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Impact of temperature increase and precipitation alteration at climate change on forest productivity and soil carbon in boreal forest ecosystems in Canada and Russia: simulation approach with the EFIMOD model

Oleg Chertov[1], Jagtar S. Bhatti[2] and Alexander Komarov[3]
[1] Bingen University of Applied Sciences,
Berlin Str. 109, 55411, Bingen am Rhein
Germany
[2] Canadian Forest Service, Northern Forestry Centre,
5320 122 Street, Edmonton, Alberta T6H 3S5,
Canada
[3] Institute of Physicochemical and Biological Problems in Soil Science,
Russian Academy of Sciences, Institutskaya 2, 142290, Pushchino
Russia

Abstracts

The results of long-term EFIMOD simulations for black spruce (*Picea mariana* [Miller]) and Jack pine (*Pinus banksiana* Lamb.) forests in Central Canada show that climate warming, fire, harvesting and insects significantly influence net primary productivity (NPP), soil respiration (Rh), net ecosystem production (NEP) and pools of tree biomass and soil organic matter (SOM). The effects of six climate change scenarios demonstrated similar increasing trends of NPP and stand productivity. The disturbances led to a strong decrease in NPP, stand productivity, soil organic matter (SOM) and nitrogen (N) pools with an increase in CO_2 emission to the atmosphere. However the accumulated NEP for 150 years under harvest and fire fluctuated around zero. Net ecosystem productivity becames negative only at a more frequent disturbance regime with four forest fires during the period of simulation. Climate change with temperature and precipitation rise leads to the increasing of forest productivity but it reduces SOM pool that can be an indication of ecosystem resilience. The results from this study show that changes in climate and disturbance regimes might substantially change the NPP as well as the C and N balance, resulting in major changes in the C pools of the vegetation and soil under black spruce forests. Soil conditions, especially the potential productivity, as determining by the N pool, modify the effect of climate change and disturbances: poor soils contrasting relative effect of climate change and damages, contrariwise more rich soil mitigates the effect of damages and climate change. The same results were obtained for some West European and Russian boreal forest. Moreover, the EFIMOD runs show that atmospheric nitrogen deposition and especially various silvicultural regimes strongly modify the impact of climate changes on boreal forests. Nitrogen deposition can mitigate the negative impact of temperature rise on forest soils, while overexploitation has the same effect as forest disturbances in Canada.

Keywords*:* Boreal forests, climate change, productivity, carbon budget, silvicultural regimes, disturbances, atmospheric nitrogen deposition

1. Introduction

Bounded between the northern tundra and the southern grassland or broad-leaved forests, the boreal or "northern" forest is a very large biome in Northern hemisphere and it occupies about 35% of the total Canadian and Russian land area and almost 70% of total forest lands in both countries. Forest biomass, coarse woody debris and soil are the three major pools of carbon in forest ecosystems. Changes in forest ecosystem C pools are mainly driven by the dynamics of the living biomass. Accumulations of organic C in litter and soil change significantly in respect to forest development stages (forest succession) and stands disturbances, such as fire, insects and harvesting. Forest primary succession (from pioneer tree species to old-growth uneven-aged forest) and secondary succession (forest restoration after disturbances and cutting) leads to consistent increase of soil C (Chertov, Razumovsky, 1980; Bobrovsky, 2004). Disturbances transfer biomass C to detritus and soil C pools where it decomposes at various rates over the years following the disturbance. In Canadian boreal forests, the disturbance frequency has increased over the past three decades - a trend that appears to be consistent with that expected from climatic warming - and this has caused significant changes in the net carbon balance at the national scale (Kurz and Apps, 1999). Numerous investigators have also examined the effects of disturbances on carbon balance, with particular focus as to whether they represent a significant carbon source to the atmosphere (Amiro et al., 2001; Wei et al., 2003; Hatten et al., 2005).

Projected climate change scenarios for the boreal forest generally predict warmer and somewhat drier conditions, and are expected to change the disturbance pattern. Fire and insect predation regimes, for example, are historically sensitive to climate and are expected to change considerably under global warming (Wotton et al., 1998). Altered boreal forest disturbance regimes - especially increases in their frequency, size and severity - may release soil C at higher rates. Will the net effect of such changes result in positive feedback to climate change and thereby accelerate global warming?

Two aspects of the impact of climate change on forest ecosystems can be distinguished: (a) direct impact of temperature growth and precipitation alteration on the ecosystem processes (tree growth and soil dynamics); (b) catastrophic impact of increased frequency of the ecosystem disturbances (increased fire hazard at draught and forest breakdown at extreme atmospheric events, e.g. storms, hurricanes, landslides etc.). Harvesting regimes are also linking up the second aspect. The first aspect relates mostly to forest stand level, the second one – to the landscape and regional level.

The primary objective of this work was a long term simulation by EFIMOD model to specify direct effects of temperature and precipitation changes at climate change on tree growth and net primary productivity (NPP), soil C dynamics and soil heterotrophic respiration (Rh) and total carbon budget (net ecosystem productivity, NEP) at climate change in boreal forests of Central Canada and European Russia. The effects of disturbances (forest fires) and various silvicultural regimes were also taken into account.

