Modelling the afforestation and underlying uncertainties

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Afforestation - planting of forests on lands were forests did not grow for last 50 years

Questions

- How much carbon will be accumulated during some time period in case of afforestation?
- What is the uncertainty of the predicted value?

Plan of the presentation

- The mathematical model
- Design of the numerical experiment
- Modelling the uncertainties
- Results
- Concluding remarks

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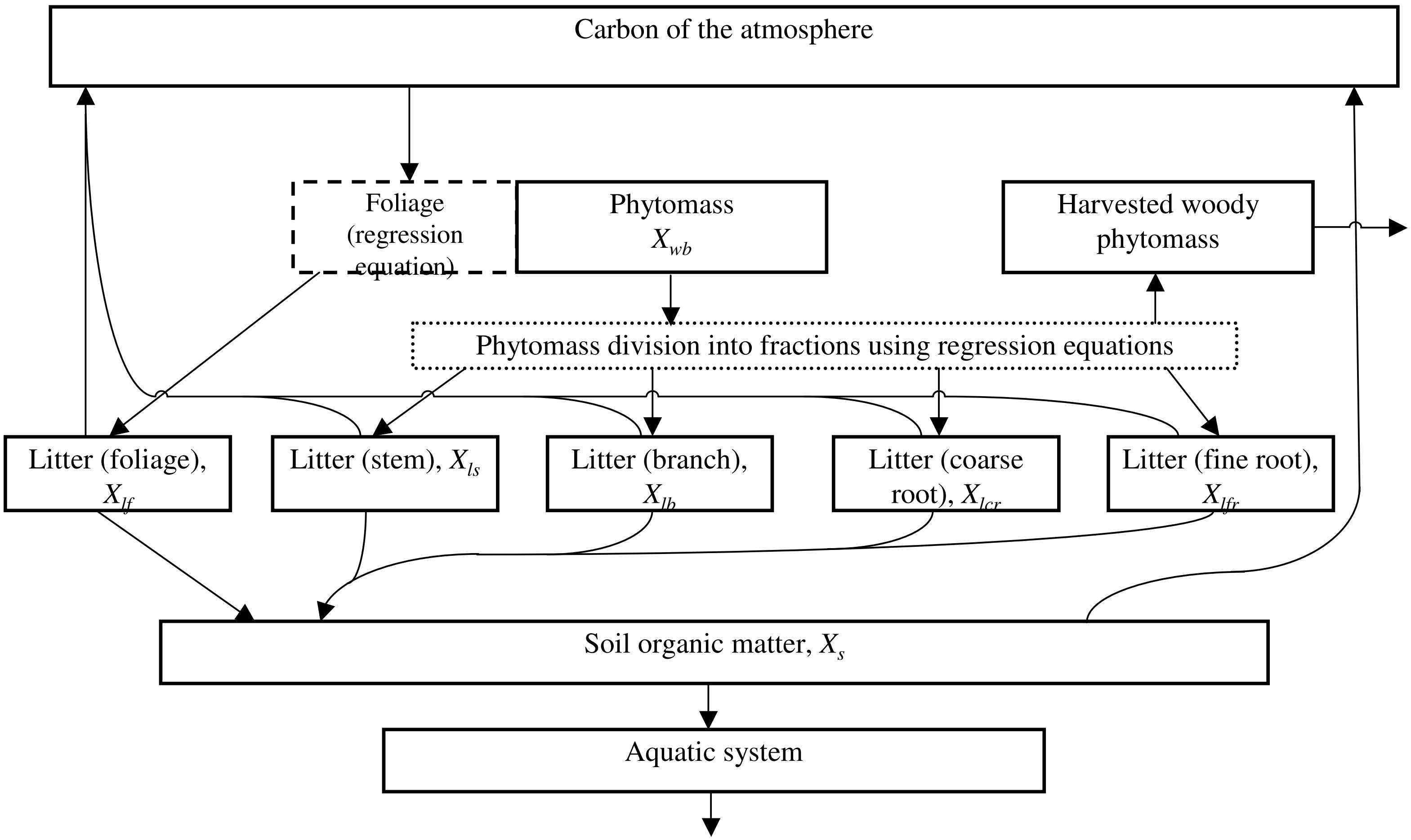
Structural scheme of the model



“Environmental” control

- Intensity of carbon flows are controlled with monthly mean temperature (T), precipitations - Wi (m.e. available water - Wa) and atmospheric carbon dioxide (C).

