

Changes in mineral soil organic carbon stocks in the croplands of European Russia and the Ukraine, 1990–2070; comparison of three models and implications for climate mitigation

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Abstract Three soil carbon models (RothC, CANDY and the Model of Humus Balance) were used to estimate the impacts of climate change on agricultural mineral soil carbon stocks in European Russia and the Ukraine using detailed spatial data on land-use, future land-use, cropping patterns, agricultural management, climate and soil type. Scenarios of climate were derived from the Hadley Centre climate Version 3 (HadCM3) model; future yields were

determined using the Soil–Climate–Yield model, and land use was determined from regional agricultural and economic data and a model of agricultural economics. The models suggest that optimal management, which entails the replacement of row crops with other crops, and the use of extra years of grass in the rotation could reduce Soil organic carbon (SOC) loss in the croplands of European Russia and the Ukraine by 30–44% compared to the business-as-usual management. The environmentally sustainable management scenario (SUS), though applied for a limited area within the total region, suggests that much of this optimisation could be realised without damaging profitability for farmers.

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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
UNFCCC	United Nations framework convention on climate change
RothC	Rothamsted carbon model
GIS	Geographical information system
IPCC	Intergovernmental panel on climate change
SRES	Special report on emissions scenarios
PET	Potential evapotranspiration
RAPS	Regional agricultural production systems
FYM	Farm yard manure
N	Nitrogen

C	Carbon
IOM	Inert organic matter
BCP	Bioclimatic potential

Introduction

Russia ratified the Kyoto Protocol to the 1992 United Nations Framework Convention on Climate Change (UNFCCC; available at: www.unfccc.de), bringing it in to force on 16 February 2005. This allows Russia to use and to trade biospheric carbon sinks for the first commitment period (2008–2012) as outlined in the Kyoto Protocol and elaborated at the 7th Conference of Parties (COP7). Soil carbon sinks (and sources), as well as above-ground stocks of carbon, can be used as biospheric sinks. A number of studies have examined the possibility of using soil carbon sequestration as a climate mitigation option (e.g. Lal 2004; Smith 2004a).

Many studies have examined the potential for climate mitigation in agriculture in Europe (Smith et al. 2000, 2001a, 2005; Sleutel et al. 2003; Dendoncker et al. 2004) and globally (Cole et al. 1997; Lal 2004; Smith et al. 2007b), as well as in other regions of the world such as North America (Lal et al. 1998; Kimble et al. 2002), but soil carbon sequestration potential for the croplands of European Russia and the Ukraine has received little attention (Smith et al. 2007a), despite the very large areas under arable cropping in this region.

Although a few studies have examined the potential impacts of climate change on the organic carbon stocks of mineral soils in Europe (Smith et al. 2005, 2006), Russia and the Ukraine were not included in these studies. In a recent study, reported by Smith et al. (2007a), one model [the Rothamsted Carbon Model (RothC); Coleman and Jenkinson 1996] was used to estimate how cropland mineral soil carbon stocks are likely to change under future climate. In the study reported here, we compare the results of three models of soil organic carbon (SOC) change, RothC (Smith et al. 2007a), CANDY (Franko et al. 1995) and the Model of Humus Balance (Shevtsova et al. 2003), all run within the same area using common spatial datasets. We compare and contrast the model results and discuss the implications for uncertainty and climate mitigation.

Materials and methods

Common spatial datasets

The geographic window

The geographic window, within which the study was performed, covers the area: longitude 19°–67°E; latitude

41°–77°N, used within the INTAS-funded Modelling Agricultural Soil Carbon sinks in the European part of the Former Soviet Union (MASC-FSU) project. The region, which is only about 20% of the country's territory, includes 74 mha of arable land in European Russia, which represents 59% of total Russian arable land (Romanenko et al. 1998). It comprises 47 administrative regions (oblasts), which are the basic units for agricultural statistics and economic analysis (Russian Statistical Agency 2000). Polygons were derived from the soils map (see below), adjusted to administrative boundaries, giving 200 U that are assumed to be homogenous with respect to soil, climate, economic and land-use parameters. The procedure was slightly different for the Ukraine, as this region is much more uniform with respect to the above-mentioned factors, so the aggregation procedure results in fewer, larger units. For 31 mha of arable land, 12 landscape-production areas have been identified by overlaying meteorological and land-use information with current agricultural statistics for 25 administrative regions of the Ukraine. The total number of polygons within the window is 212. The details for this linkage within a Geographical Information System (GIS) are described in this issue in Rukhovich et al. (2007).