2. EFIMOD model

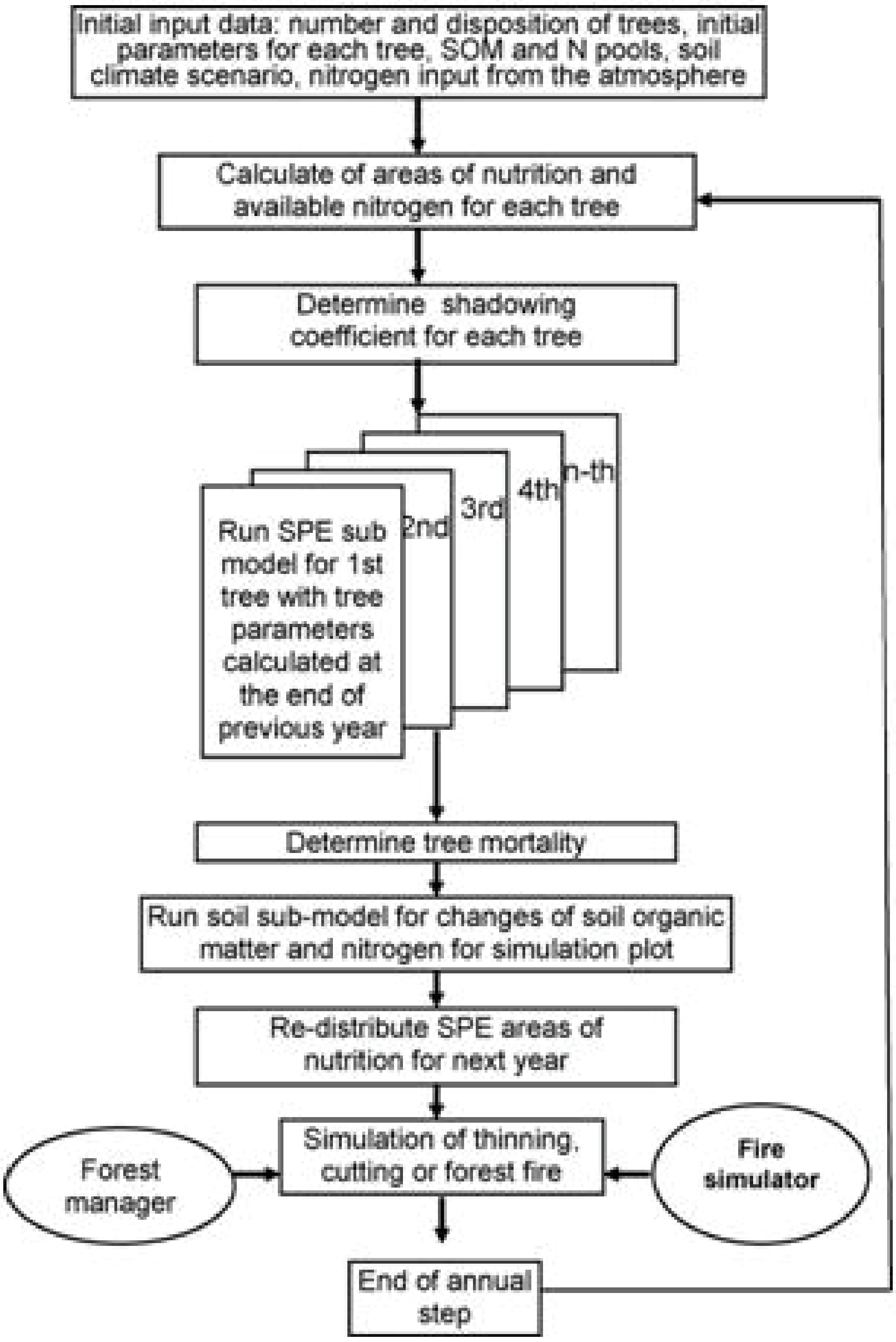

Fig. 1. Flow chart of the EFIMOD model

The model of forest growth and elements cycling in forest ecosystems EFIMOD (Chertov et al., 1999; Komarov et al., 2003, 2007) is an individual-based spatially explicit simulator of tree-soil system that calculates parameters of carbon (C) balance and standard forest inventory characteristics: NPP, Rh, soil available nitrogen (N), tree and stand biomass by tree compartments, soil organic matter (SOM) and N pools, stand density, height, DBH, growing stock and some other parameters. It includes soil model ROMUL as an important component (Chertov et al., 2001) that is driven by soil water, temperature and SOM parameters. The EFIMOD allows for a calculation the effect of silvicultural operations (Fig. 1, “forest manager”) and forest fires (“fire simulator”).

There is a positive promising experience for the implementation of models ROMUL and EFIMOD at a wide range from East Europe till North America in combination with regional forest databases for the estimation of the components of carbon balance (Chertov et al., 2002, 2005; Nadporozhskaya et al., 2006; Shaw et al., 2006; Komarov et al., 2007; Bobrovsky et al., 2010; Yurova et al., 2010). They were also implemented for Germany in a frame of the EU Project RECOGNITION (Komarov et al., 2007; Kahle et al., 2008). The special version of the EFIMOD model (IMPACT, Chertov et al., 2003) is now implementing in Finland for ecological certification of forest products to calculate C, N and energy losses from forest ecosystems due to forest exploitation. The EFIMOD was also implemented for evaluation of the different forestry regimes in terms of their impact on carbon budget and forest productivity (Mikhailov et al., 2004; Komarov et al., 2007) and for modelling carbon balance in a frame of the Program of Russian Academy of Sciences “Change of Environment and Climate”.

Both the SOM model ROMUL and the ecosystem model EFIMOD were previously comprehensively calibrated and validated for European boreal and temperate forests in a frame of the European Forest Institute (EFI) projects, EU Project RECOGNITION (Kahle et al., 2008) and later for Canadian boreal forests (Shaw et al., 2006; Chertov et al., 2009; Bhatti et al, 2009).

3. Objects and methods of simulation

The objects of EFIMOD simulation for determination of climate change effects on boreal forests were Central Canadian boreal forests at the Boreal Forest Transect Case study (BFTCS) of Canadian Forest Service, some permanent sample plots in West Europe and a part of forest enterprise in European Russia. Due to a strong difference of natural and economic conditions in North America and Europe the simulation scenarios for climate change in Canada and Europe are slightly different: the scenarios for Canada accentuate an importance of forest fires and insect attacks with constant cutting regime; the scenarios for Europe and Central European Russia emphasize the various cutting regimes and N deposition from the atmosphere (without fire and insect damage).

Canadian sites. The EFIMOD model was parameterized and calibrated for jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* [Miller]) forests along BFTCS (Shaw et al., 2006; Bhatti et al., 2009; Chertov et al., 2009). The BFTCS was established with the primary goal of understanding the response of boreal forest ecosystems to climate change and how this is affected by natural and anthropogenic disturbances (Price and Apps, 1995). The 1000-km transect has a set of permanent sites.

Jack pine is a typical post-fire pioneer tree species that forms pure stands of low productivity on dry sites. The jack pine sites along the BFTCS have a sandy to sandy-loam soil with rapidly drained conditions with a thin raw humus layer and low soil C concentration in mineral topsoil. Black spruce is widespread in the Canadian boreal ecoregions where it forms late-succession forests (Gower et al., 1997). In the Canadian boreal forest, black spruce occupies both upland and lowland sites. Commonly it grows in pure stands on organic soils and in mixed stands on mineral soils. In the absence of fire, the accumulation of organic matter forms a thick forest floor layer dominated by feather moss and sphagnum (Oechel, Van Cleve, 1986).

Initial forest stand parameters for all the simulations were identical. Stand density were 2500 trees ha^{-1} for jack pine and 10000 trees ha^{-1} for black spruce, age of seedlings was 5 years, their height 0.3 (s.d. 0.1) m with initially random pattern of the seedlings on the simulated plot. The same characteristics were used for simulation of forest regeneration after harvesting, insect and fire disturbances.

The model validation was performed using the stand and soil parameters of 14 sample plots at BFTCS sites as an experimental dataset. For atmospheric N deposition, we used values reported by Shaw et al. (2006) as 2.04 kg [N] ha^{-1} year^{-1}. Additionally, the published data on NPP, Rh, and NEP estimated by Nakane et al. (1997), Bond-Lamberty et al. (2004), Howard et al., (2004), Wang et al. (2002, 2003) and Zha et al., (2009) were used as well.

To study the effects of climate change and disturbances, the simulations were carried out with initial soil C and N data from Candle Lake BFTCS site situated approximately in the centre of this transect.

For the climate change simulations, we used the 150-year scenarios compiled by Price et al. (2004) with three General Circulation Models (GCMs): the Canadian Climate Centre for Modelling and Analysis, CGCM2; the UK Hadley Centre, HadCM3; and the Australian CSIRO Mark 2 GCM. For each GCM scenario, we used two IPCC SRES carbon dioxide emissions scenarios (A2 and B2) for the period 1901-2100. In all scenarios, the data for 1961-1990 are identical, and were extracted for the BFTCS sites from the complied climatic database described at http://www.glfc.cfs.nrcan.gc.ca/landscape/climate_models_e.html. The climate change scenarios with altered values of temperature and precipitation begin only in 1991 only. Additionally, a constant climate scenario (i.e. before the period of major, human-induced climate change) was compiled from the data for the period 1901-1975 that was repeated twice to reach a 150-year time series. It should be pointed out that all three GCMs showed increasing trends of monthly air temperature and precipitation, although the UK model had the lowest rate of increase in these parameters and the CSIRO model had the highest. The data from these GCMs, on minimal and maximal monthly air temperature and precipitation, for 150-year period starting from 1961 were processed by the statistical climate generator SCLISS (Bykhovets and Komarov, 2002) to compile soil climate time series (soil temperature and moisture for organic and mineral soil horizons) which was required for EFIMOD runs. Finally, a set of seven soil climate scenarios was obtained: constant climate; CGCM A2; CGCM B2; SCIRO A2; SCIRO B2; HADCM A2; HADCM B2.

Model simulations were carried out for stand replacing disturbances; namely harvesting, fire and insect disturbances as defined by Kurz et al. (1992). Harvesting represents one thinning at the age of 40 (30% of stand biomass cutting), and clear cutting at age 70. All residues from the mid-rotation thinning remained on the site for decomposition. At harvest, the 90% of stem wood and 10% for branches and leaves were removed from the forest. Two rotations were simulated.

The intensity of crown (canopy) forest fire was the following (as percentage combustion during fire): foliage 100; twigs 60; wood 5; fine roots 30; forest floor (L horizon) 100; forest floor (F+H horizons) 25.

In the simulation of insect-induced disturbance, 90% of the foliage was transferred to the forest floor as insect excrement and 10% was transferred into insect biomass plus their expenses for respiration.

Trees killed by fire and insect attack were not removed from the forest. After harvest, fire, or insect attack, we simulated successful forest regeneration five years following the disturbances. Simulations were conducted under a total of seven different disturbance regimes resulting in a matrix of 49 simulation scenarios. The parameters of C balance used to analyses of the simulation results which included: net primary productivity, soil and deadwood respiration, and loss of C from disturbances (harvested wood, burned trees and forest floor). The C balance was calculated as net ecosystem productivity:

NEP = NPP – [Rh+DIST], where NEP, NPP and, Rh defined above, and DIST is C loss with disturbances. We did not calculate standard deviation because NPP and NEP values are strongly variable due to disturbance events, and the C losses due to disturbance have a pulsating character.

