MODELING REGIONAL ALTERNATIVE MANAGEMENT SCENARIOS WITH FUTURE CLIMATIC CHANGE INFLUENCE ACCOUNTING

Dr. Romanenko Irina

Contact: All Russian Research Institute for Agricultural Problems and Informatics, Kharitonievsky per., 21/6 Bld.l, 103064 Moscow, Russia
e-mail:romanenko@raf.org.ru

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Abstract

The methodology of construction of the alternative agricultural production scenarios at regional level includes profitability and feasibility analysis based on assessment the effect of global climate change on productivity parameters for the main agricultural crops, cost efficiency of crop growing and cattle breeding. To propose links between economic adaptation to climate change and carbon (organic C) stock management in agricultural ecosystems for use in developing long-term adoption strategies at regional level, the regional economic-mathematical model was elaborated. It allows us to unify soil C driving variables and human environment factors.

Key words: Regional Economic-Mathematical Model • Regional Alternative Management Scenarios • Climate change • Linea Programming Task • Model of humus balance•` European Russia

Abbreviations

BAU	Business-as-usual management scenario
OPT	Optimal economic management scenario
SUS	Environmentally sustainable management scenario
HadCM3	Hadley centre climate model Version 3
SOC	Soil organic carbon
GIS	Geographical information system
IPCC	Intergovernmental panel on climate change
SRES	Special report on emissions scenarios
RAPS	Regional agricultural production systems
FYM	Farm yard manure
N	Nitrogen
C	Carbon
BCP	Bioclimatic potential

Introduction

Scientific evidence about the seriousness of the climate threat to agriculture is now unambiguous, but the exact magnitude is uncertain because of the complex interactions and feedback processes in the ecosystem and the economy. Five main factors will affect agricultural productivity: changes in temperature, precipitation, carbon dioxide (CO_2) fertilization, climate variability, and surface water runoff. Initially, rising atmospheric concentrations of carbon benefit crop growth and could offset yield losses from heat and water stress (World Bank Annual Report, 2007, Focus F).

Agricultural intensification and expanding cropland area can potentially lead to additional greenhouse gas emissions (Smith et al. 2007a). The three most common approaches to estimate the impact of climate change on socio-economic systems in agriculture are cross-sectoral models, agronomic-economic models (Rounsevell et al. 2006) and agro-ecological zones (AEZ) models

(Mendelsohn et al. 2001; Fischer et al. 2005; Metzger et al. 2006; Schroter et al. 2005). The first two approaches usually do not include adaptation, while the more comprehensive AEZ approach gives the best estimates based on existing soil-climate-crop relationships. For using AEZ as a forecasting tool, linking economic variables into the AEZ model is necessary.

The objectives of this study were to: (1) develop a set of indicators for representing sustainable development of Regional Agricultural Production Systems (RAPS), (2) integrate the impacts of different plausible future climatic changes into consistent future scenarios for RAPS, and (3) propose links between economic adaptation to climate change and carbon (organic C) stock management in agricultural ecosystems for use in developing long-term adoption strategies at regional level.

Main results of the research:

We propose a system of indicators for express analysys of regional agro-ecosystem (fig.1).

Sustainable agriculture indicator for express analysis of RAPS		
Theme	**Sub theme**	**Indicator**
Capital	Economic results	Renovation index
Nature capital	Materials consumption	Fuel per hectar
	Soil assets	Humus balance
Human capital	Incomes difference	Products consumption per capita in groups with different incomes
Integrated capital	Sustainable development	Integrated indicator: **carbon dioxide (CO2) fertilization**

Figure 1. Indicator system for express analysys of regional agro-ecosystem

Table 1. Economic and human capital indicators for express analysis of RAPS dynamics (European part of Russia)

Regions	Humus balance, t/ha·year (the sign) 1990-2005	Meat consumption per capita, kg			Renovation index for tractors, %			Fuel per hectar arable lands, tones		
		1991	2001	2005	1991	2001	2005	1991	2001	2005
North-West(Vologda oblast)	+	71	46	55	10	2,3	0,03	0,23	0,05	0,03
Central(Moscow oblast)	+ -	79	58	72	7,9	3,5	0,11	0,27	0,09	0,06
South(Rostov oblast)	-	71	38	53	7,8	1,8	1,03	0,12	0,07	0,07

The table 1 shows a considerable decrease of the main economic and human capital indicators value in 1990-2005 (table 1). As an example, three regions are presented, which are situated in the North-West of of the European part of Russia - Vologda oblast, in the center of the Non-Chernozem zone - Moscow oblast and a typical Chernozem region in the South of Russia - Rostov oblast.

