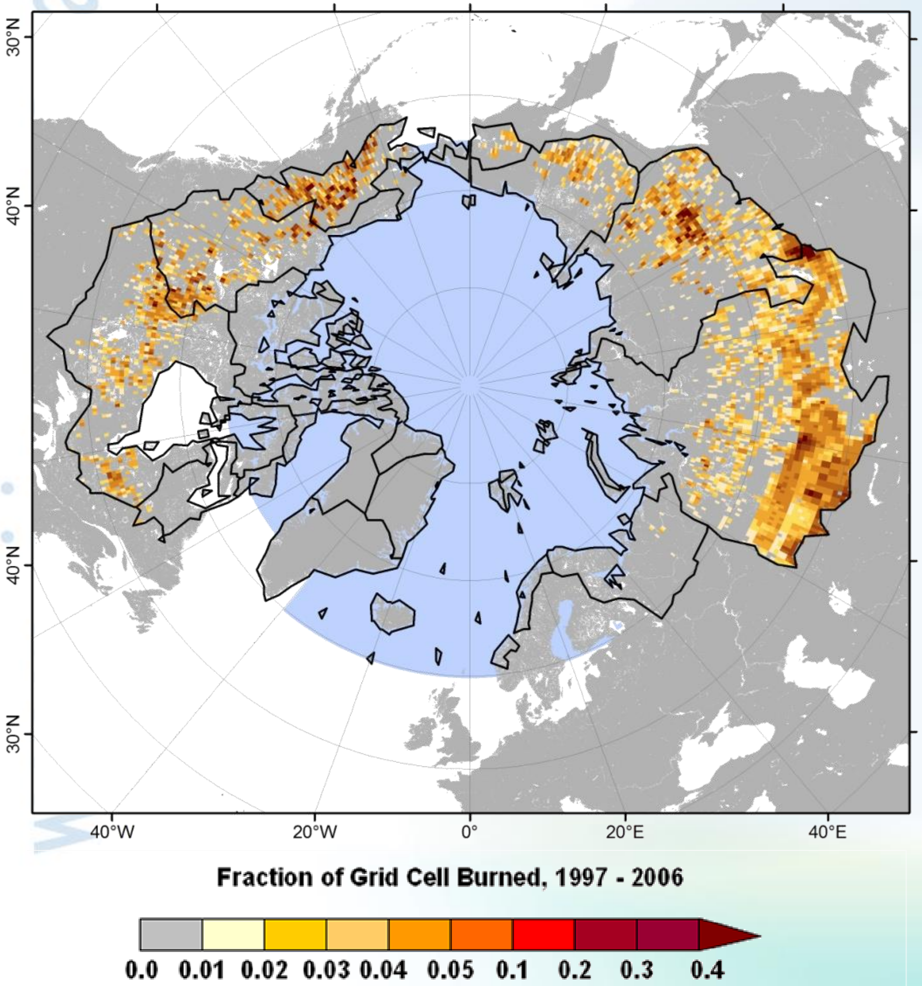
Average DGVM results for Russia (Tg C yr^{-1})