Simulations were conducted under a total of 7 different disturbance regimes (No disturbance for 150 years, Two harvests at 70 and 145 years, Two fires at 70 and 145 years, Four fires at 32, 70, 107 and 145 years, One harvesting at 70 and one fire at 145 years, One fire at 70 and one harvesting at 145 years, One insect attack at 70 and one harvesting at 145 years), each in combination with 7 climate scenarios (Constant climate, CGCM2 A2 and B2, CSIRO A2 and B2, HADCM A2 and B2).

European sites. The Russian, Finnish and West European experimental data (from the EU RECOGNITION Project) were used for the validation and calibration of EFIMOD model (Chertov et al., 2003; Komarov et al., 2003; Van Oijen et al., 2008). Then EFIMOD was implemented for the analysis of impact of climate warming in combination with atmospheric N deposition in a frame of RECOGNITION Project. The Project was devoted to growth trends in European forests to specify factors affecting consistent increasing of forest productivity in the second half of 20th century in Europe (Kahle et al., 2008; Komarov et al., 2007).

Seven sites with long-term experimental data on tree growth were selected (4 Scots pine, *Pinus sylvestris* L. and 3 Norway spruce, *Picea abies* L. [Karst.]): 2 from Finland, 2 from Sweden, 2 from Germany and 1 from Scotland) to represent North Scandinavian and Central West European forests. The forests were represented by pure stands of these coniferous trees on well drained soils with rather high soil C both in forest floor and mineral topsoil. We analyzed a set of scenarios for 80 years simulation for scenarios of natural development (no thinning) and managed forest with 5 thinning and final clear cutting.

The climatic scenarios for the simulation were as follows: actual climate and nitrogen deposition for 20th and 21st centuries – measured and predicted by climatic models (*actual climate, actual N*), stable initial climate and stable low N deposition as at the beginning of 20th century (*low climate, low N*), stable initial climate and actual N deposition (*low climate, actual N*), actual initial climate and stable low N deposition (*actual climate, low N*). For 21st century, we used time courses of weather variables from simulations run by the Hadley Centre in the

UK using the HadCM3 GCM. (Mitchell et.al., 2004; van Oijen et al., 2008). Three start times were used: 1920, 1960 and 2000 to cover periods with different combination of climates and nitrogen deposition for two centuries.

The initial tree parameters were as follows: age 3 years, height 0.3 (s.d. 0.04) m, initial tree density was 10000 tree per ha for German sites, 5000 for Swedish and Scottish sites, and 3000 for Finnish sites. The initial site specific soils parameters were the same for the runs with different start time.

At the analysis of the results, we postulated that the difference between scenarios starting in 1960 and in 1920 reflects the effects of increasing nitrogen deposition, because there are no still strong temperature changes in the scenarios. The comparison of the parameters between scenarios starting in 2000 and in 1960 demonstrates the effects of temperature increasing because both scenarios have rather high nitrogen deposition (but not absolutely the same). The comparison of the ecosystem parameters between scenarios starting in 2000 and 1920 shows the cumulative effects of nitrogen deposition and temperature increasing. The results were aggregated in two clusters: North Europe (Finland and Sweden, "North" on Fig. 4-6) and the rest of Europe (Germany and Scotland, "South" on these figures).

The Russian site for forest management regimes and climate change study at landscape level (Mikhailov et al., 2004, 2007; Komarov et al., 2007) represents a part of forest enterprise that located 100 km south of Moscow on the East European Plain. It possesses a continental climate and contains both coniferous and mixed forests (Mikhailov et al., 2004, 2007). The State Forest "Russky Les" occupies the left bank of the Oka River with sandy and loamy well drained soils (Alfisols). These forests were intensively exploited since the 17th century, and overexploited in the 20th century. Secondary forests are now widespread in the "Russky Les". Silver birch (*Betula pendula* L.), Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) mixed stands dominate the forests. Young stands (<40 years of age) occupy 12% of the enterprise area, mean-aged stands (40–60 years) occupy 53%, and pre-mature stands (60–80 years) cover 35%. Generally, the forests have high density and productivity.

Four management blocks in the "Russky Les" state forest were selected for the case study. They contain 104 forest compartments (stands) comprising 300 ha. The selected forest is typical among forest enterprises with regard to stand composition, forest age, and soils. Current inventory data were used as initial input parameters for the simulations.

Four simulation scenarios were compiled: 1. *Natural development* (NAT). This scenario prevents cutting in all forest compartments. 2. *Russian legal system* (LRU). This scenario permits managed forests with four thinning (at 5, 10, 25, and 50 years), a final clear cutting (90-year age for conifer and oak, 60-year age for birch and lime), and natural regeneration by the target species with a mixture of deciduous species. In these forests, clear cutting must be followed by obligatory forest regeneration, either natural undergrowth or forest planting. 3. *Selective cutting system* (SCU). This scenario creates a managed forest with two thinning in young and mean-aged stands, and then selective cuttings after the stand reaches the age of 80 years (each 30 years in uneven-aged stands, intensity is 30% of basal area from above). 4. *Illegal practice* (ILL). This represents heavy upper thinning and removing of the best trees, and clear cutting without careful natural regeneration, often dominated by deciduous stands. All residues after the final harvest (leaves and branches) in LRU and ILL scenarios are removed (burning on clear-cut area). This treatment follows the Russian legislation, but causes a loss of carbon and nitrogen from the forest ecosystem. These scenarios reflect existing and theoretically possible silvicultural regimes in the simulated forest. A 200-year

period was selected because it is a period when so-called ‘managed’ even-aged forests will be transformed into ‘close-to-nature’ uneven-aged forests in the NAT scenario.
The model’s runs were performed with current climate and with climate change for 150 years using British GCM HADCM3 A1 Fi (Mitchell et.al., 2004) that predicts in this region about 4°C increase of mean annual temperature for 21st century.

4. Results

EFIMOD validation for Canadian sites. The early EFIMOD validations (including the RECOGNITION project) demonstrated a good correlation between simulated and measured dendrometric parameters, soil C and N pools (Chertov et al., 2003; Komarov et al., 2003), The results of validation at Canadian BFTCS also showed correspondence of measured and calculated dendrometric parameters (Shaw et al., 2006). The validation of functional ecosystems characteristics represented at Fig. 2. The deviation of simulated and measured values is a result of variation of stand parameters and SOM pools and unknown stand history at the used experimental dataset
General impact of climate change on boreal forest without disturbances and cutting in Canada and Russia. The results of 100-year simulation of tree growth and soil dynamics at constant and changing climate are represented in Tables 1 and 2 and Fig. 3.

Tree species	Constant climate		Changed climate		%% of changes at changed climate
	mean	s.d.	mean	s.d.	
Black spruce	278.5	87.1	314.7	96.4	12.9
Norway spruce	360.5	113.9	406.1	118.2	12.6
Jack pine	134.4	43.4	156.1	42.15	16.4
Scots pine	403.3	68.2	301.8	37.6	-25.2

Table 1. Simulated growing stock, m^3 ha^{-1}, at 100 years without disturbances; results of Monte-Carlo simulations

The data of simulation clearly show that expected climate change will mostly lead to the increase of forest stand productivity both for Biomass (not shown) and especially for growing stock (Table 1). Proportional increase in growing stock is similar for both spruce species in spite of significant differences in their total productivity. Both spruces grow on wet sites that can minimise the effects of precipitation change and possible water deficit on tree growth. However, growth of American and European pine species is strongly different. There is a strong increase of growing stock in unproductive jack pine stands growing in cold continental climate of Central Canada. From the other hand, rather productive Scots pine forest on dry sandy site in European Russia near the south border of boreal forests is predicted to lose just a quarter of growing stock at climate change.