The resulting indicators value are driven by some economic regulators. Among them are the external and internal ones.

The external regulators are the incomes of the people.

The internal regulators are the structure parametres of the RAPS:

the renovation index depends on the invesment volume;

fuel per hectar arable lands depends on area structure;

humus balanse depends on fertilizer doze (organic and mineral) and area structure, different groups percent in the cattle herd, animal rations structure.

The main market regulator : the part of sold agricultural production . The investment structure depends on the part of sold agricultural production, depends on the consumption volume and structure, depends on the income level.

Integrated indicator: carbon dioxide (CO_2) fertilization is a complex characteristic of the RAPS development.

For cropland, the activities that have the highest potential for storing C are afforestation, conversion of cropland to permanent grasses and conservation tillage, and better use of organic inputs (Smith et al. 2000). Lower C storage potentials include changing crop rotation, expanding the use of winter cover crops, eliminating fallow periods, changing fertilizer management, using more organic soil amendments, improving irrigation, shifting land to conservation buffers and restoring wetlands (Lewandrowski et al. 2004; Smith et al. 2000).

Table 2. Comparative scenario characteristics

Scenario	Business-as-usual **BAU**	Optimal management **OPT**	Economically and environmentally sustainable **SUS**
Criteria definition	No criteria	Maximum profitability (P to maximum)	Maximum P with $(\Delta SOC) \geq 0$ constraint
Crop yield calculation*	No climate effect on current crop yield	Economic effective yield change projected at 10-year intervals	
Crop rotation	Current 2000 rotation	New rotation pattern based on economic model outputs	
Crop growth parameters	Shifts in vegetation period according to crop growth model outputs		
Fertilization	Current 2000 rates years	Mineral N and FYM– optimal for plant nutrition , FYM rates based on outputs of economic model, correction for not exceeding ecological safe rates	

* percentage change from average 1990-2000 data for the administrative regions

To integrate the impacts of different plausible future climatic changes into consistent future scenarios for RAPS the principles, shown in the table 2, were applied.

Three land management scenarios were generated as follows: the business-as-usual scenario (BAU), the optimal economic scenario (OPT) and the economically and environmentally sustainable agriculture (SUS) scenario (table 3).

The BAU scenario (without the implementation of any adaptation strategy, with indicators value, shown in the table 1) assumes crop yield change in 2000-2070 for fixed crop rotations and fertilisation patterns. N mineral and FYM fertilisation rates were assumed to stay the same as in 2000 and applied to the most valuable cash crops in the rotation.

Among the different management practices that can potentially lead to C sequestration, the following have been tested: cropping rotation change, improved crop nutrition, organic fertilisation and more extensive use of perennial crops. Because the effects of the practices are interactive, several

key factors were taken into account to make predictions feasible, (a) the possibility for increasing primary production is based on the positive effects of future climate on crop productivity and also on improved crop nutrition (Izrael and Sirotenko 2003), and (b) the introduction of cropping systems that include perennial forage legumes or grasses, based on regional demands of fodder for cattle breeding and adequate supply of mineral N.

Intensified cropping systems were proposed where climate change lengthens the growing season, thus enabling early ripening crops, with winter crops to reduce the period where the soil is bare. On the other hand, the fallowing frequency was increased in the continental south-east regions of Russia where the arid farming zone is expected to expand, with severe limitation of crop yields through reduced water availability.

The OPT scenario assumes an optimal RAPS structure and rotation for maximising profit. Yield forecasts of the Soil-Climate-Yield model (Sirotenko et al. 1995) for optimal N fertilisation in dryland conditions were used. Fertilisation rates in the OPT and SUS scenarios can alleviate nutrient mining and thus prevent depletion of the SOC pool whilst enhancing crop residue inputs (Janzen et al. 1998; Lai 2004). N fertilisation rates and timing were also optimised based on fertiliser recommendations for optimal yields. FYM rates were equal to outputs of livestock farming production of the region and were not allowed to exceed ecologically safe rates.