Climate data, 1990–2070

Monthly temperature and precipitation for each polygon were determined from climate data downloaded from the University of East Anglia, Climate Research Unit (Mitchell et al. 2004) at 0.5° resolution. Monthly values were provided 1990–2070 using outputs from the Hadley Centre climate model (HadCM3) forced by four Intergovernmental Panel on Climate Change (IPCC) CO₂ emissions scenarios reported in the Special Report on Emissions Scenarios (SRES; Nakićenović et al. 2000). The four climate scenarios examined (based on the emission scenarios) were A1FI (“world markets-fossil fuel intensive”), A2 (“provincial enterprise”), B1 (“global sustainability”) and B2 (“local stewardship”; Nakićenović et al. 2000; Parry 2000; Smith and Powlson 2003). Potential evapotranspiration (PET) for each polygon was calculated according to Ivanov (1957). Climate data were available for all polygons.

Soil data

Mean SOC stocks in t C ha⁻¹ to 20 cm depth (calculated from percentage carbon content and bulk density), together with the percentage clay content in that layer, were derived from the Dokuchaev soils of Russia and Ukraine databases derived from the Soil Map of the Russian Federation

(1:2,500,000), the Map of Land Use in the Soviet Union (1:4,000,000) and the Map of Natural–Agricultural Zoning of the Soviet Union and the database of Russia's soils based on published and reference data. The database was constructed using the division of soil types, granulometric composition, administrative unit, natural and agricultural zoning, and the percentage of cultivated soil in the polygon. Differences in agrochemical properties (including soil C content) and soil profiles for natural soils, cropland soils and rangelands were taken into account when deriving SOC. Each mapping unit is characterised by 1–4 different soils or soil complexes. Complexes include 1–3 from the 205 possible soils. Therefore, one mapping unit of the Soil Map can represent a maximum of $4 \times 3 \times 2 = 24$ soils. It was assumed that the share of ploughed soils within the specific complex is the same for each soil. These data were then fitted to administrative boundaries (Rukhovich et al. 2007). SOC and percentage clay content were available for all 212 polygons. Significant changes (including land abandonment) occurred during the 1990s, but abandoned land is not explicitly included in this study since data on the presence and location of these lands do not exist at sufficient resolution.

Land management data

The methodology for construction of the scenarios was based on a description of the regional agricultural production systems (RAPS), which were constructed by linking information on crop rotations, fertilisation practices, vegetation period and crop growth characteristics (Romanenko 2005). A regional economic model was then used, which tracks the processes of agricultural crop production, livestock production (separately for different branches), fodder production and continuation of soil fertility, defined for the available land resources of the RAPS, as described in Romanenko (2005). For each scenario, the rotation, crop that year, harvest date, crop yield and farm yard manure (FYM) addition was specified for each polygon for each year between 1990 and 2070. 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.

The BAU scenario (without the implementation of any adaptation strategy) 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. In 1990–2000, there was ninefold decrease in the application of mineral fertilisers, and an

approximate sixfold decrease in organic fertiliser applications in Russia. Not more than 50 kg N ha^{-1} and $4.9 \text{ t FYM dry matter ha}^{-1}$ were applied each year (average rates for arable land in 2000 were 8 kg ha^{-1} and 0.6 t ha^{-1} , respectively). 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; Lal 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. Table 1 summarises the characteristics of the three scenarios. Further details are given in Romanenko et al. (2007).

Table 1 Comparative characteristics of the scenarios

Scenario	Business-as-usual (BAU)	Optimal soil management (OPT)	Economically and environmentally sustainable (SUS)
Criteria definition	No criteria	Maximum profitability (P)	Maximum P with (Δ SOC) \geq 0 constraint
Crop yield calculation	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		
Fertilisation	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	

Crop yield calculation was expressed as a percentage change from the average 1990 to 2000 yield for each administrative region

The models

The CANDY model

The CANDY model (Franko et al. 1995) was first tested and adjusted to run under Russian conditions and was shown to simulate SOC dynamics well in this region (Franko et al. 2007). CANDY was used for all four different climate scenarios in combination with three management options. The model structure was extended to use monthly climate data. Averages of temperature and radiation were used for each day in the month and rainfall was distributed over the number of rainy days in the month. Since it was not possible to estimate the number of rainy days each month accurately, the value was set to ten for each month, as soil organic matter dynamics were found to be relatively insensitive to the rainfall distribution. The usual format of climate data is dbf-files, but for this application the model was extended to accept data held in MS-ACCESS format.

The model parameters for crop residues were calibrated using data from long-term experiments. Because of lower yields in Russia and the Ukraine compared to Central Europe, it was necessary to adapt the parameters needed for the calculation of the amount of organic matter entering the soil from crop residues and roots after harvest. The general relationship was then also applied to crops that were included in the management scenarios.

Data for soil physical parameters were derived from soil data in Russia. The CANDY model requires soil parameters for each horizon within the rooting depth. The soil parameters provided in the Russian databases were transformed to meet the requirements of CANDY. As soil texture is quite important for soil organic matter turnover and is also very important for a number of physical properties, it was important to transform the texture parameters from the Russian standard to the German standard that is used in CANDY. All other topsoil parameters were used as provided in the database. The depth of the total profile had to be estimated from the description of the soil type, distin-

guishing between shallow and deep soils. In general, the bulk density of lower soil horizons increased compared to the topsoil.