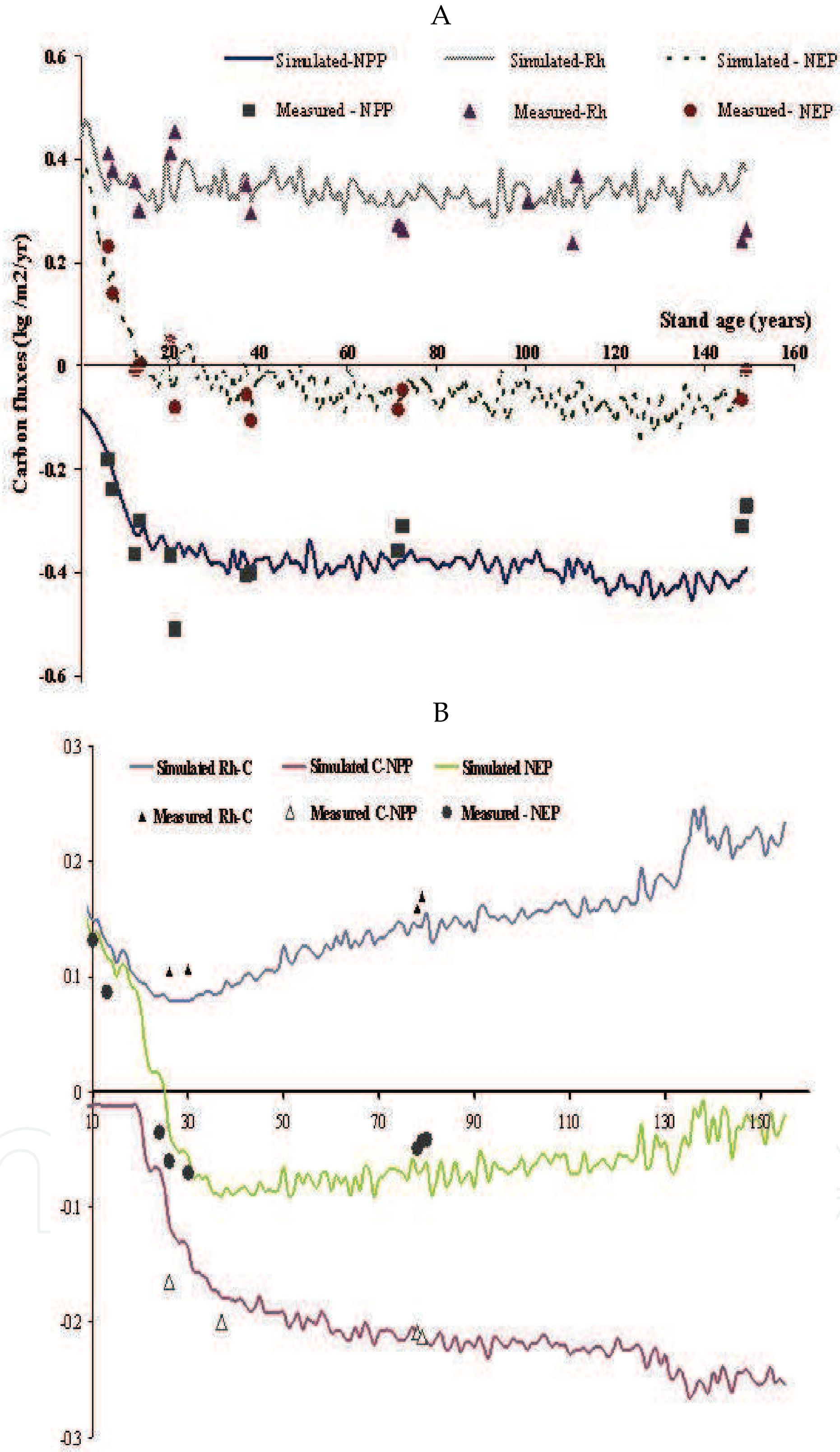

Fig. 2. EFIMOD validation against experimental data at Boreal Forest Transect Case Study (BFTCS) sites, Central Canada; components of carbon budget: A, black spruce (Chertov et al., 2009); B, jack pine (Bhatti et al., 2009). NPP, net primary productivity; Rh, soil respiration; NEP, net ecosystem productivity. Rh includes dead wood respiration.

Soil C pools respond similarly in Canada and Russia, with all soils losing organic matter at climate change. In Canada, the scale of soil C reduction is comparable for black spruce and jack pine. In Russia, the C loss in Norway spruce forest on wet site is relatively low, while it is very high in the Scots pine forest. It happens simultaneously with a strong decrease of stand productivity determining the input of litter fall in soil and the trends of soil C dynamics.

Tree species	Constant climate		Changed climate		%% of changes at changed climate
	mean	s.d.	mean	s.d.	
Black spruce	8.89	2.42	7.72	2.08	-13.2
Norway spruce	5.61	1.53	5.36	1.28	-4.5
Jack pine	3.14	0.81	2.71	0.83	-13.7
Scots pine	8.93	1.01	6.07	0.59	-32.2

Table 2. Simulated soil C pools, kg m^{-2}, at 100 years without disturbances; results of Monte-Carlo simulations;

The temporal dynamics of tree and soil C under constant climate and climate change scenarios can be compared in Fig. 3. The curves of tree biomass growth are of monotonous type while soil dynamics demonstrates soil C decrease in young stands due to low litter fall production at this age. Clear positive trends of forest floor and mineral soil C increase are typical for post-fire forest ecosystems. These figures also show that the effect of climate change becomes clearly visible mostly in mean-aged and old forests.

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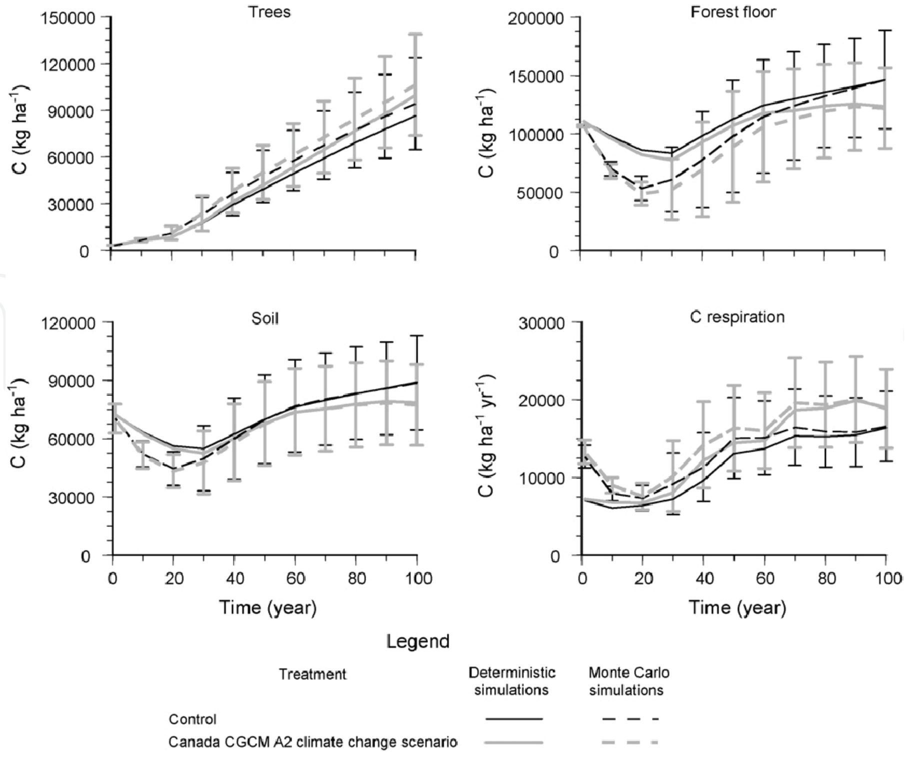