System of differential equations

$$\frac{dX_{ph}}{dt} = v_{ap} - (v_{plf} + v_{pls} + v_{plb} + v_{plcr} + v_{plfr} + v_{ph}),$$

$$\frac{dX_{lf}}{dt} = v_{plf} + v_{hlf} - (v_{lfa} + v_{lfs}),$$

$$\frac{dX_{ls}}{dt} = v_{pls} + v_{hls} - (v_{lsa} + v_{lss}),$$

$$\frac{dX_{lb}}{dt} = v_{plb} + v_{hlb} - (v_{lba} + v_{lbs}),$$

$$\frac{dX_{lcr}}{dt} = v_{plcr} + v_{hlcr} - (v_{lcra} + v_{lcrs}),$$

$$\frac{dX_{lfr}}{dt} = v_{plfr} + v_{hlfr} - (v_{lfra} + v_{lfrs}),$$

$$\frac{dX_{s}}{dt} = v_{lfs} + v_{lss} + v_{lbs} + v_{lcrs} + v_{lfrs} - (v_{sa} + v_{saq}),$$

Introduction of dependence on forest stand age

Regression expressions (Lakida et al. 1996)

$$R_i = a_0^i * A^{a_1^i}$$

Growth functions (Shvidenko et al. 1996)

$$GS = c_1 * [1 - \exp(-c_2 * A)]^{c_3}$$

Implementation …

Flow atmosphere - phytomass

$$v_{ag} = \alpha_{ap} * F_l * \min\{F_T, F_c, F_w\}$$

Mass of leaves

$$F_l = \frac{1}{1 + \exp(0{,}9 * (-T + T_{\lg}))} * \frac{R_f * X_{ph}}{R_{tot}}$$

Flow phytomass-foliage litter

$$v_{plf} = \begin{cases} 15 * \left(\frac{1}{1 + \exp(1{,}2 * (T - T_{lfe}))} - \frac{1}{1 + \exp(1{,}2 * (T - T_{lfb}))} \right) * \frac{R_f * X_{ph}}{R_{tot}}, & if \quad \frac{dT}{dt} < 0 \\ 0, & otherwise \end{cases}$$

Implementation …

Flow phytomass – litter reservoirs

$$v_{pli} = \alpha_{pli} * \left(dM * R_i * \frac{X_{ph}}{GS * R_{tot}} + \frac{X_{ph} * R_i}{Turn_i} \right), \quad i=\{s,b,cr,fr\}$$

Submodel of available water in ecosystem

$$W_a = \begin{cases} W_i + v_a + v_p + v_{SR} - v_{wt}, & \text{if } T > 0 \text{ and } m_s > 0 \\ 0, & \text{if } T < 0 \\ W_i, & \text{if } T > 0 \text{ and } m_s = 0 \end{cases}$$

W_i – precipitations amount

m_s – snow amount

v_a – snow melted because of heat exchange between snow and air

v_p – snow melted because of heat exchange between snow and rain water, and also kinetic energy of rain

v_{SR} – snow melted because of snow heating with solar radiation

v_{wt} – snow, weathered and blown by the win

Submodel of available water in ecosystem

$$\frac{dm_s}{dt} = -(v_a + v_p + v_w) * (1 - \exp(-2 * m_s)) * \gamma$$

Calibration and testing of the model

Comparison of measured and modeled phytomass and net increment of **oak forest**

	Age, years	33	54	75	106	Root-mean-square error, %
Phytomass, kgC/m^2	Measured	5,40	8,70*	11,56*	13,67*	16
	Modeled	5,40	10,05	12,99	15,58	
	Difference	0,00	1,35	1,43	1,91	
Net increment, kgC/(m^{2}year)	Measured	0,36	0,17	0,16	0,11	24
	Modeled	0,34	0,16	0,12	0,05	
	Difference	0,02	0,01	0,04	0,06	

* Values reduced to forest stand stocking 0,79

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Design of the numerical experiment

- Oak forest is “planted” on the place of cropland.
- As initial data about carbon stored in modelled ecosystem components (phytomass, litter and soil) the results, produced by carbon balance model of cropland was used.
- Monthly mean temperature, precipitation and solar radiation averaged over long period for Lviv Region, and monthly mean atmospheric carbon dioxide were used for modeling.
- “Planted” forest is monitored for 20 years.

Experiment: Additional notes

- Oak forest is “planted” in oak forest vegetation one.
- It is expected (assumed) that the forest will be of IIIrd site index.

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Modelling the uncertainties

- The parameter relative uncertainties and probability distributions (U – uniform distribution and N – normal distribution):
  T – 10N, $Topt$ – 10U, α – 10U, C – 10N, β – 10U, W – 10N,
  kw – 20U, GS – 20N, dM – 20N, Ri – 20N, ki – 20U,
  $Q10$ – 20U, p – 20U.
- A Monte-Carlo simulation was performed to determine how the parameter uncertainties influence the result. For that the uncertain parameters were modelled with generators of random values with uniform or normal probability distributions.
- Initial condition values were modelled with 20% uncertainty of uniform probability.
- The system of differential equations was solved 650 times.
- The model was solved without variation of environmental parameters and including environmental parameters.