The simulation runs were made in daily time steps from 1991 to 2070, assuming that the soil organic matter in 1991 was in steady state according to the management data from 1991 to 2000. CANDY was run for two scenarios, BAU and OPT, as described above. Following the procedure described above, there were 305 simulation objects. Simulation results were written to an MS-ACCESS database. The result records contain reproduction rate of soil organic carbon (C_{rep}), content of decomposable soil organic carbon (C_{dec}) and biologic active time (BAT) as an index for turnover activity. For representation in thematic maps, the data were aggregated according to the abundance of the soil types in a selected unit. In order to indicate changes, the difference in values between 1991 and 2070 were calculated.

The Rothamsted carbon model (RothC)

Rothamsted carbon model is one of the most widely used SOC models (e.g. Jenkinson et al. 1991; Post et al. 1982; McGill 1996) and has been evaluated in a wide variety of ecosystems including croplands, grasslands and forests (e.g. Coleman et al. 1997; Smith et al. 1997b). RothC and SUNDIAL, the model that incorporates RothC but also includes nitrogen dynamics, have been shown to perform well in the croplands of Russia and the Ukraine when compared against data from long-term experimental sites (Smith et al. 2001b; Shevtsova et al. 2003; Smith 2004c). Further, when compared to a statistical model, constructed from experimental data on SOC change from 60 long-term experiments in the Russian Federation, Belarus, Ukraine, Latvia and Lithuania (838 records with the time span varying from 7 to 60 years), discrepancies between RothC and the statistical model were <0.02% for equilibrium SOC stock calculations for 2010, 2030 and 2050 climate under business-as-usual management (BAU), further demonstrating that RothC works well for agricultural mineral

soils in this region (Romanenkov et al. 2007). RothC does not simulate erosion losses.

Rothamsted carbon model has been used to make regional, continental and global scale predictions in a variety of studies (Wang and Polglase 1995; Post et al. 1982; Falloon et al. 1998b; Tate et al. 2000; Smith et al. 2005, 2006). The model was adapted to run with large spatial datasets and to use PET in place of open pan evaporation (Smith et al. 2005, 2006) as described in Smith et al. (2007a).

The method of running the model was described in Smith et al. (2007a) and is summarised here. For each soil unit within each polygon, the model was run to equilibrium at 1990 using the specified clay content and the mean soil carbon inputs and mean annual FYM during the first decade of data provided. The initial carbon content of the soil organic matter pools and the annual plant addition to the soil were obtained by running the model to equilibrium under constant environmental conditions (Coleman and Jenkinson 1996). The constant climatic conditions were taken to be the average of climate data for 1990–2000. RothC is known to be relatively insensitive to the distribution of C inputs through the year; the proportions of plant material added to the soil in each month were set to describe the pattern of inputs for typical arable crops in Russia and the Ukraine, as given in Table 2.

After the first equilibrium run using the input distributions in Table 2, the annual plant addition was adjusted to give the measured soil carbon content given in the soils database with the inert organic matter (*IOM*) fraction set according to the equation given by Falloon et al. (1998a) as described in Smith et al. (2007a) to fit to measured SOC. The simulations were continued from 1900 to 2000 using the measured climate and predicted climate, and land use data were used to run the simulations between 2000 and 2070.

Farm Yard Manure inputs to the soil were specified for each scenario. FYM inputs varied according to crop and management scenario (see above and Romanenko 2005). For each crop in each year, the FYM addition (in a specified month) was read from the scenario database and used directly by the model. Carbon inputs to the soil as crop debris in each polygon were calculated from the change in yield for each crop in each year as predicted for each climate scenario by the Soil–Climate–Yield model (Izrael and Sirotenko 2003), which incorporates the effects of changing management and climate on crop yield. Changed sowing and harvest dates were also simulated by Soil–Climate–Yield and were used to adjust the period of crop cover for each crop. Impacts of increasing atmospheric CO₂ concentration were included in the yield estimates of Soil–Climate–Yield, based on CO₂ concentration growth in the climate scenarios examined. Crop yield changes dif-

Table 2 Distribution of carbon inputs to the soil (as a proportion of the total annual input) and plant cover (1 = ground covered, 0 = ground bare) for each month for grass, crops under-sown with grass, spring crops and winter crops as used by RothC (adapted from Smith et al. 2007a)

Month	Grass and under-sown crops		Spring crops		Winter crops	
	C input proportion	Plant cover	C input proportion	Plant cover	C input proportion	Plant cover
1	0.05	1	0	0	0	1
2	0.05	1	0	0	0	1
3	0.05	1	0	0	0	1
4	0.05	1	0	1	0	1
5	0.1	1	0.167	1	0.167	1
6	0.15	1	0.167	1	0.167	1
7	0.15	1	0.167	1	0.167	1
8	0.1	1	0.5	1	0.5	1
9	0.1	1	0	0	0	0
10	0.1	1	0	0	0	1
11	0.05	1	0	0	0	1
12	0.05	1	0	0	0	1

fered among climate and land-use scenarios (see Table 1). A change in C input to the soil proportional to the yield change was assumed (Smith et al. 2007a). Because crop yields during 1990–2000 were used as baseline yield, results were analysed from 2000 to 2070. The model was run to the year 2070 for four climate scenarios, A1FI, A2, B1 and B2, and for the three management scenarios, BAU, OPT and SUS as described above, giving 12 combinations of climate × management scenarios.