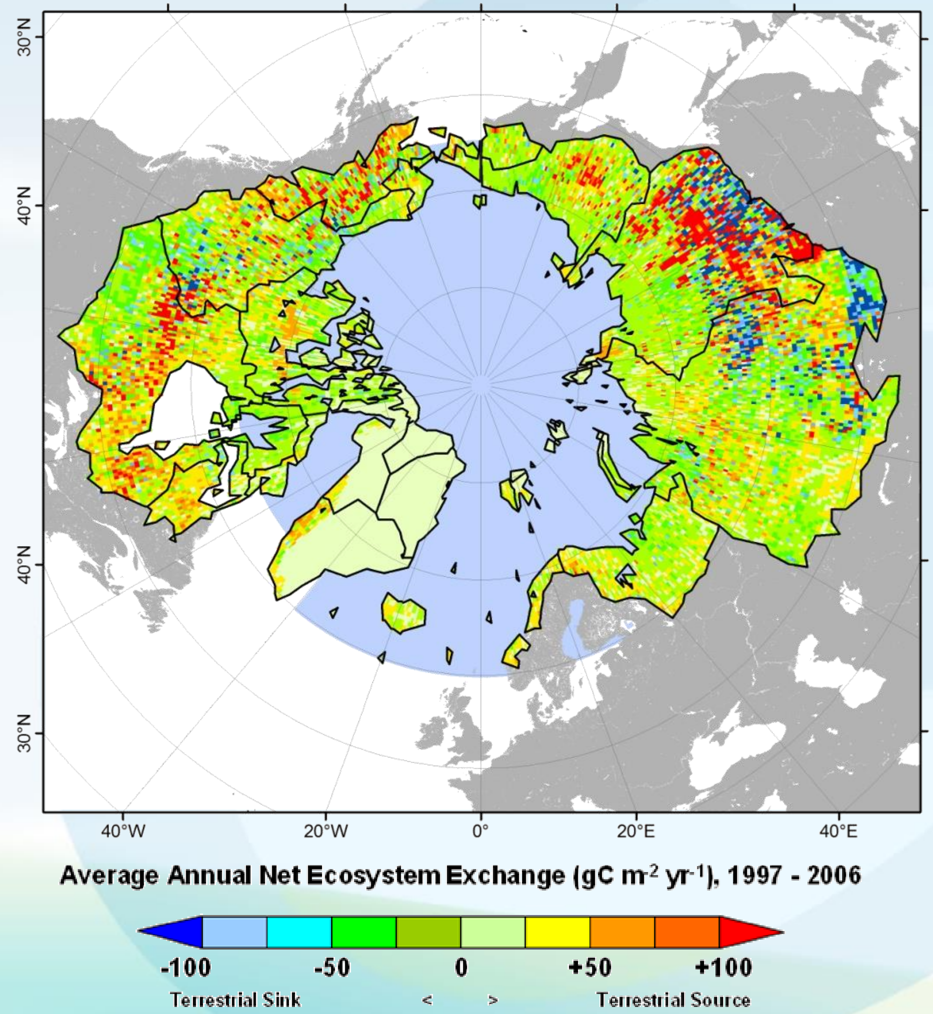
Carbon fluxes from DGVMs	Mean	IAV (σ_{year})
	1921–2008	
GPP	8401	2612
NPP	4076	2186
NBP	91	110
	1990–2008	
GPP	9239	2857
NPP	4712	1780
NBP	199	160