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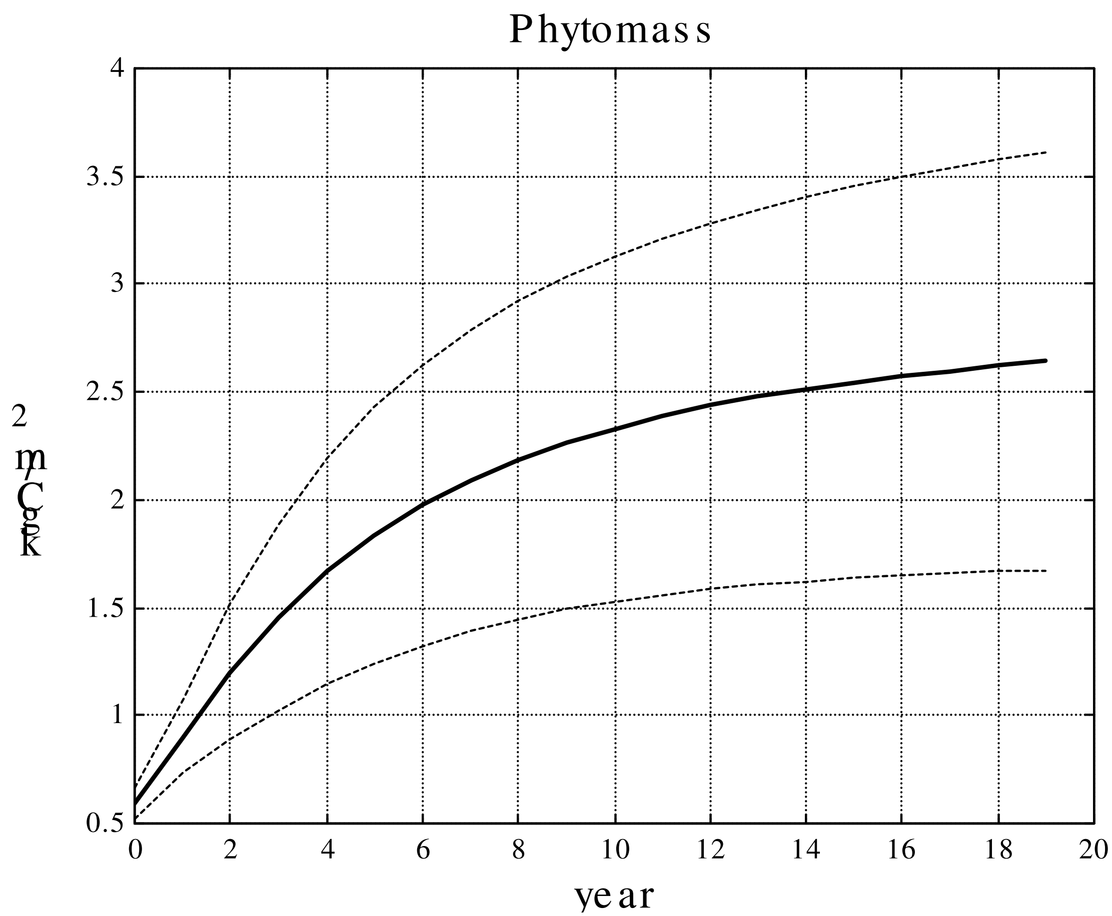
Results

Accumulated carbon and its standard deviation after 10 years of Monte-Carlo simulation without climatic parameters and atmospheric CO_2 and including climatic parameters and atmospheric CO_2