The model of humus balance

The Model of Humus Balance relates data on the climate, soil and land management practices to simulate the conditions necessary for sustaining the SOC level, and it estimates possible effects of changes in land management on C sequestration (Shevtsova et al. 2003; Romanenkov et al. 2005; Sirotenko et al. 2005). It was developed initially as a regression model in the 1980–1990s for assessing the effect of changes in agricultural practices on the SOC balance in arable soddy-podzolic (FAO: podzoluvisol) soils (Shevtsova et al. 1992). The database for the model was developed from 60 long-term experiments in the Russian Federation, Belarus, Ukraine, Latvia and Lithuania (838 records with the time span varying from 7 to 60 years). Integrating information from many field experiments allows a reduction of several sources of error and, therefore, more reliable estimates (Kätterer and Andrén 1999).

To answer the question if the SOC response to cultivation is climatically controlled, meteorological indices were introduced in the database as independent variables. These indices represent output data from the Climate–Soil–Yield dynamic model, calculated locally for the study period at each of the sites (Sirotenko et al. 1995). The latest version of the model, used here, describes C dynamics as mean annual changes in C stocks;

$$\Delta C = f(C_{\text{init}}, L, M, N, R_p, G_p, H, BCP) \quad (1)$$

containing the eight driving variables: C_{init} , initial C content (%); L , content of soil particles <0.01 mm (%); M , annual FYM (farmyard manure) rate for the modelling period ($\text{Mg ha}^{-1} \text{ year}^{-1}$); N , annual mineral N rate ($\text{kg ha}^{-1} \text{ year}^{-1}$); R_p , per cent of row crops and fallow in the rotation (%); G_p , per cent of perennial grasses in the rotation (%); H , humidity coefficient (precipitation/evaporation ratio per growing season ($T > 5^\circ\text{C}$)); BCP, bioclimatic potential corresponding to a permanent grassland yield under multi-cutting regime during the growing season ($\text{kg } 10^3 \text{ ha}^{-1}$).

To provide for an even geographical distribution of the sites, some treatments were excluded from the database. The best-fit structure was identified on the basis of double and triple non-linear interactions between parameters, and posterior information on their interdependence. Estimates of the values of parameters are shown in Table 3. Probability estimates of all the values were <0.02 and significant within 98% of the confidence interval. Standard deviation of the model was 0.01605, and the multiple correlation coefficient was 0.78. The model can be applied within an L -value range from 20 to 45%. The most significant variable was C_{init} , as this mainly controls the intensity of biochemical processes in the soil. The significance of L as the driving variable is explained by the role of surface area in the activity of biogeochemical soil processes. The relationship between C_{init} and L is mediated by the rotation system and humidity coefficient (Table 3). The specificity of rotation systems can be defined as the ratio between R_p ,

G_p and cereals. The per cent of cereals is calculated as $100 - (R_p + G_p)$. The BCP controls phytomass production and, hence, C inputs from the above- and below-ground parts of plants. The decomposition rate is controlled by H and increases with an increase in the soil moisture content (up to a certain limit). Relationships were found between the potential productivity (BCP), fertilisation efficiency (FYM and N rates) and soil fertility (initial SOC level). The influence of the per cent of row crops in rotation on the SOM dynamics is expected to be dependent on soil texture.

The model was used for regional and local modelling. On a local scale, the model was used for choosing optimal fertilisation practices and crop rotation systems, providing rotations that were either stable or increased the initial SOC level (Romanenkov et al. 2005), for defining the SUS scenario for other models (see below). By linking the model to the GIS database, it is possible to outline the areas where the effect of changes in management practices will be most pronounced and to suggest optimal land management strategies for particular regions. For the Moscow Region it was demonstrated that a change in the crop rotation system is a more promising option for additional C sequestration compared to additional FYM application (Savin et al. 2002).

The model was run (a) with the economic model for choosing SUS scenarios among the different management practices based on maintaining or enhancing SOC levels (see section *Land Management Data*, above), (b) for equilibrium SOC stock calculations in 2010, 2030 and 2050 for climate scenarios under BAU to compare steady-state conditions of the Model of Humus Balance and RothC (see section *The RothC*, above) and (c) for calculation of mean annual changes in SOC in the years 2010, 2030 and 2050 for the four climate scenarios: A1FI, A2, B1 and B2, and for the three management scenarios: BAU, OPT and SUS as described above, giving 12 combinations of climate \times management scenarios. As this model was developed for soddy-podzolic soils, calculations were implemented for only those regions with soddy-podzolic soils, representing 19 of the 47 regions.