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

TEM – Terrestrial CO_2 Exchange

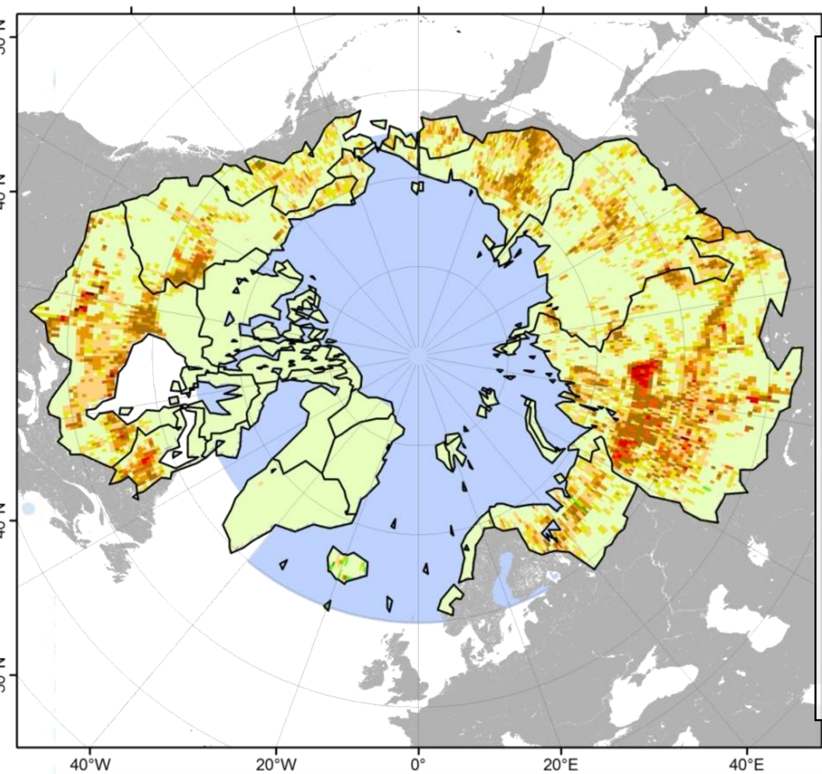




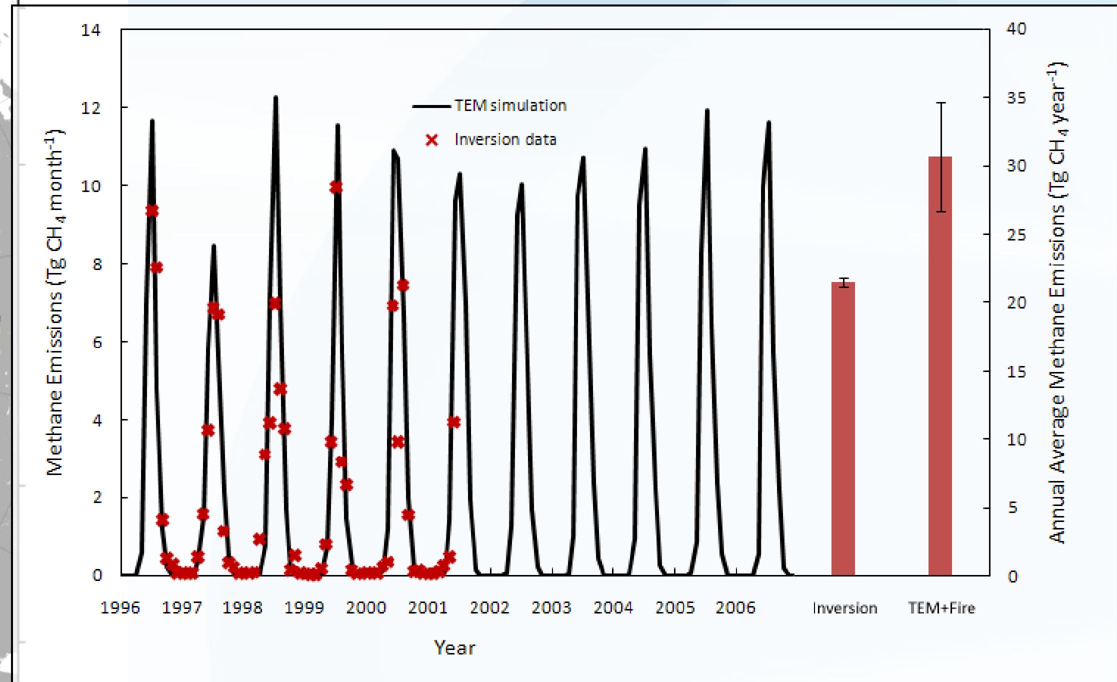
McGuire et al. 2010

Sink 302 Tg C yr-1 = NPP (3260)-HR(2958); fire 255 [178 in soil]