In the SUS scenario, profit maximisation was additionally restricted by imposing the condition that management must maintain or increase soil C. The combined effect of different management practices on steady-state C values was estimated using the static Model of Humus Balance (Shevtsova et al. 2003) and only those found to maintain or enhance SOC levels were used. The SUS scenario assumes that row crops are mostly replaced with grasses in crop rotations. As this model was developed for soddy-podzolic soils, the last scenario was implemented for only 19 of the 47 regions, i.e. those with podzoluvisol soils.

The main parts for the following research work were:
- model for alternative management scenarios assessment elaboration;
- model calibration on regional information.

The regional economic model is a core model for research, which tracks the processes of crop agricultural production, livestock farming and fodder production, as well as soil fertility reproduction, defined for the available land resources of the RAPS. Economic data necessary for constructing alternative management scenarios from 47 regions of European part of Russia for period from 1990 to 2005 were collected. The regional economic model e includes an interrelated system of several submodels (fig.3), which tracks the processes of agricultural crop production, livestock farming production (separately for different animal systems), fodder production and soil fertility reproduction, defined for the available land resources of the RAPS. Relationships within the each submodel are based on balance calculations, linear and nonlinear functions and normative information. The model outputs for future scenarios assume regional RAPS change as a result of land-holder adaptation to climatic change only in the livestock farming and cropproduction sectors. A distinct feature is the assessment of soil fertility dynamics based on driving parameters from other submodels (crop yield, mineral and organic fertilizer rates, etc.).

The model provides information on costs, incomes and profits for the specific production practices (including crop rotations and production inputs) using a whole-system approach.

The RAPS parameters that define the profit gain or loss are the percentage of cows in the cattle herd, and the share of marketable production in the crop sector. Percentage of cows in the cattle

herd determines whether a farm specializes in milk or meat production. Milk production in most regions of Russia is currently profitable, but meat production is not (Agriculture in Russia 2002, 2006). The ratio of market prices for different types of agricultural production is considered to be stationary. Linking of the model results with map units is based on the definition of a 10-year crop sequence within the calculated crop pattern. Changes in the livestock farming and crop production sectors are based on the solution of general linear programming (Ognivtsev and Siptitz 2002; Romanenko 2005b, c).

The main output parameters for evaluation include the structure of arable land, application rates of FYM and mineral fertilizers, percentage of cows in the cattle herd, the structure of livestock feed rations, and the share of marketable production in the crop growth sector.

Regional specialization in the long-term is connected with changes in the highest possible yield for the main crop/region driven by climatic scenarios. Baseline figures of crop productivity were average yield data for 1990-2000 for the administrative regions, available from agricultural statistics (Agriculture in Russia 1998, 2002). The procedure of scenario construction includes the following successive steps:

- summing croplands for all crops within the classes: cereals, row crops, and grass;
- defining the dominant crop within each class/region (potatoes or sugar beet for row crops, wheat or barley for grain crops, etc.);
- identification of attributive data (the highest possible and real yields, sale price of the specific product, etc.) assuming only dominant crop growing within the class; and
- calculation of costs for the specific crop across regions.

The normative sources for determining the structure of livestock farming and crop production sectors within each unit are soil texture, initial soil C content (soil database), potential yield of the main crops (a dynamic crop growth model Climate-Soil-Yield outputs according four different climate scenarios; Smith and Powlson 2003; Smith et al. 2007b, c), milk, livestock and crop production input and output standards per 1 U (head) and 1 ha (Kuznetsov et al. 2002), metabolizable energy and dry matter per unit weight of the feedstuff component (Planning Agriculture Handbook 1974), constraints on regional crop rotation systems and share of the foodstuff components in animal rations (Planning Agriculture Handbook 1974), with correction of mineral fertilization rates so that they do not exceed ecological safe rates.

The crop model projected grain crop (with no detail for the specific cereal) and grass yield changes, given as percentages under limited or optimal N fertilization in dry-land conditions (Sirotenko et al. 1995). Simulated climate outputs were the same as those used in Smith et al. (2007c), i.e. data 2000-2070 from the HadCM3 climate model (IPCC 2001) using four IPCC emission scenarios—A1FI, A2, Bl, B2 (Nakicenovic et al. 2000)—were used for the crop modelling. HadCM3 provides a warming projection for the region by the year 2010 in the middle of the range given in IPCC. The climate database with 0.5° resolution and monthly mean data was used as inputs for those sites within the administrative divisions at which the crop model was run. Other model outputs include a shift in emergence and harvest dates due to climate change, and changes in crop growth rate in the specific administrative divisions (Sirotenko et al. 1995).