Table 3 Estimates of linear parameter values for all independent variables and their significance for calculating annual C changes in soddy-podzolic soils ($\%$, year^{-1}) for the Model of Humus Balance

Independent variables	Parameter values	SD	t-criteria
Constant	-7.2368×10^{-4}	2.54996×10^{-3}	-0.2838
$R_p \cdot C_{\text{init}}^{4.4} \cdot L^{0.9}$	-1.02595×10^{-5}	7.50023×10^{-7}	-13.679
$G_p \cdot C_{\text{init}}^4 \cdot L^3$	1.83512×10^{-9}	1.47516×10^{-10}	12.4402
$(M + 4)^{0.6} \cdot C_{\text{init}}^{2.7} \cdot (\text{BCP} > 40)$	6.66184×10^{-5}	9.12897×10^{-6}	7.29747
$H^{5.5} \cdot C_{\text{init}}^{3.1}$	-1.3692×10^{-2}	5.63296×10^{-3}	-2.4231
$(PP + 25)^2 \cdot \text{BCP}^{1.5}$	7.45441×10^{-9}	1.35285×10^{-9}	5.51016
$L^3 (M + 2)^{0.6}$	4.36274×10^{-8}	7.57494×10^{-9}	5.75945
$(N + 35)^{0.5} \cdot C_{\text{init}}^4 \cdot \text{BCP}^{3.3}$	1.85033×10^{-10}	6.8096×10^{-11}	2.71724
$L \cdot \text{BCP}^3$	-2.05859×10^{-9}	2.96247×10^{-10}	-6.94891

Results

Results from the CANDY model

The CANDY model suggests that the average SOC storage increases in all land management and climate scenarios (see Table 4, C_{inc}). When the mean values of C_{rep} and BAT of the first (1991–2000) and last (2061–2070) 10 years are compared, an increase of C reproduction flow under the OPT management scenario is seen. This led, in turn, to a significant increase of SOC. Biological activity increased in the A1FI, A2 and B2 climate change scenarios, but decreased slightly under the B1 scenario.

The greatest accumulation of SOC was simulated under the B1 scenario. Figure 1 shows the regional distribution of carbon accumulation for the BAU scenario. There are some spots where a carbon change takes place, but in most cases no significant changes could be detected.

Due to data limitations, the CANDY simulations were restricted to European Russia (197.5 mha arable land). CANDY calculates carbon dynamics as result of the reproduction flux of carbon (C_{rep}) into SOM and the biological activity for SOM turnover expressed as BAT. Under all climatic scenarios, BAU management was found to decrease the C_{rep} flux slightly (–5.2 to –9.3%), but the OPT management scenario led to a large increase in C_{rep} (48.3–56.6%). The climatic scenarios had a significant impact on turnover conditions when compared to current climate. The best conditions for carbon mineralisation, with an improvement of 8.6%, were found for the A1FI climatic scenario, whereas the B1 scenario leads to a reduction of turnover rates. Only with this climatic scenario (B1) could an impact of management on BAT be observed. The combination B1-BAU reduced BAT by 0.5%, whereas the B1-OPT combination gave a BAT reduction of 1.9%. BAT and C_{rep} values are quite heterogeneously distributed within the whole territory. For this reason and the non-linearity of C-dynamics, the average C balance is different as suggested by the mean BAT and C_{rep} -values.

Table 4 Aggregated simulation results from the CANDY model comparing the BAU and OPT scenarios for European Russia

Climate	Management scenario					
	BAU			OPT		
	ΔC_{rep} (%)	ΔBAT (%)	C_{inc} (t ha ⁻¹)	ΔC_{rep} (%)	ΔBAT (%)	C_{inc} (t ha ⁻¹)
A1	-9.3	+8.6	0.0085	+48.6	+8.6	6.7187
A2	-9.2	+3.2	0.2776	+51.0	+3.2	7.2801
B1	-5.2	-0.5	0.7968	+56.6	-1.9	7.9362
B2	-8.8	+1.1	0.3183	+48.3	+1.1	7.0768