TEM – Terrestrial CH_4 Exchange



Average Annual Methane Flux ($gCH_4\ m^{-2}\ yr^{-1}$), 1997 - 2006

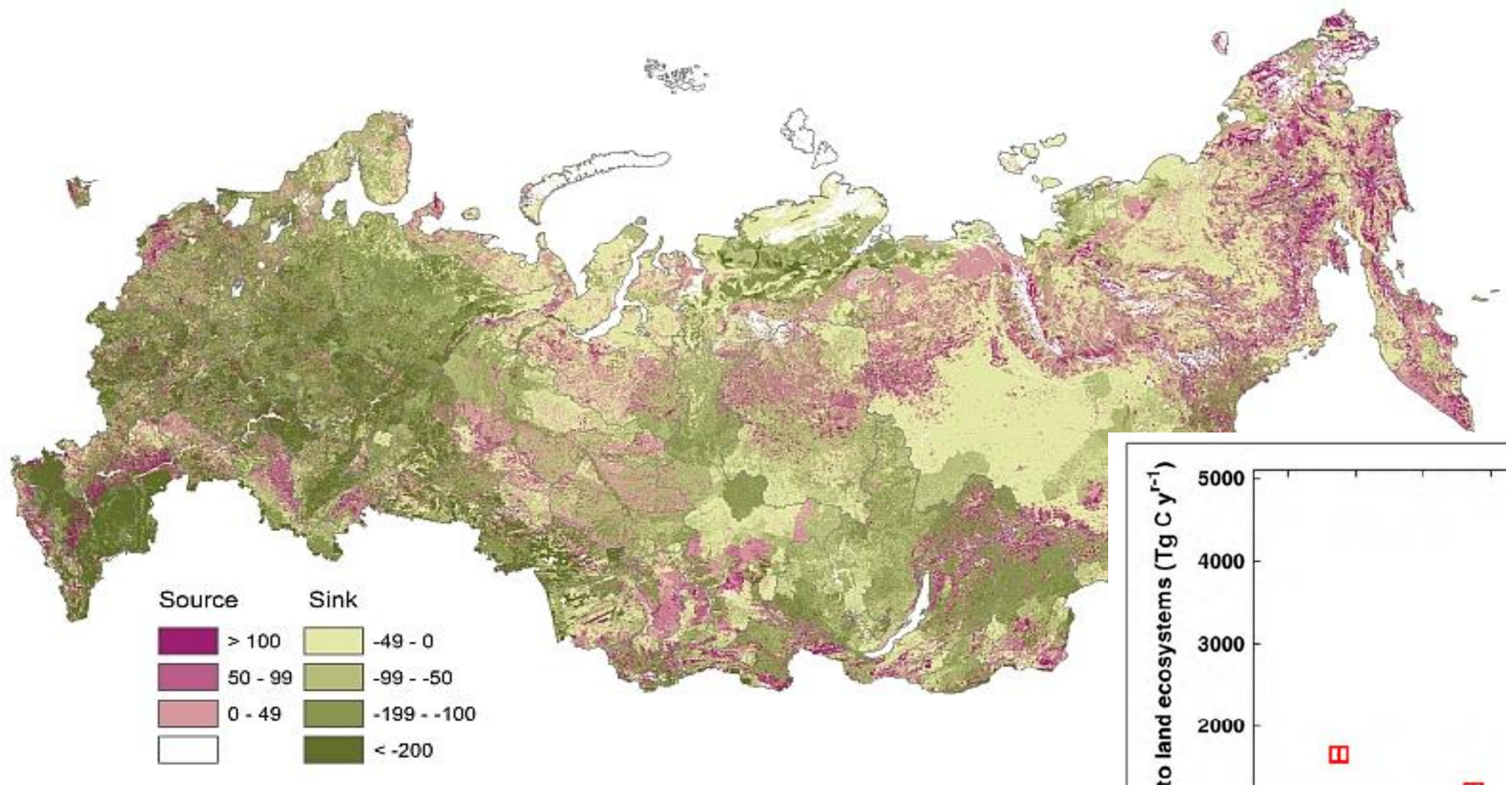


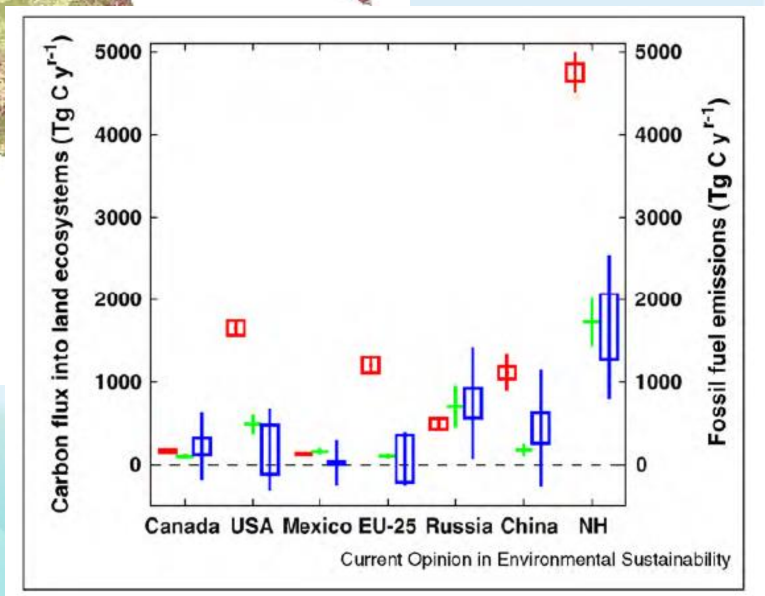
McGuire et al. 2010

Methane emissions: McGuire et al. (2010) 38 Tg CH4 yr^{-1}