Baseline figures for the calculation of crop productivity change were average yield data for 1990-2005 for the administrative regions, available from agricultural statistics (Agriculture in Russia 1998, 2002, 2006). Change in the yield of row crops was calculated separately for sugar beet, sunflower, fodder roots and potatoes as follows: modern agro-climatic analogues of future climate were found based on the sum of T > 10°C, the vapour deficit and the temperature of the coldest month of the year (Sirotenko and Pavlova 2003). For the RAPS systems without adaptation, current yields of modern analogues were used for the economic modelling. For the system including adaptation, the highest possible yield under optimal mineral fertilization strategy of the current agro-climatic analogue for the specific row crop/region was used (Methodology and standards of estimation mineral fertilizer requirements in agriculture, 1983). At the same time, extrapolation from the modelled grain crops and grasses based on the statistical approach for row crop yield prediction was unsatisfactory. The possible role of soil in this is important, but its exact role remains uncertain and adds complexity to the assessment. Besides, analysis of potato yields under optimal fertilization revealed only small changes from region to region.

The economic model describes the crop rotation structure as the percentage of cereals, row crops and grass (annual or perennial). Defined rotational patterns for each region were constructed based on a 10-year crop sequence, in accordance with agricultural statistics and expert knowledge. The output percentages were rounded to the nearest 10. The procedure of assigning specific crops to the specific year in the RAPS was followed by identifying the sowing and harvesting dates and the fertilization pattern during the 10-year rotation. Future sowing and harvesting shifts were available for spring cereals and grass as outputs of Climate-Soil-Yield model, or were set using expert judgement for winter cereals and row crops, based on the analysis of dynamics of the vegetation periods from current agro-climatic analogues.
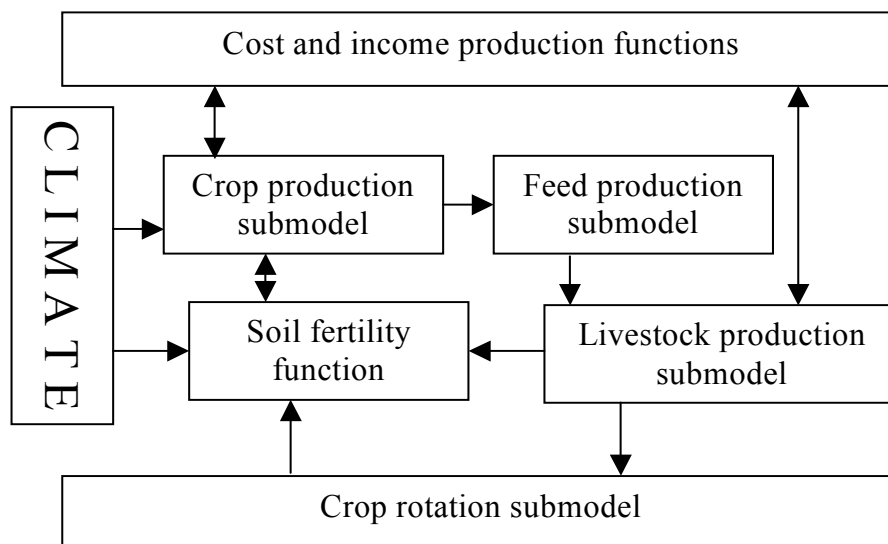

Figure 2. The economic-mathematical model structure

The list of necessary equations(functions) in the model includes:
- Soil fertility function (Humus balance);
- Manure production function (depends on livestock structure and number);

- Livestock structure and number functions (depends on feed production volume and structure);
- Feed production volume and structure (depends on crop production volume and structure);
- Crop production structure (depends on arable land structure);
- Crop yield functions;
- Cost functions for crop and livestock production (fig. 2).

A distinct feature of the model is the assessment of soil fertility dynamics based on driving parameters from other submodels (soil texture, initial soil C content, the arable land structure, crop yield, mineral and organic fertilizer rates, etc.).

Livestock production input and output standards per 1 U (head) are based on the metabolizable energy and dry matter per unit productivity (weight and milk) of the feedstuff component (Planning Agriculture Handbook 1974). That's why the number and structure of the cattle herd depends on the arable land structure and crop yield.