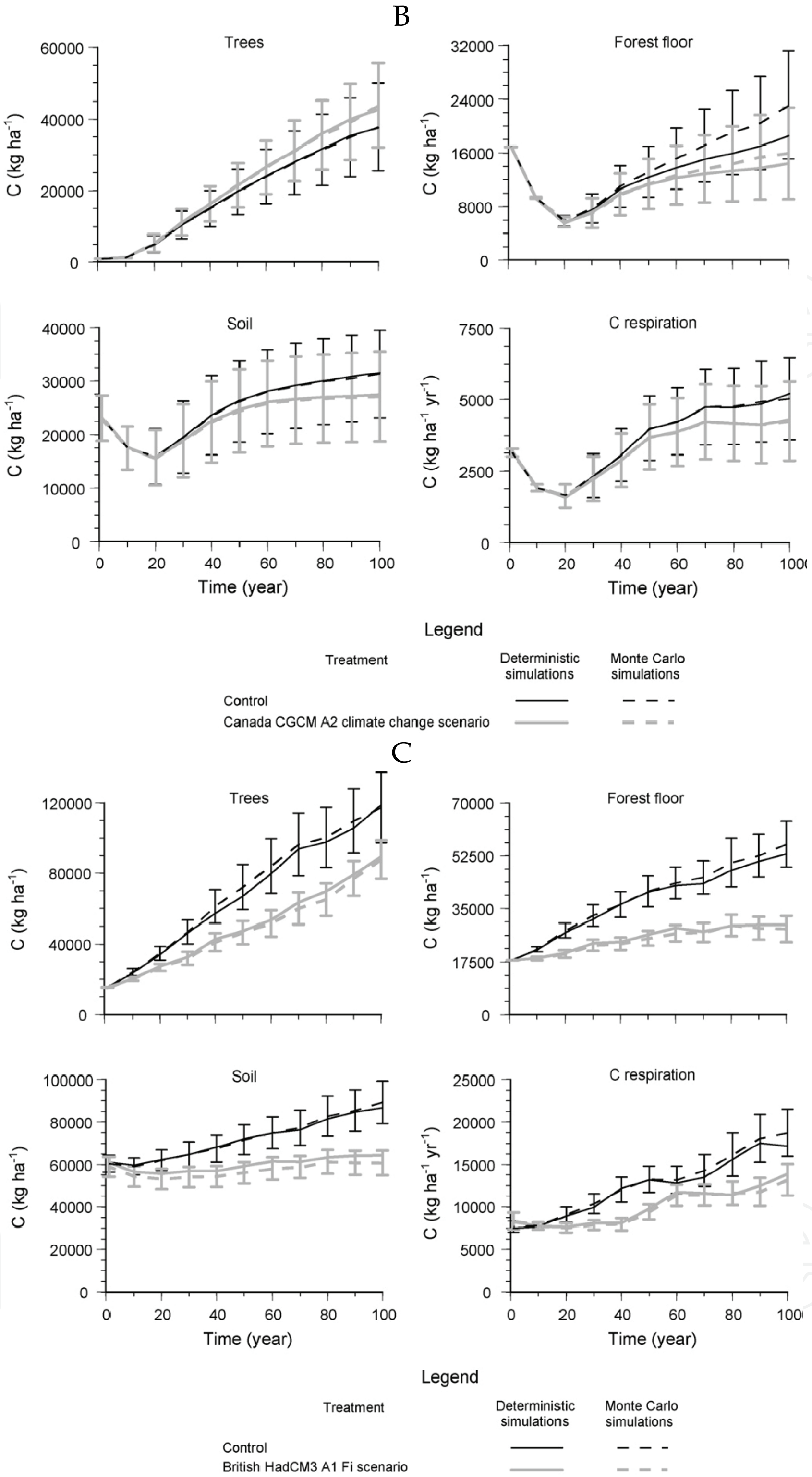

Fig. 3. Comparison of predicted carbon pools in (A) black spruce, (B) jack pine and (C) Scots pine forest ecosystem located in Canada and Russia using EFIMOD, following prescribed and Monte Carlo simulations. Error bars represent the standard deviations computed from the Monte Carlo predictions (Larocque et al., 2008). The dynamic pattern of Norway spruce in Russia is the same as black spruce in Canada; therefore we don't put Norway spruce on the graph.

In conclusion we should point out that impact of climate warming is also site-specific. It is positive on mesic and wet forest sites with productive soils. However, on dry and poor soils it can lead to a strong decrease of forest productivity and soil C pools.

Climate scenarios	Jack pine		Black spruce	
	Growing stock, $m^3\ ha^{-1}$	% changes	Growing stock, $m^3\ ha^{-1}$	% changes
Constant	242	0	366	0
CGCM A2	280	16	439	20
CGCM B2	273	13	429	17
CSIRO A2	282	17	455	24
CSIRO B2	278	15	450	23
HADCM A2	258	7	397	8
HADCM B2	256	6	394	8

Table 3. Growing stock, $m^3\ ha^{-1}$, at harvesting without disturbances and six climate change scenarios, sum of two rotations over 150 years

Tree species	Climate scenario	Harvesting	2 fires	4 fires	Harvest-fire	Fire-harvest	Insect
Jack pine	Constant	0.126	0.114	0.043	0.128	0.113	0.130
	CGCM	0.143	0.133	0.055	0.149	0.131	0.151
	CSIRO	0.148	0.133	0.054	0.149	0.132	0.152
	HADCM	0.136	0.123	0.049	0.137	0.122	0.140
Black spruce	Constant	0.323	0.288	0.122	0.326	0.285	0.323
	CGCM	0.388	0.354	0.154	0.393	0.350	0.389
	CSIRO	0.402	0.367	0.161	0.407	0.363	0.404
	HADCM	0.351	0.322	0.139	0.355	0.318	0.351

Table 4. Mean net primary productivity (NPP) over 150 years of simulation (kg m^{-2} $year^{-1}$).

Impact of climate change on jack pine and black spruce forests with cutting, fire and insect attacks in Central Canada. The results of these simulations show that the effects of six different climate change scenarios demonstrated the similar trends of stand productivity increase in 21st century (Table 3). The highest increase of forest productivity was found with Australian CSIRO GCM, the lowest one was with British HADCM.

The same dynamic trends exhibit NPP data (Table 4). Moreover they show a strong effect of disturbance regimes on forest NPP: it is significantly lower at all fire scenarios and about 3-fold lower at the 4-fires scenario. However, the ecological effect of "harvest-fire" and "insect attack" is the same as harvesting because all burned and killed tree biomass did not remove from the forest in these scenarios. The important aspect is that the absolute values of disturbance effects are significantly higher of the effects of climate change on NPP.

Tree species	Climate scenario	Harvesting	2 fires	4 fires	Harvest-fire	Fire-harvest	Insect
Jack pine	Constant	0.092/0.122	0.089/0.106	0.037/0.051	0.092/0.117	0.089/0.111	0.107/0.120
	CGCM	0.109/0.143	0.106/0.124	0.046/0.060	0.110/0.136	0.104/0.129	0.125/0.147
	CSIRO	0.110/0.145	0.107/0.125	0.045/0.059	0.112/0.138	0.106/0.130	0.126/0.148
	HADCM	0.099/0.131	0.097/0.115	0.042/0.055	0.100/0.126	0.097/0.119	0.115/0.135
Black spruce	Constant	0.278/0.320	0.250/0.293	0.125/0.154	0.277/0.320	0.251/0.286	0.294/0.318
	CGCM	0.343/0.392	0.311/0.357	0.152/0.183	0.341/0.388	0.312/0.357	0.362/0.393
	CSIRO	0.356/0.408	0.324/0.370	0.158/0.189	0.355/0.403	0.325/0.372	0.376/0.409
	HADCM	0.308/0.353	0.280/0.325	0.139/0.169	0.306/0.350	0.282/0.324	0.324/0.350

Table 5. Mean soil CO_2-C emission/Total C loss with soil emission and disturbances over 150 year simulation, kg m^{-2} $year^{-1}$

Tree species	Climate scenario	Harvesting	2 fires	4 fires	Harvest-fire	Fire-harvest	Insect
Jack pine	Constant	0.005	0.007	-0.007	0.011	0.003	0.006
	CGCM	0.004	0.009	-0.005	0.012	0.002	0.004
	CSIRO	0.003	0.008	-0.005	0.011	0.002	0.004
	HADCM	0.005	0.008	-0.006	0.011	0.003	0.005
Black spruce	Constant	0.003	-0.005	-0.032	0.006	-0.001	0.005
	CGCM	-0.004	-0.003	-0.029	0.005	-0.005	-0.004
	CSIRO	-0.006	-0.003	-0.028	0.004	-0.009	-0.005
	HADCM	-0.002	-0.003	-0.030	0.005	-0.006	0.001

Table 6. Mean net ecosystem productivity (NEP) over 150 year simulation, kg m^{-2} $year^{-1}$;

Climate warming has the same pattern in relation to soil heterotrophic respiration (CO_2 emission) as a main feedback from ecosystem to the atmosphere (Table 5): it becomes about 10-20% higher in a case of climate change. Again, a significant impact of disturbances on soil C emission was simulated here.

The values of total C loss from forest ecosystems (sum of Rh and C loss with fires, insect and harvested wood) repeat the differences of Rh data. They are the highest in scenarios with wood harvest but lowest in fire scenarios where burned wood remains in the forest for decomposition. There is one seeming contradiction in the data on total C loss: the scenario with four fires has twice lower values of C loss in comparison with other ones though, logically thinking, we could expect an opposite picture. It happened because all four fires were simulated in 37-year old stands with a low tree biomass.