ILIS-16.2 incl. forest 1.3 Tg CH4 yr^{-1}

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





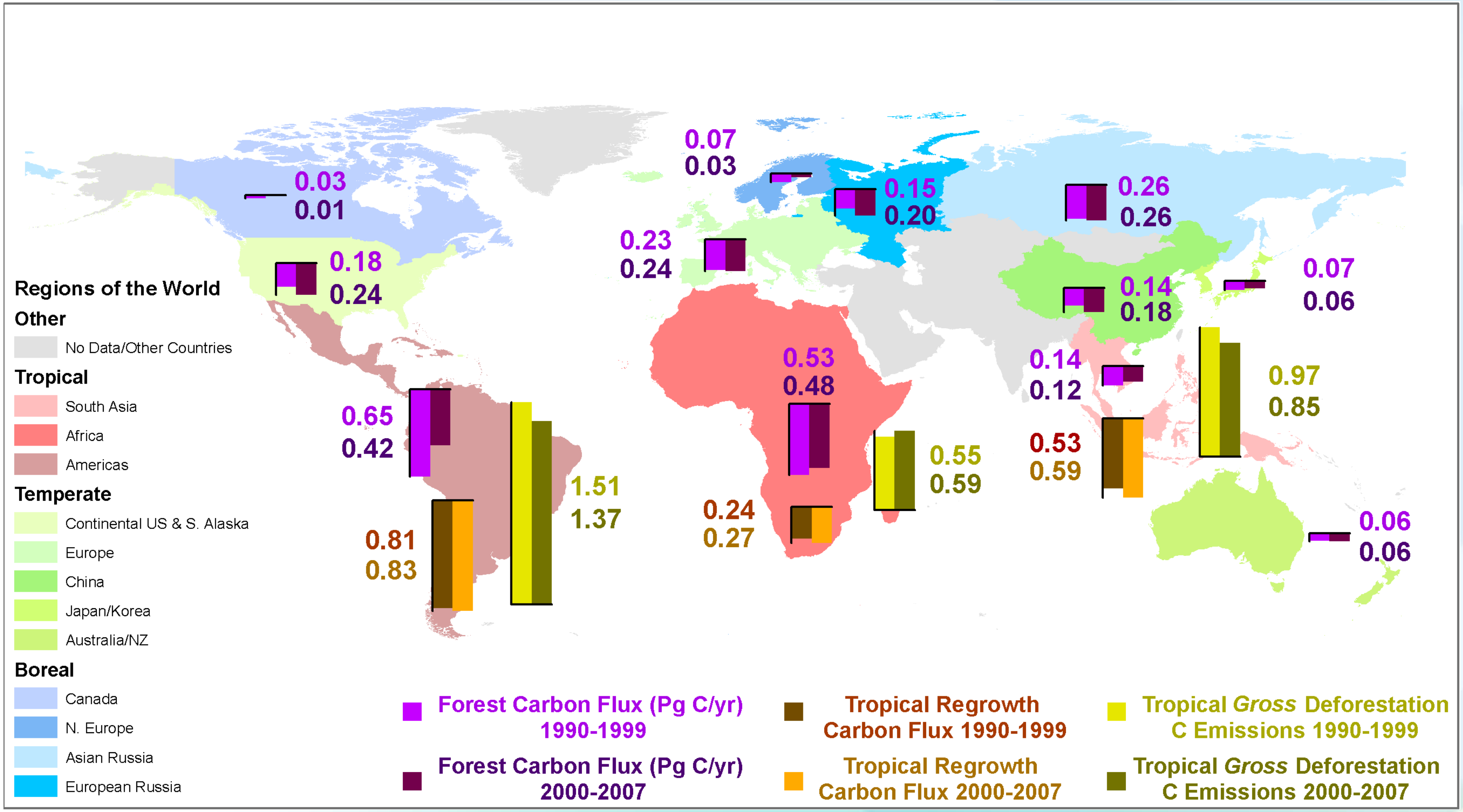
All ecosystems of Russia in 2000-2010 served as a net carbon sink at 0.5-0.7 Pg per year