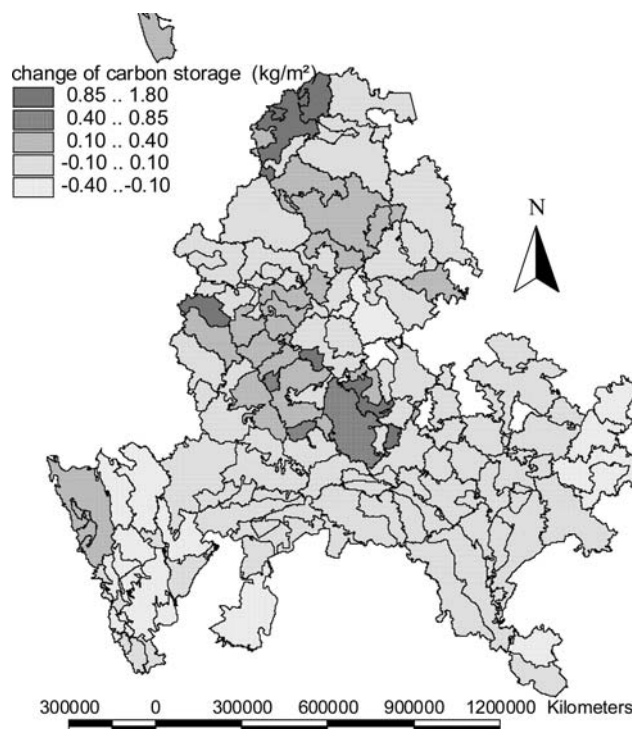


Fig. 1 Change of carbon storage in Russian cropland soils from 1990 to 2070 for a continued land use (business as usual) and the climate change scenario B1 as simulated by the CANDY model

The greatest accumulation of 1,568 Tg C of SOC occurred under the OPT management scenario, with an increase of 157 Tg C of SOC under the BAU management scenario and the B1 climatic scenario. Figure 1 shows the regional distribution of C accumulation for the BAU scenario. The lowest accumulation of 1.8 Tg C was simulated under A1-BAU scenario combination. Under the BAU scenario, accumulation of SOC ranged between 1.8 (A1-BAU) and 157 Tg C (B1-BAU), and under the OPT scenario SOC accumulation ranged between 1,327 (A1-OPT) and 1,568 Tg C (B1-OPT). The most intensive increase under the combination B1-OPT is the result of the highest C_{rep} flux and the most reduced turnover conditions. Results from CANDY are summarised in comparison with results from RothC in Table 6.

Results from the RothC model

The outputs from RothC were reported in detail in Smith et al. (2007a), but are summarised here. Under all future climate scenarios, taking European Russia and the Ukraine as a whole, RothC projects that SOC will be lost due to climate change over the next 70 years, with losses ranging from 434 (B1-OPT; Fig. 2b) to 1,098 Tg C (A1FI-BAU; Fig. 2a). Assuming no change in land management (i.e. BAU), it is projected that SOC will be lost under all

Table 5 Changes in C content change (%) under BAU management estimated by the Model of Humus Balance with C equilibrium values derived from RothC model

Scenario, year	Mean value, %	Mean change	Upper quartile	Lower quartile	SD	Skewness	Kurtosis
A1FI, 2010	1.38	0.013	-0.001	0.019	0.031	1.59	3.94
A1FI, 2030	1.68	0.012	-0.001	0.018	0.030	1.86	4.91
A1FI, 2050	1.58	0.009	-0.001	0.015	0.023	1.70	4.83
B1, 2010	1.71	0.009	-0.001	0.015	0.023	1.70	4.83
B1, 2030	1.66	0.010	-0.001	0.017	0.026	1.62	4.08
B1, 2050	1.61	0.009	-0.001	0.015	0.023	1.59	3.80

climate scenarios. More SOC is lost under the A1FI scenario (1,098 Tg for A1FI-BAU), and the least SOC is lost under the B1 and B2 scenarios (778 Tg for B1-BAU). Figure 2 shows how the change in SOC content (2060–2000) varies across the different climate scenarios for the same management scenario (BAU) (Fig. 3).

The difference between climate scenarios becomes more pronounced after the middle of the century (around 2050). The difference in total SOC lost over the whole region for different climate scenarios is shown in Fig. 4 comparing BAU and OPT. Figure 3 shows the difference in total SOC lost for the limited number of polygons for which the SUS scenario was run (for BAU and SUS).

For any given climate scenario, optimal management is able to reduce the loss of SOC by between 324 and 344 Tg, which is a reduction of the SOC loss of between 29 (A1FI) and 44% (B1) compared to BAU management. Figure 5 shows how the change in SOC content (2060–2000) varies among the three management scenarios (BAU, OPT and SUS) for the same climate scenario (B1).

The difference in total SOC lost over the whole region for the BAU and OPT land management scenarios is shown in Fig. 6. Figure 7 shows the difference in total SOC lost for the limited number of polygons for which SUS scenario could be run (for BAU and SUS). The impact of management on decreasing SOC loss in absolute terms is similar across all climate scenarios (324–345 Tg C), but in terms of the percentage reduction in the SOC loss compared to the BAU scenario, the optimal management scenario is least effective in the A1FI climate scenario (30% reduction in SOC loss) compared to the others (A2 = 39%, B1 = 43% and B2 = 44% reduction in SOC loss).