The data on net ecosystem productivity (NEP, Table 6) integrate all C flows and represent a general C budget of the ecosystem. At a glimpse, all values are fluctuating around zero. However, there is irregular difference between climate change scenarios, disturbances (four fires regime leads to maximal C loss) and tree species (negative values in black spruce are dominating).

Additional simulations for Canadian jack pine and black spruce sites with variation of soil C and N pools showed that soil conditions, especially its productive potential determining by the N pool, modify the effect of climate change and disturbances: poor soils contrasting relative effect of climate change and damages, contrariwise more rich soil mitigates the effect of damages and climate change.

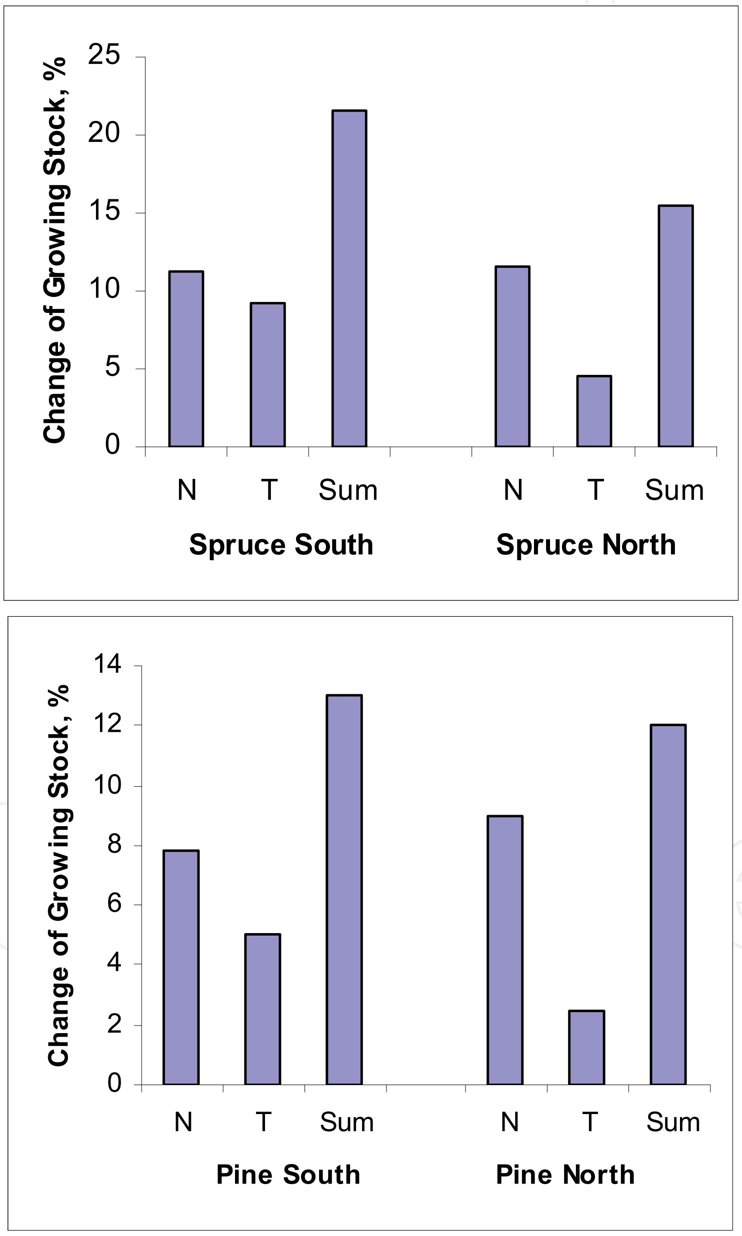

Fig. 4. Differences in growing stock as affected by climate change and atmospheric nitrogen. Symbols on the figure (here and below): N – nitrogen deposition increasing, T – temperature increasing, Sum – cumulative effect of nitrogen deposition and temperature increasing.

The simulated results show significant increases in NPP and Rh under changing climates as compared to a constant climate, suggesting a strong increase in biological C cycle capacity under climate change. The data on the effects of climate change shows differences among climatic scenarios. The greatest increases in ecosystem processes took place under the Australian (CSIRO) scenarios, while the UK scenarios (HADCM) showed slower ecosystem changes. Therefore, the projected climate change led to increases in wood production, reaching 17-24% in the Australian (CSIRO A2) scenarios. The simulated results show that increased concentration of atmospheric CO_2 (high at A2 and twice higher at B2) significantly smoothed the influence of difference of climatic scenarios themselves in relation to the forest productivity.

The effects of climate change and nitrogen deposition on European forests. The simulation data at seven forest sample plots across West Europe show rather interesting results on the comparative effects of climate change and atmospheric N deposition mostly due to industrial pollution (Chertov et al., 2006; Chertov, Komarov, 2007). Initially, we should call attention to the absence of principal difference in ecosystem responses for naturally developed and managed forests with regular thinning.

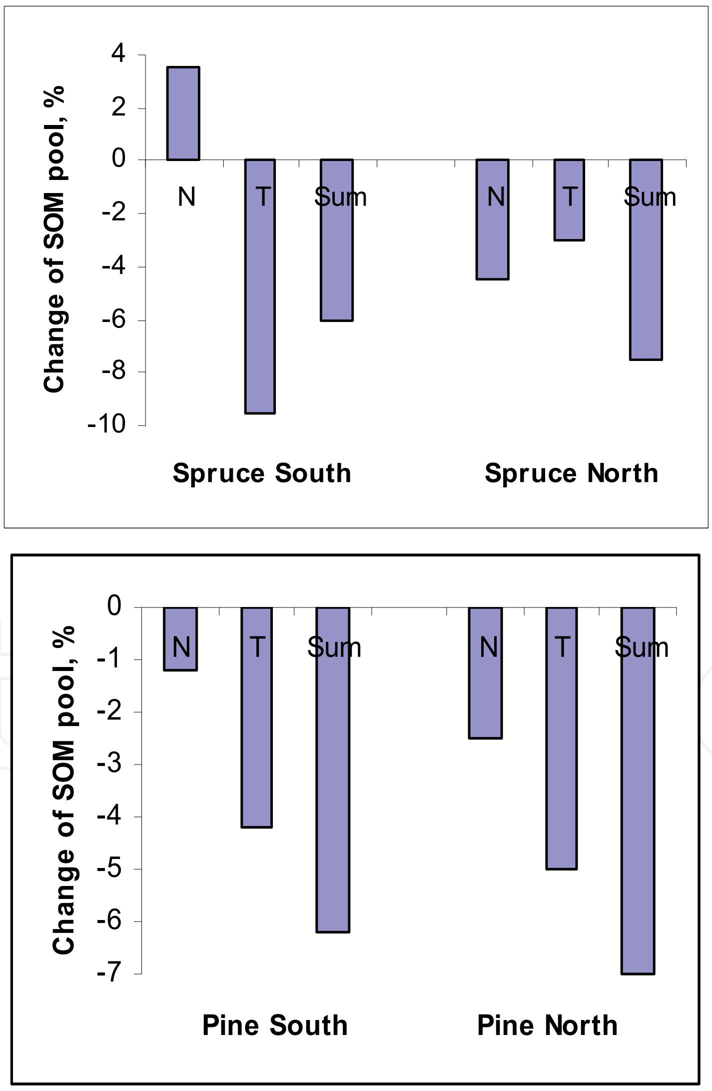

Fig. 5. Differences in soil organic matter (SOM) pools as affected by diverse ecological factors. Symbols corresponds to Fig. 4

First of all we should point out that the differences in stand height and basal area are totally positive for all comparisons reflecting effect of different factors. These positive changes vary from 0.5 to 10%. Both species in south sites demonstrate a little bit higher height changes, although basal area has no so clear changes. Unexpectedly, the differences of growing stock for both species are significantly higher of height or basal area changes (Fig. 4) reaching in some cases 22%. The effect is stronger for south sites and in Norway spruce stands. The nitrogen response was found to be sufficiently higher of temperature response.