Of this sink ~95% was provided by forests

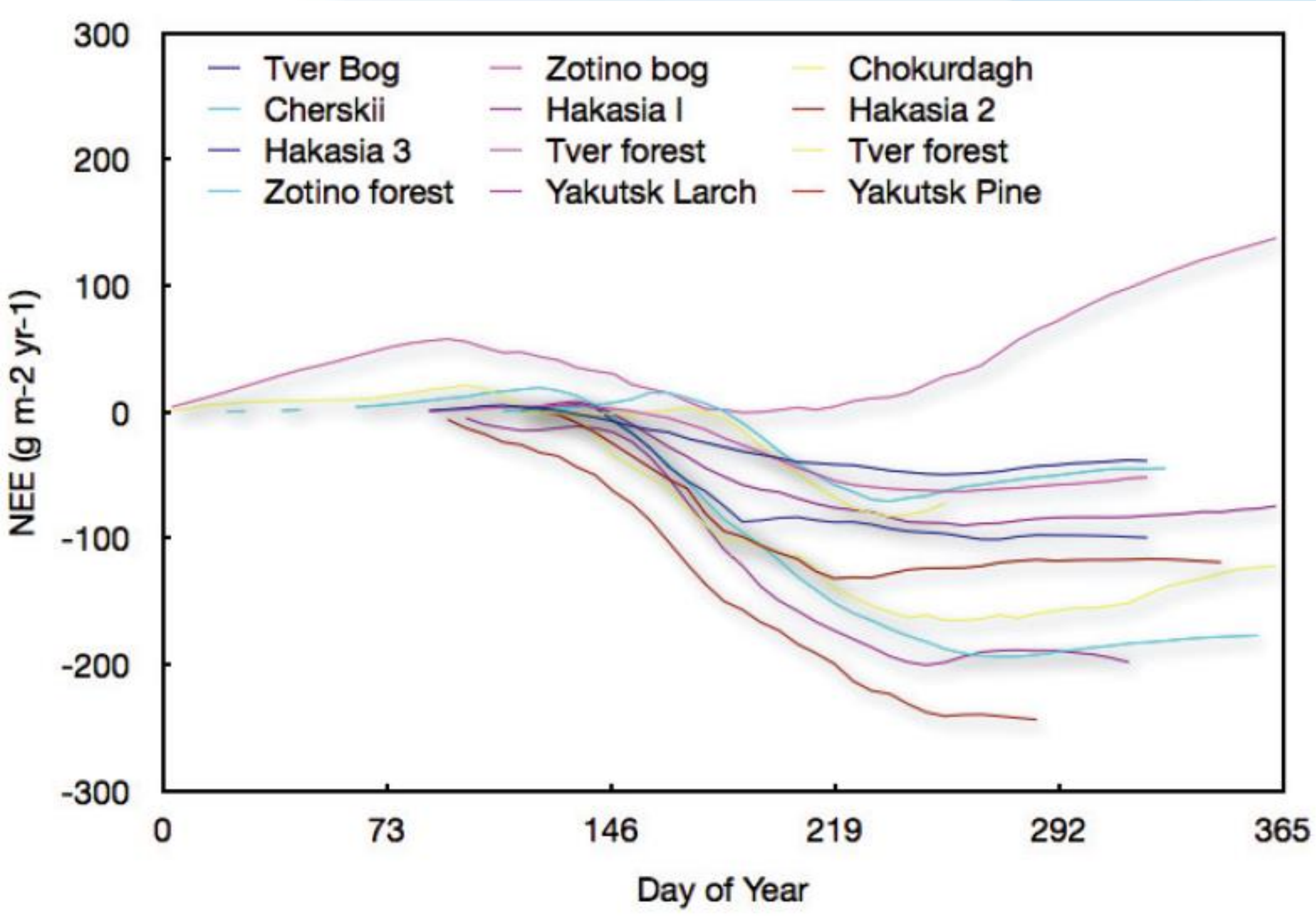
Source: Shvidenko et al. 2011

Source: Ciais et al. 2010