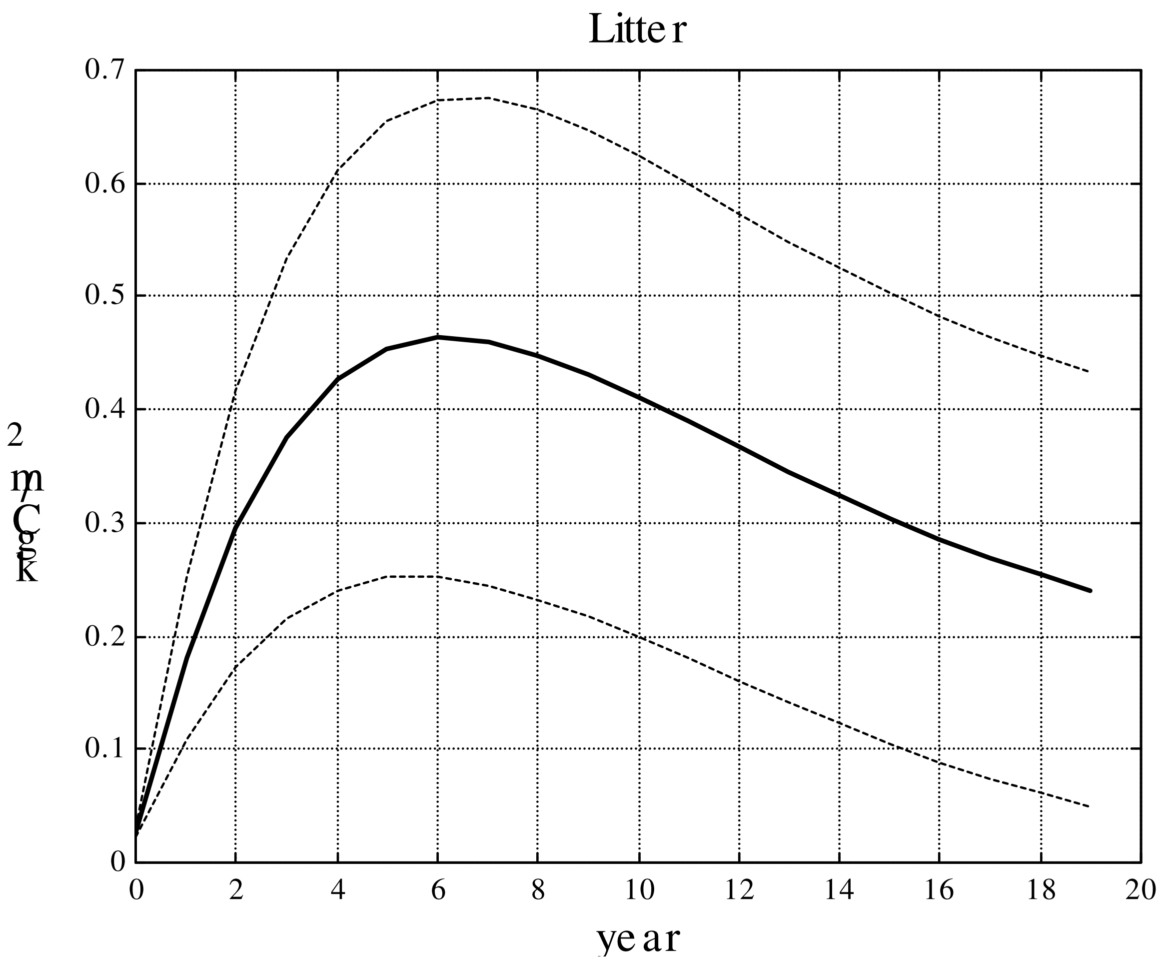
	Phytomass, kg C/m^2		Litter, kg C/m^2		Soil, kg C/m^2		Total, kg C/m^2	
	Value	std	Value	std	Value	std	Value	std
w/o cl. & CO_2	2,1	0,5 22%	0,4	0,2 43%	1,4	0,2 12%	4,0	0,7 16%
Incl. cl. & CO_2	2,3	1,0 44%	0,4	0,2 44%	1,4	0,3 16%	4,1	0,9 22%

Dynamics of phytomass carbon and its standard deviation



Phytomass increases from 0,6 kg C/m2 to 2,7 kg C/m2 in 20 years; RSTD changes from 20% at the beginning of experiment to 37% at the end.