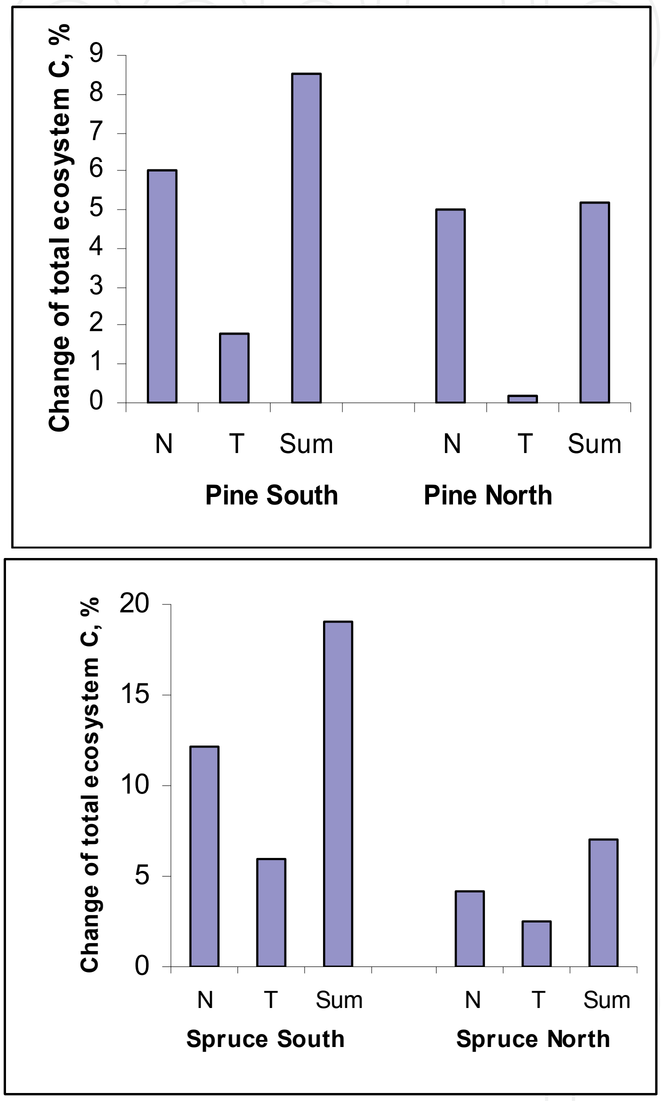

Fig. 6. Differences in total ecosystem carbon pools (sum of trees, dead wood and soil carbon) as affected by diverse ecological factors. Symbols corresponds to Fig. 4

The differences of SOM pools (Fig. 5) have the opposite trends in comparison with stand height, basal area and growing stock. The higher is the positive impact of temperature growth and N deposition the stronger is a loss of organic matter in the soil due to more intensive soil C mineralization. In terms of SOM, the effect of temperature increasing is stronger of the effect of N deposition.

The responses of total ecosystem carbon pools to climate warming and N deposition are very expressive (Fig. 6). In spite of the decrease of soil organic matter, all ecosystems accumulate carbon because significantly higher rise of stand productivity. The differences are larger in managed forest. South forests and Norway spruce stands demonstrate significantly higher response to the climate warming.

Simulation of climate change and forest management regimes at landscape level in European Russia. The generalised data of 200-year EFIMOD runs for 300-ha forest area with 108 forest compartments representing various coniferous and mixed stands are reflected on Fig. 7 and 8. The Fig. 7 shows that the more intensive is forest harvest regime the less is difference of C pools in tree biomass and soil in comparison with their values at constant climate. However, the rise of tree biomass C is higher the loss of soil C at all forestry regimes. The increase of atmospheric N deposition slightly mitigates the negative impact of forest overexploitation on soil C pools. The data on C balance (NEP, Fig. 8) clearly exhibit a positive effect of climate change at different silvicultural regimes. Selective cutting and Russian legislative scenarios have just a zero C balance in current climate with low and high N deposition. Though, they become C sequestering regimes at climate change. The scenario of legislation breach with forest overexploitation remains a C source even at climate change with increase of forest productivity.

The results of this simulation also show that other environmental factors (N deposition) and human-generated disturbances (forestry regimes) strongly modify the impact of climate change on forest territory.

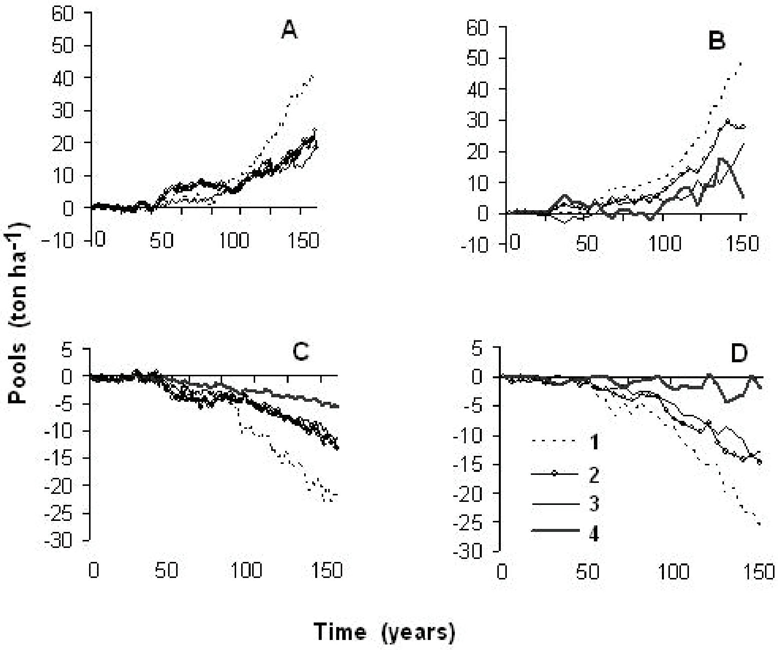

Fig. 7. Difference of C accumulation between scenarios with climate change and constant climate in forest landscape/unit in European Russia at two levels of nitrogen deposition [6 (A, C) and 12 kg ha^{-1} yr^{-1} (B, D)] for trees (A, B) and soil (C, D). Scenarios of forest management: 1, natural development, 2, selective cutting, 3, Russian legislative forest management, 4, legislation breach (Mikhailov et al., 2007)

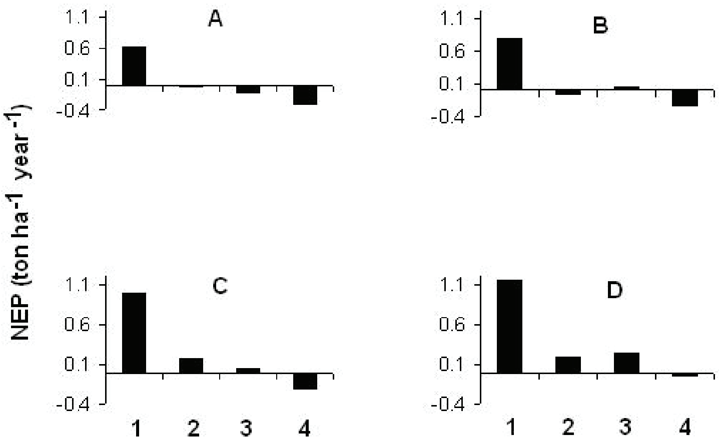

Fig. 8. Carbon balance (net ecosystem productivity, NEP) of forest landscape at constant climate (A, B) and climate change (C, D) in forest landscape/unit in European Russia at two levels of atmospheric N deposition [6 (A, C) and 12 kg ha^{-1} yr^{-1} (B, D)]. Scenarios of forest management: 1, natural development; 2, selective cutting; 3, Russian legislative forest management; 4, legislation breach (Mikhailov et al., 2007)

5. Discussion and conclusion

The results of EFIMOD model simulations to specify a possible effect of forthcoming climate warming allowed for preliminary quantification of the effects of this environmental change on boreal forests in North America and Europe. In Central Canada, the black spruce and jack pine forests respond to climate warming, fire, harvesting and insects by significant modification of net primary productivity (NPP), soil respiration (Rs), net ecosystem production (NEP) and pools of tree biomass and soil organic matter (SOM). The simulated effects of six climate change scenarios demonstrated the similar increasing trends of NPP and stand productivity. The disturbances led to a strong decrease in NPP, stand productivity, soil organic matter (SOM) and nitrogen (N) pools with an increase in CO_2 emission to the atmosphere. However the accumulated NEP for 150 years under harvest and fire fluctuated around zero. In jack pine forest, it becames negative only at a more frequent disturbance regime with four forest fires. In black spruce stands, it is slightly negative also in a case of four fire scenario as well as for harvest and two fires during the period of simulation. The results from this study show that climate warming and disturbance regimes might substantially change the NPP as well as the C and N balance, resulting in major changes in the C pools of the vegetation and soil under black spruce forests. Soil conditions, especially its productive potential determining by the N pool, modify the effect of climate change and disturbances: poor soils contrasting relative effect of climate change and damages, contrariwise more rich soil mitigates the effect of damages and climate change.