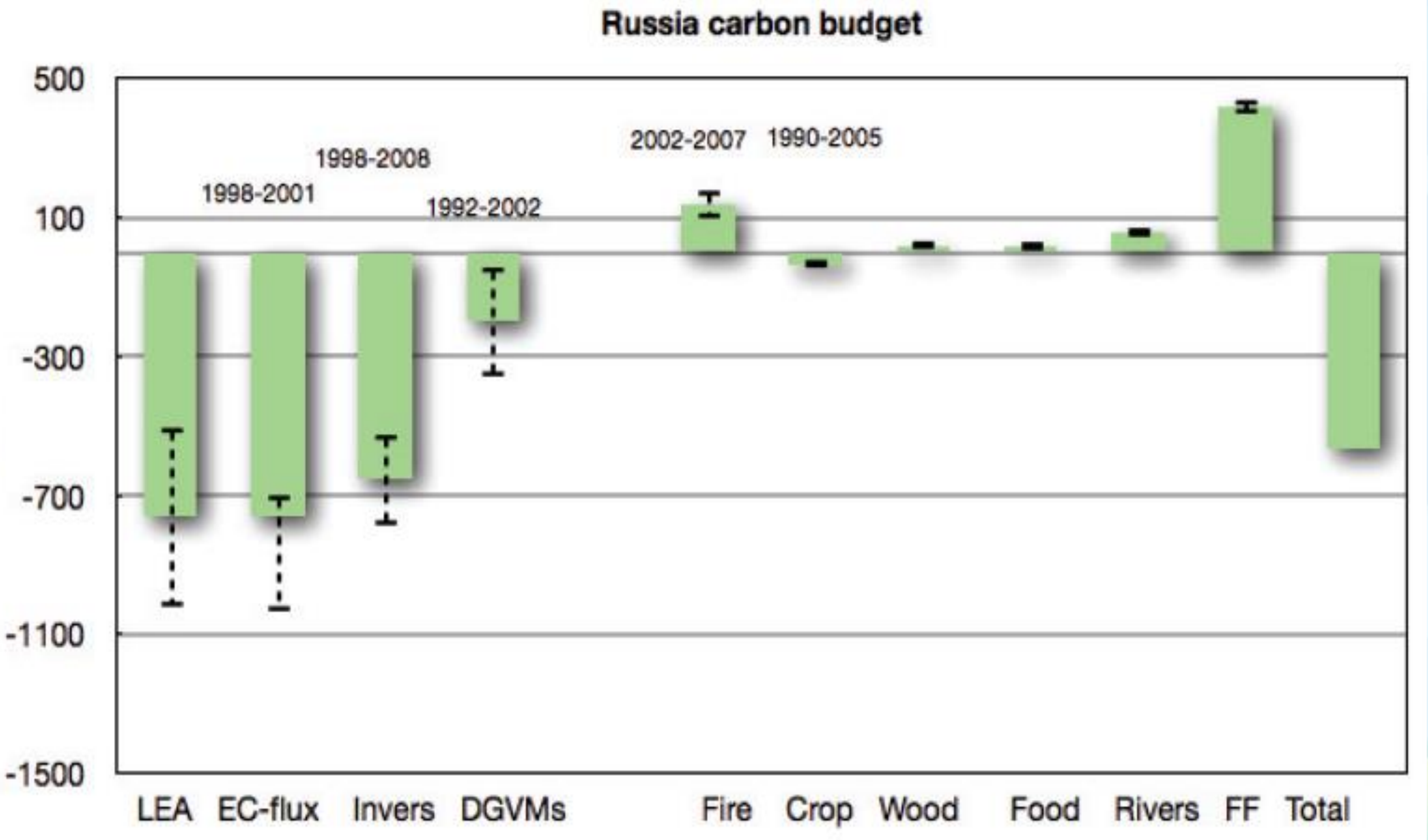
Full carbon account of Russian forests – pool based approach (Pan et al. 2011)