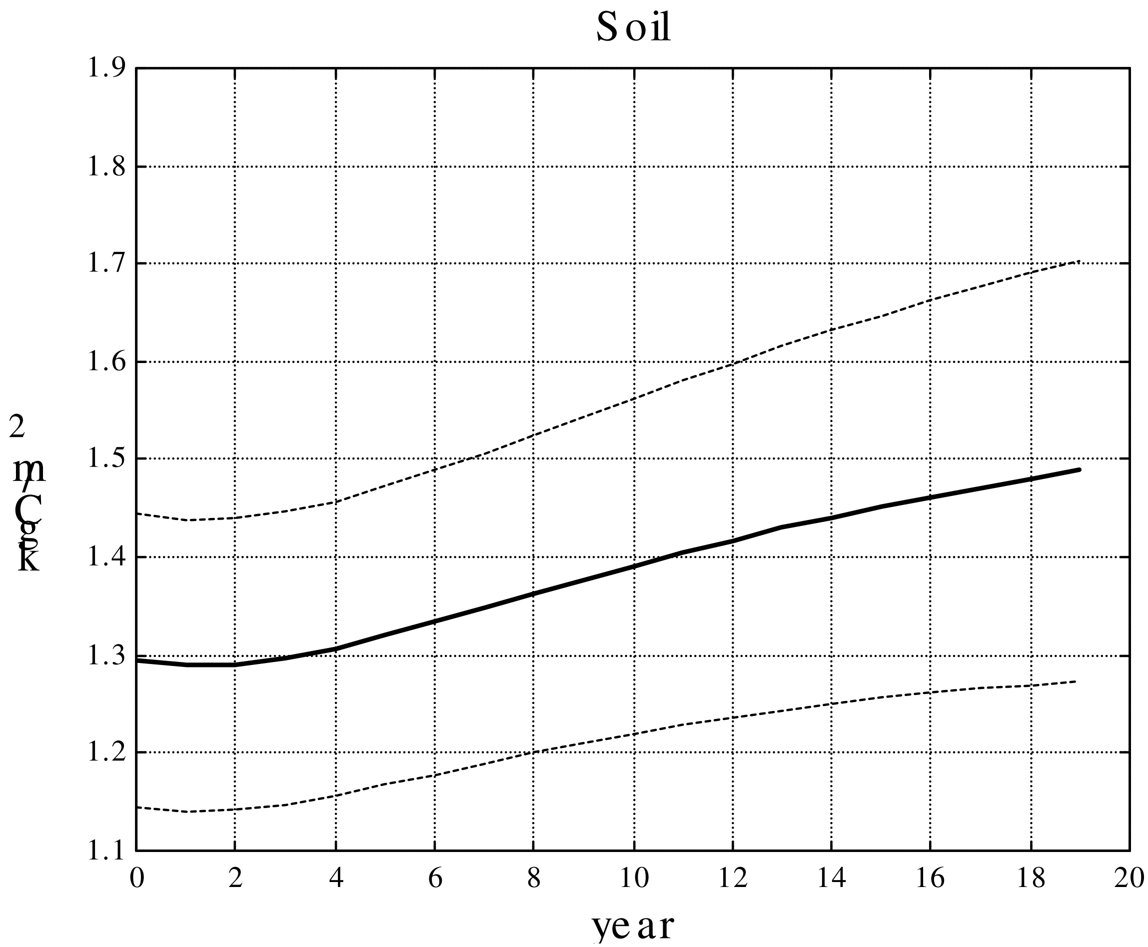
Dynamics of litter carbon and its standard deviation



Carbon stock of litter increases from zero to 0,2 kg C/m2 in 20 years;

RSTD increases from 20% at the beginning of experiment to 83% at the end.

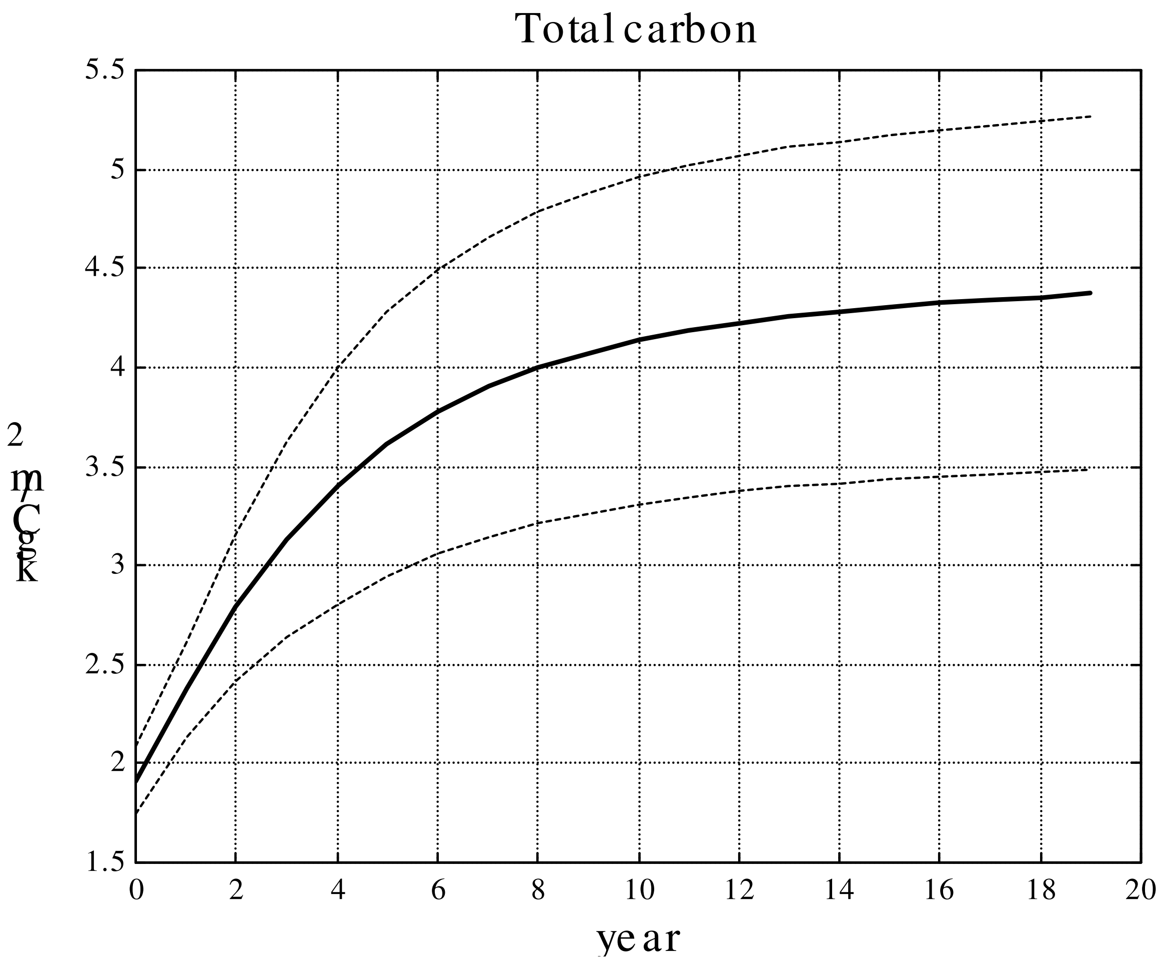
Dynamics of soil carbon and its standard deviation