Comparing the average SOC stock over the final 10-year rotation (2050–2069) with the starting SOC value, RothC suggests that SOC stocks can be increased (-0.9, 2.0, 1.2 and 3.1% increase for SUS under the A1FI, A2, B1 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 SUS, though applied for only a limited area within the total region, suggests

Fig. 2 Maps showing the change in SOC content (2060–2000) across the four climate scenarios for the business-as-usual (BAU) management scenario; **a** A1FI, **b** A2, **c** B1 and **d** B2 as predicted by RothC (adapted from Smith et al. 2007a)

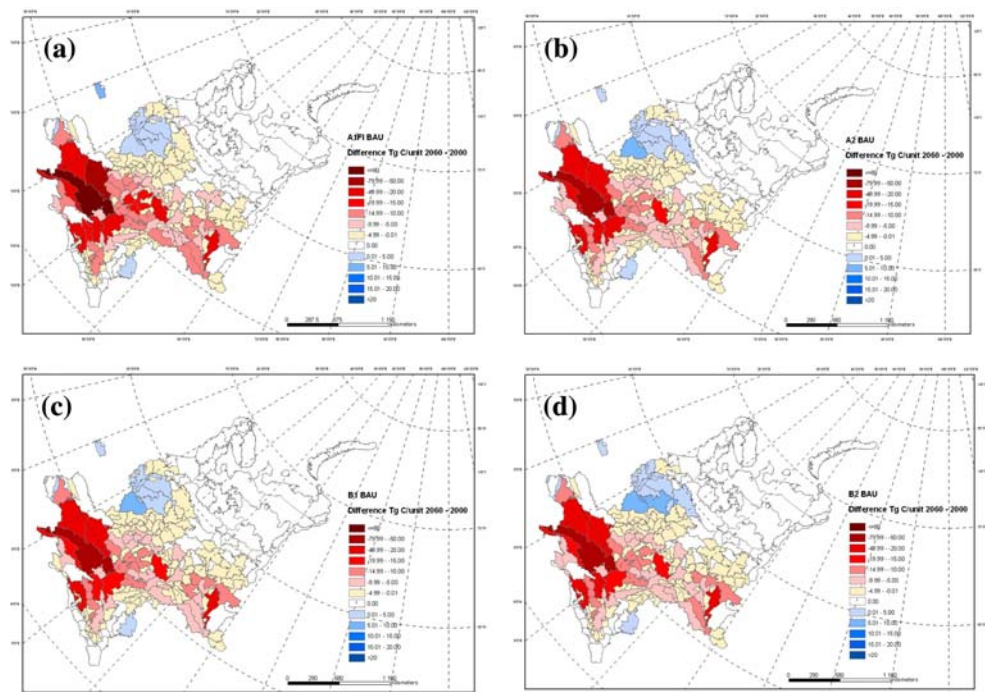


Fig. 3 Change in cropland SOC stock of European Russia and the Ukraine under the four climate scenarios, A1FI, A2, B1 and B2 as implemented by the HadCM3 climate model; **a** Business-as-usual management (*BAU*), **b** Optimal management (*OPT*) as predicted by RothC (adapted from Smith et al. 2007a)