Mean annual net uptake and release of carbon for a set of eddy-covariance site (Dolman et al. 2013)



The carbon balance of terrestrial ecosystems of Russia



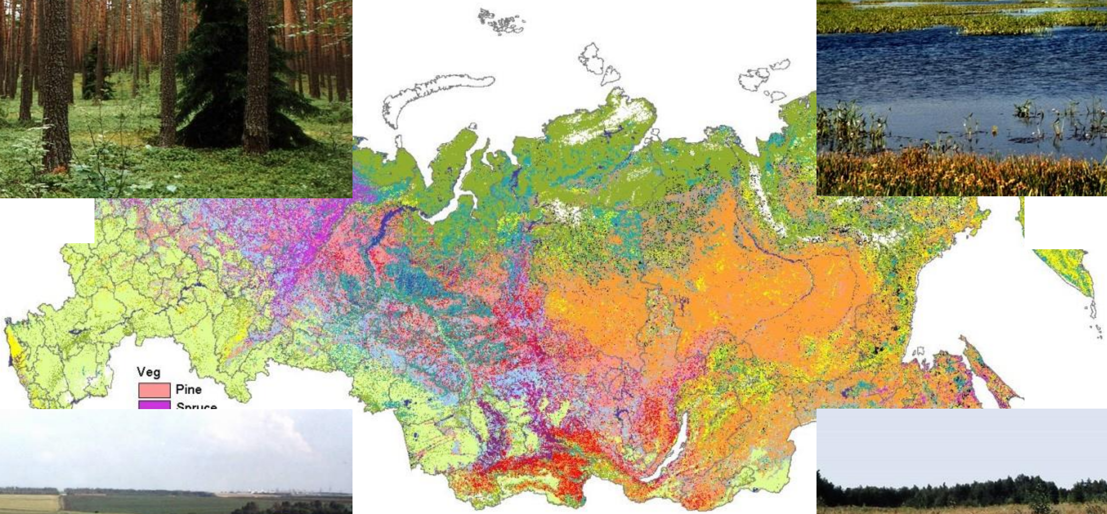
Bayesian harmonization

- Application of the Bayesian approach to results of LEA, inverse modeling (3 series of inversion) and pool-based method (Pane et al. 2011) gave the result 560 ±117 Tg C yr-1R
- Results obtained by DGVMs and eddy covariance cannot be used for the mutual constraints
- The overall results are to some extent illustrative: different proxies and different sense of uncertainties

Conclusions

- The outlined methodology allowed substantially decrease potential biases; assess the most important strengths and weaknesses of methods used
- However, current level of knowledge and information capacity of all methods of FCA do not allow to completely exclude “soft knowledge” from the account
- A major lesson of this study is that any substantial improvement of certainty of FCA requires the system improvement of all methods used in many ramifications
- There is a need of an improved theory of multiple constraints

Thank you



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