Carbon stock of soil organic matter increases from 1,3 to 1,5 kg C/m2;

RSTD decreases from initial 20% to 15%.

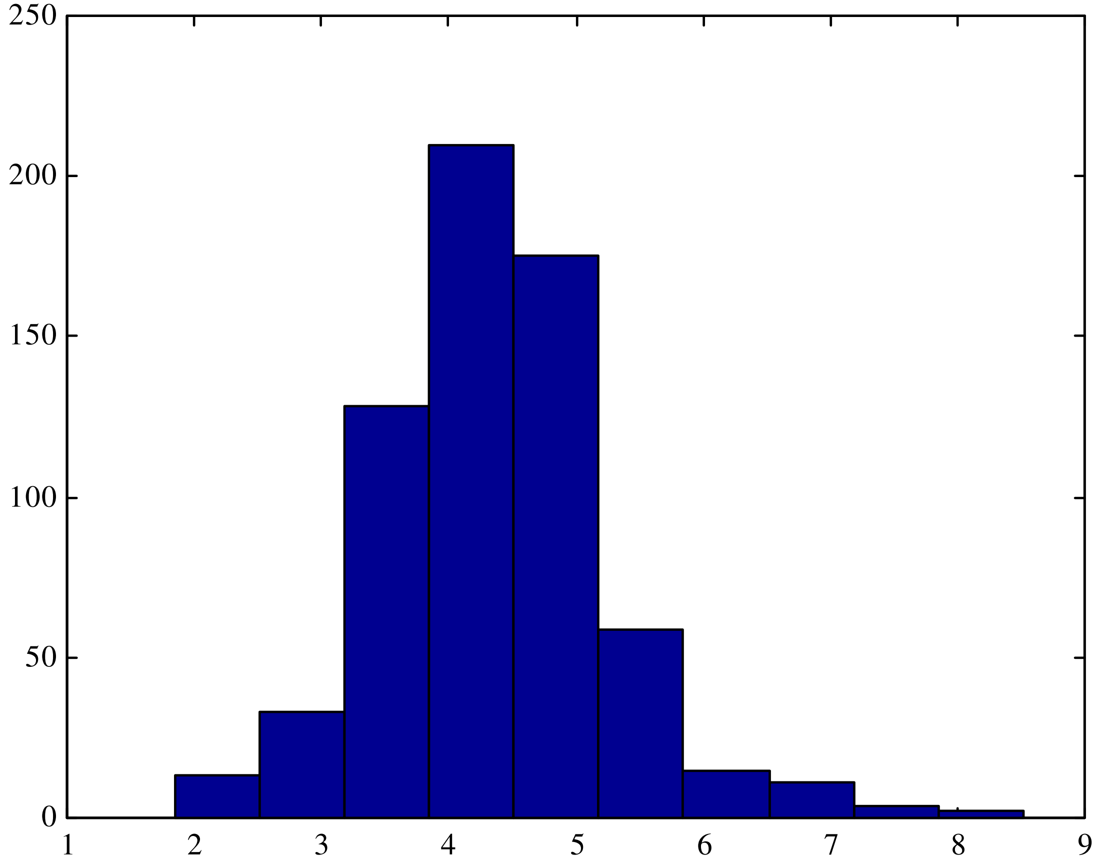
Dynamics of total ecosystem carbon and its standard deviation