Climate-Soil-Yield crop growth model was used for yield forecasts (Sirotenko et al., 1995). It takes to account the resource variability (such as water and nutrients, bioclimatic potential). A dynamic crop growth model Climate-Soil-Yield (Sirotenko et al. 1995) has been run separately for each 10-year interval for all Russian and Ukrainian administrative regions (2000-2050), and the results of the crop model were then used as inputs for the economic model to select adaptation strategies.

The economic model solves a profit maximization routine based on costs and profits per unit of production using linear constraints, the main of which are:

arable land cannot exceed the amount existing in the region;

percentage of cows in the cattle herd cannot exceed 67% (reproduction constraint); and

share of the foodstuff components in animal rations is not more than normative ones.

Criteria description

$$P = \sum_{\tau=1}^{T} [\Omega \sum_{i=1}^{K} \delta_i s_i(\tau) Y_i(\tau) C_{i\,prod}(\tau) + N(\tau)\{\alpha(\tau) U(\tau) C_{milk}(\tau) + M(\tau) C_{meat}(\tau) - Z_M(\tau)\} -$$

$$- \Omega \sum_{i=1}^{K} Z_i(\tau) s_i(\tau)] \rightarrow MAX\{s_i(\tau), N_y(\tau), \delta_i, \alpha(\tau)\},$$

P – profit, rub.;
Ω – arable land of the region, ha;
τ – year number, $\tau \in 1 \div T$;
δ_i – the share of sold i-crop production;
$s_i(\tau)$ – the share of the i-crop in the arable land of the region;
$Y_i(\tau), C_{i\,prod}(\tau)$ – the yield (tones per hectar) and the price (rub.)of the i-crop production unit;
i – the type of the crop production, $i \in 1 \div K$;
$N(\tau)$ – the number of cattle herd;
$\alpha(\tau)$ – the share of the cows in the herd;

$U(\tau)$ –milk productivity per cow, kg;

$C_{milk}(\tau), C_{meat}(\tau)$ - the milk and the meat unit realization price, rub.;

$M(\tau)$ – meat productivity per head, kg;

$Z_M(\tau)$ – production costs per head, rub.;

$Z_i(\tau)$ – production costs per hectare of the i-crop (rub.).

Parameters to determine:

- Arable land structure, $s_i(\tau)$

- Fertilizer doze (organic and mineral), $N_y(\tau)$

- Cows percent in the cattle herd, $\alpha(\tau)$

- Part of marketable production in crop sector, δ_i

For definition of geographical subdivisions with unique sets of driving variables several maps were used. The Soil Map of the Russian Federation, the Map of Land Use in the Soviet Union, the Map of Natural–Agricultural Zoning of the Soviet Union were adjusted to administrative boundaries of 47 administrative regions in the European Russia, which are the basic units for agricultural statistics and economy analysis (Rukhovitch et al., 2005). The linked land-use, soil and meteorological layers give 200 units characterised by the maximum possible uniformity with respect to climatic, soil, economic, and land-use parameters.

Economical expertise of crop productivity forecasts makes it possible not only to define agronomically feasible yields, but also top define an inter-related set of other management and economic parameters of specific land management practices which have been verified in many environments.

Profitable agriculture management scenarios were built for 47 regions of European Part of Russian Federation; for each region according to 4 climatic scenarios with 20 years step (2010, 2030, 2050) a linear programming task was solved to find an optimal structure of land-use with profit maximization;

Sustainable agriculture management scenarios were built for 19 regions of Nechernjzemnaya Zone of Russia; for each region according to 4 climatic scenarios with 20 years step (2010, 2030, 2050) a linear programming task was solved to find an optimal structure of land-use with profit maximization plus $\Delta C \geq 0$ constraint, where ΔC is soil organic carbon (SOC) per year balance.

The model provides definition of the following variables, which characterize different land use systems:

Crop area structure, share of different livestock groups, organic and mineral fertilizer doze.