In Russia, the effect of climate change in Norway spruce forests has the same dynamic patters as in Canadian black spruce forests. However, Scots pine forests on dry sandy sites lose both soil C and forest productivity. This reaction reflects a difference of environmental condition in Canadian jack pine stands in central boreal forest with harsh continental climate and Russian Scots pine stands in rather warm climate near the border of boreal and temperate broad-leaved forests.

The results of selective analysis of EFIMOD simulations using experimental data of long-term ecological researches (Recognition project, Kahle et al., 2008) show the uniformity of forest ecosystem reactions to climate warming and N deposition changes. We can conclude that this reaction in the Central Europe is more expressive than in the North Europe, especially for growing stock in Scots pine and Norway spruce. Low response of the forest ecosystems to temperature increasing in these simulations can be explained by the lower nitrogen deposition during most part of 20th century in comparison with prognosis for 21st century. This circumstance can smooth the effect of temperature growth.

The landscape level simulation in Central European Russia shows that silvicultural regimes and atmospheric N deposition strongly modify the impact of climate warming on forest ecosystems. The higher is harvesting intensity (maximal at legislation breach scenario) the less is relative effect of climate change. Therefore the regime of heavy disturbances or forest overexploitation strongly reduces absolute amplitude of the impact of climate change (warming with slight changes of precipitation) on boreal forests. Actually the negative impact of increased disturbances (together with overexploitation) can outbalance the positive effect of climate change on forest productivity. It can lead to the decrease of carbon sequestration by forests with a positive feedback on carbon dioxide concentration in the atmosphere and climate change.

We should point out that the decrease of soil C pools at climate change was also widely reported and simulated both for forest and agricultural ecosystems (Bondeau et al., 2007; Schulze, Freibauer, 2005; Smith et al., 2005, 2006; Yurova et al., 2010). The loss of soil C can be a sign of decrease of forest stability because soil system plays a role of ecosystem stabiliser in a case of any disturbances.

The EFIMOD has no response function to simulate CO_2 fertilization effect on NPP. Its influence was evaluated only by the change in temperature and precipitations trends affecting the rate of soil processes and consumption of soil N. The increase in boreal NPP due to CO_2 fertilization remains a subject of debate (Kurz et al., 2007). Recently Bond-Lamberty et al. (2007) observed that CO_2 fertilization have no significant effect on net biome productivity of central Canadian boreal forest expect its interaction with climate (temperature and precipitation) which significantly influence the fire disturbance regime. Percy et al. (2002), from their Aspen FACE experiment which simulate open-air environment for tree growth, also concluded that positive effect of CO_2 was being overestimated insofar as the productivity of these northern boreal forests is concern.

Some ecophysiological models (Van Oijen et al., 2008) take into account the effect of CO_2 concentration on photosynthesis. Peng and Apps (1999) and Kang et al. (2006) used a simple empirical function to simulate NPP under CO_2 fertilizer effect without explicit calculation of N budget in plant and soil in boreal forests. Tree growth in these models is calculating by consistent multiplication by growth multipliers including CO_2 response. In the EFIMOD model tree growth is calculating by Liebig's bottle neck principle. So, if we take into account CO_2 influence on potential NPP, but the ecosystem has nitrogen deficit, then the tree growth will be determined only by the pool of available nitrogen. In this case, effect of NPP increase due to carbon dioxide fertilization will be equal to zero. Therefore, the including of any dependence of NPP on CO_2 concentration will also not influence tree growth in the EFIMOD.

We suppose that increasing of CO_2 concentration in the atmosphere and corresponding increasing of photosynthetic rate in forest stands on nitrogen-deficit soils can slightly increase wood increment (by formation mainly a spring lignin-poor part of tree ring). But the main mechanism of CO_2 influence supposes to be an indirect effect by the acceleration of soil processes. There is a well known "priming effect" (Blagodatskaya, Kuziakov, 2008) as the impact of easy decomposable organic compounds on the increase of slow decomposable soil C mineralization. It can take place if excessive primary photosynthetic assimilates that cannot be transformed into tree biomass (because nitrogen and other elements deficit) go to soil as root exudates. It will lead to the intensification of soil N mineralization with the increase of available for tree growth N and correspondingly to the NPP rise.

Many simulation models have been used to understand the influence of climate change and disturbances on C dynamics in boreal forests. However, EFIMOD carried out these simulations with significant feedback from the soil dynamic processes, specifically the N feedback mechanism and soil microclimatic conditions over stand age since EFIMOD uses soil climatic scenarios for soil temperature and moisture with a monthly time step allowing to include the climate change data in the simulation. The performance of the EFIMOD for boreal forests in Canada and Russia exemplifies the satisfactory results of this model implementation for these conditions. The impacts of disturbances and harvesting regimes on ecosystem C dynamics were substantial as compared to climate change alone. The feedback mechanism between aboveground NPP and changes in soil N availability under different climate change and disturbance scenarios had pronounced effects on C cycle and therefore these processes need to be more fully represented in models of forest ecosystem responses to climate change.

The data presented here describes generally a picture of forest productivity growth with reduction of soil C at climate warming with small changes of precipitation. In reality, the boreal forests along the climatic gradients have the same pattern of forest and soil changes. In Canada, the comparison of old jack pine forest at climatic gradient with identical soils along BFTCS (between Thompson and Candle Lake) with a slope of mean annual temperature 3.2°C (from -3.4 to -0.2°C) and the same summer precipitation shows a significant increase of forest productivity at warmer site (Shaw et al., 2006). The stand height increases from 10.1 to 14.7 m, DBH from 10.3 to 13.9 cm, stem C from 1.7 to 4.0 kg m^{-2}. Though this gradient is about twice higher of predicted changes by GCMs this comparison gives a clear picture of a significant rise of forest productivity at climate warming in boreal forest.

The same is clearly seen at East European Plane in Russia (Molchanov, 1961; Kurnaev, 1973; Usoltsev, 2001): there is an increase of forest productivity from North to Central taiga by one site index (Bonität) and from Central to South taiga also by one site index but with change of forest vegetation and especially soil. In ecological optimum (mesic relatively productive sites), there are raw humus gley-podzols with poor plant diversity in North taiga and modern and mull podzolic soils with rich plant diversity in South taiga. It is a main functional difference of natural climatic gradients with projected ecosystem changes reported here. It seems that fast warming does not still lead to qualitative changes of forest vegetation and soil in contrast with forest ecosystems along the natural climate gradients. Perhaps we can tell on some kind of “climatic succession” in a case of fast climate change with slow invasion of flora and fauna of warmer ecosystems and rather fast rise of net ecosystem exchange and carbon sequestration.

The very last conclusion that is obvious on the base of this simulation experiment is as follows: the NEP increase in boreal forest ecosystems in optimal edaphic conditions at climate change is an important negative feedback of the biosphere on environmental change.

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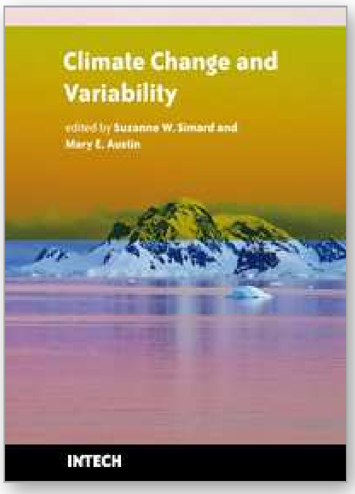

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Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.

Oleg Chertov (2010). Impact of Temperature Increase and Precipitation Alteration at Climate Change on Forest Productivity and Soil Carbon in Boreal Forest Ecosystems in Canada and Russia: Simulation Approach with the EFIMOD Model, Climate Change and Variability, Suzanne Simard (Ed.), ISBN: 978-953-307-144-2, InTech, Available from: http://www.intechopen.com/books/climate-change-and-variability/impact-of-temperature-increase-and-precipitation-alteration-at-climate-change-on-forest-productivity

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821