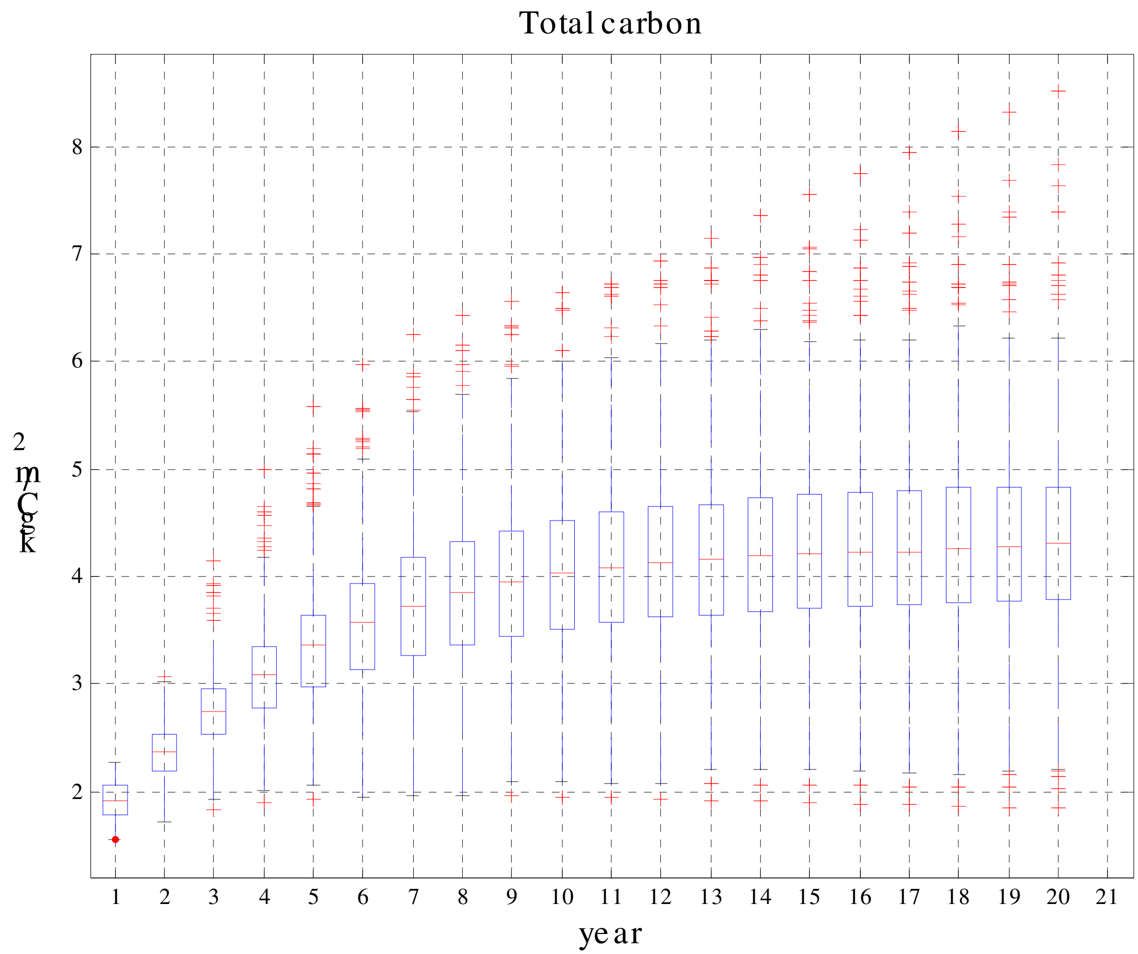
Total carbon amount increases from 1,9 kg C/m2 to 4,4 kg C/m2 during 20 years;

RSTD increases from 9% to 21%.

Histogram of total ecosystem carbon at the end of modelling



Box-plot of dynamics of total ecosystem carbon



the boxes represent lower quartile, median, and upper quartile values;

the solid lines in both sides of the boxes comprise values in the range ±1,5 times of inter-quartile distance;

outliers are plotted with “+”.