Conclusions

After linking the results of land management changes of RAPS under modelled scenarios and modelled soil C by three soil carbon models—RothC (Jenkinson and Rayner 1977), CANDY (Franko et al. 1995, 2007) and the Model of Humus Balance (Sirotenko et al. 2002) the estimation of the impacts of climate change on agricultural soil carbon stocks in the European Russia and Ukraine was done. These models have been shown to perform well for agro-ecosystems of the former Soviet Union (Smith et al. 2001; Shevtsova et al. 2003). The dynamic models, RothC and CANDY, were run through the 70-year period of 2000-2070 for each soil group within each unit (Smith et al. 2007c; Franko et al. 2007). The statistical Model of Humus Balance was tested for assessment conditions of zero C change or C accumulation in the selected years for the zone of podzoluvisols (Romanenkov et al. 2007). The RothC and CANDY model year-end SOC outputs (t ha"1) were multiplied by the proportion of that soil group in the unit and weighted mean soil C values within each unit were calculated for the each year from 2000 to 2070. The resulting values of SOC were analysed to determine the total SOC changes in cropland for 70 years as Tg per unit and assess aggregated impacts of changes in management practices or t ha"1.
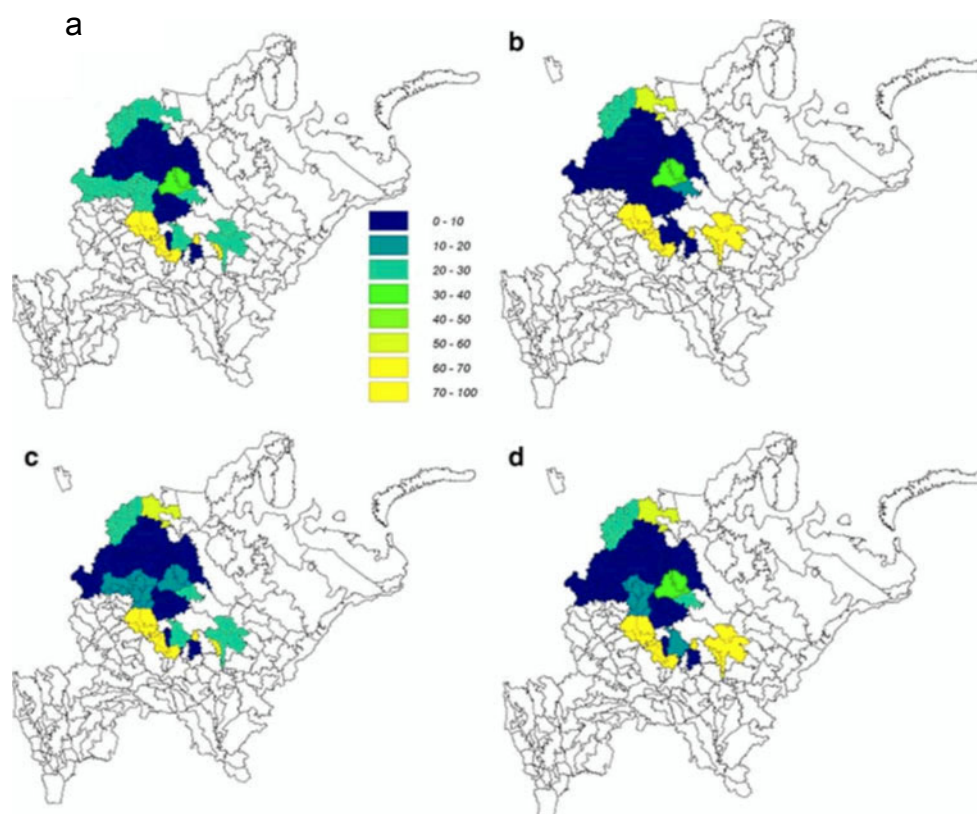
Figure 3. Maps showing the change in costs for maintaining or increasing SOC stocks in 2050 across the four climate scenarios for 19 regions of European Russia representing the podzoluvisol zone, as a percentage of total RAPS income; a A1FI, b A2, c Bl and dB2 (Romanenko et al. 2007)

per unit to access local impacts of the practices. This criterion was used to constrain the management whereby the SOC may not decrease or increase, thereby defining the management used in the SUS scenario. The results were then used for comparing BAU- OPT and SUS scenarios for the selected 19 administrative regions as described in Smith et al. (fig.3).

Comparing the average SOC stock over the final 10 year rotation (2050-2069) with the starting SOC value shows that SOC stocks can be increased (-0.9, 2.0, 1.2 and 3.1% increase for SUS under the A1FI, A2, Bl and B2 climate scenarios, respectively, compared to losses of 7.5, 5.0, 5.9 and 4.3% for BAU for the same climate scenarios).

The economically sustainable management scenario (SUS), though applied for only a limited area within the total region, suggests that for this region at least, economically sustainable land management could not only reverse the negative impact of climate change, but could increase soil carbon stocks, most effectively in the B2 climate scenario (Smith et al. 2007c).

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