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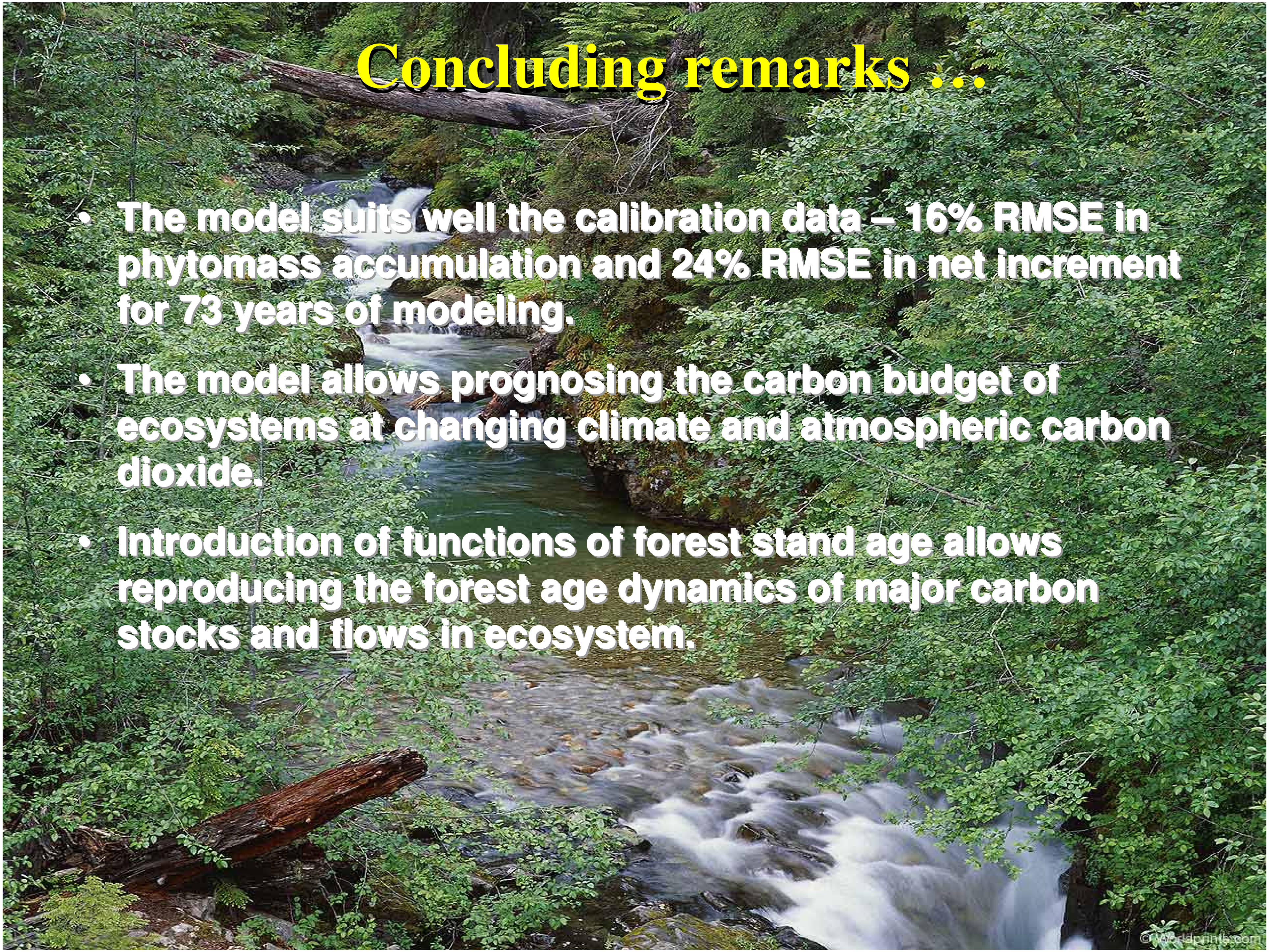

Concluding remarks …

- The model suits well the calibration data – 16% RMSE in phytomass accumulation and 24% RMSE in net increment for 73 years of modeling.
- The model allows prognosing the carbon budget of ecosystems at changing climate and atmospheric carbon dioxide.
- Introduction of functions of forest stand age allows reproducing the forest age dynamics of major carbon stocks and flows in ecosystem.

Concluding remarks …

- Uncertainty of litter accumulation is the largest: relative standard deviation increases from 20% at the beginning of experiment to 83% at the end. But portion of litter is small in the overall carbon stock and so it does not influence the total uncertainty substantially.
- Relative standard deviation of phytomass carbon changes from 20% at the beginning of experiment to 37% at the end.
- Relative standard deviation of soil carbon is the smallest and even decreases from initial 20% to 15%.
- Relative standard deviation of total carbon accumulated in the ecosystem increases from initial 9% to 21% in 20 years.
- From the point of view of verification time concept the signal is detectable if one considers 1-sigma confidence interval, but in case of 3-sigma the signal becomes non-detectable (we consider prognostic modelling).

Concluding remarks …

- Outliers represent a risk of underestimation or overestimation of accumulated carbon in the planted forest. In this case the risk of underestimation is greater which is positive.
- Variation of temperature, precipitations and atmospheric carbon dioxide influence the total uncertainty substantially. In 10 modelling years
  - relative standard deviation of phytomass increases two times,
  - uncertainty of soil compartment and total accumulated carbon increase almost 1,4 times,
  - uncertainty of litter compartment stays almost on the same level.
  - Number of outliers increases.

Thus the climate variability must be taken into account when one prognoses the gain of an afforestation project.