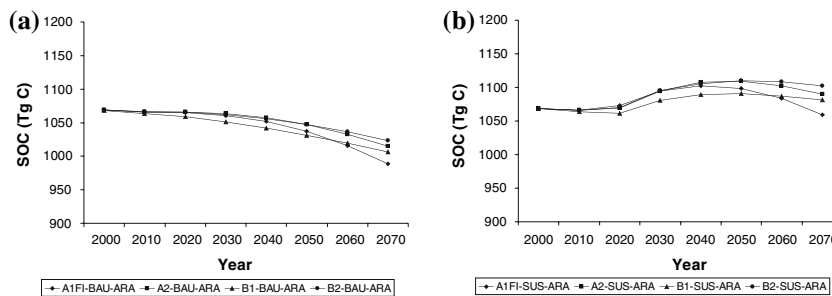
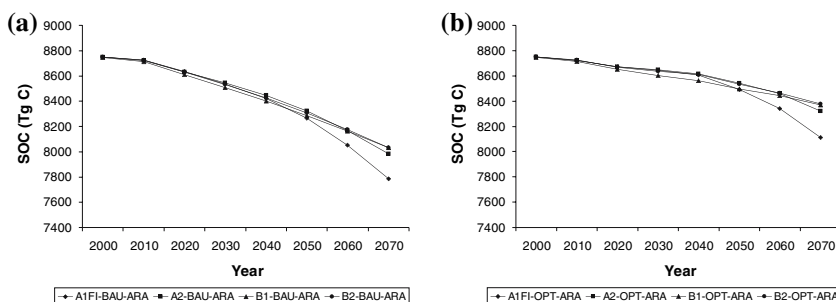
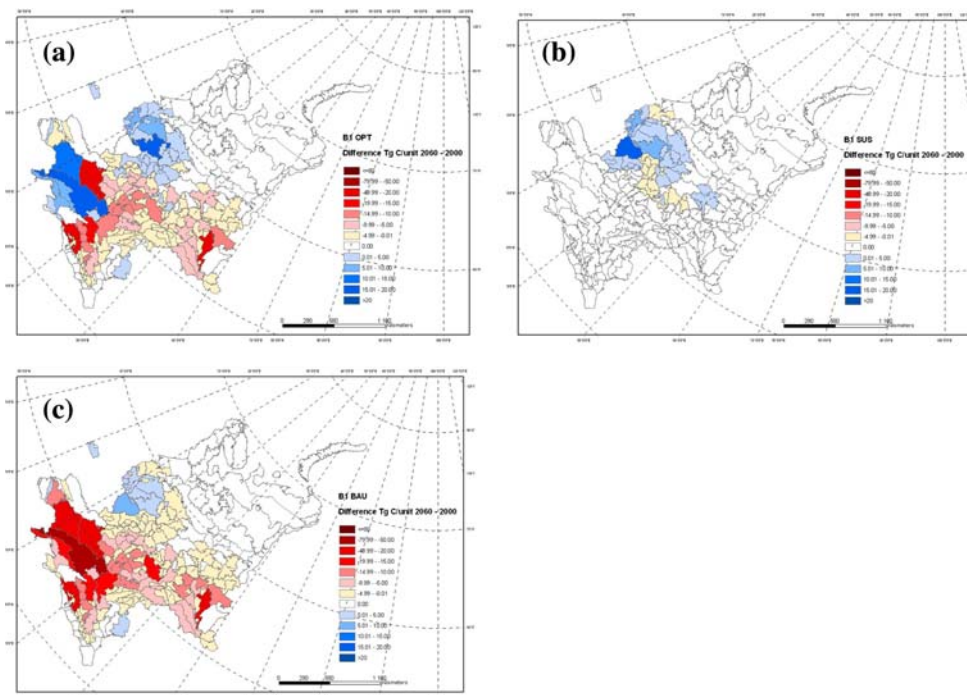


Fig. 4 Change in cropland SOC stock for the area of Russia for which the SUS scenario could be run under the four climate scenarios, A1FI, A2, B1 and B2 as implemented by the HadCM3 climate model;

a Business-as-usual management (*BAU*), **b** Economically sustainable management (*SUS*) as predicted by RothC (adapted from Smith et al. 2007a)

Fig. 5 Maps showing change in SOC content (2060–2000) over the three land management scenarios for the B1 climate scenario; **a** BAU, **b** OPT and **c** SUS as predicted by RothC (adapted from Smith et al. 2007a)



that for this region at least economically sustainable land management could not only reverse the negative impact of climate change, but could also increase soil carbon stocks. Smith et al. (2005) also found that technological

improvements could reverse climate-driven loss of cropland soil carbon in western Europe (EU25). Results from RothC are summarised in comparison with results from CANDY in Table 6.

Fig. 6 Change in cropland SOC stock of European Russia and the Ukraine under two land management scenarios (BAU and OPT) for each climate change scenario; **a** A1FI, **b** A2, **c** B1 and **d** B2 as implemented by the HadCM3 climate model as predicted by RothC (adapted from Smith et al. 2007a)

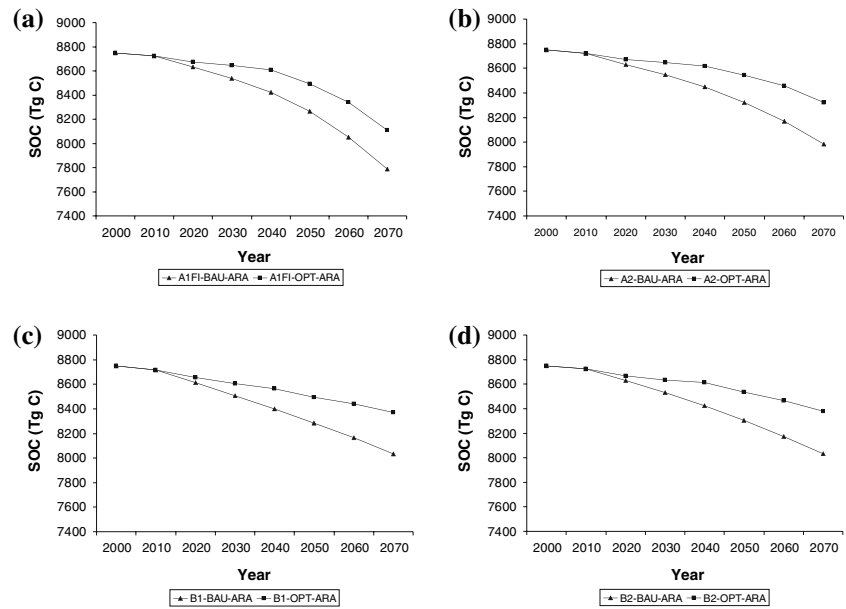
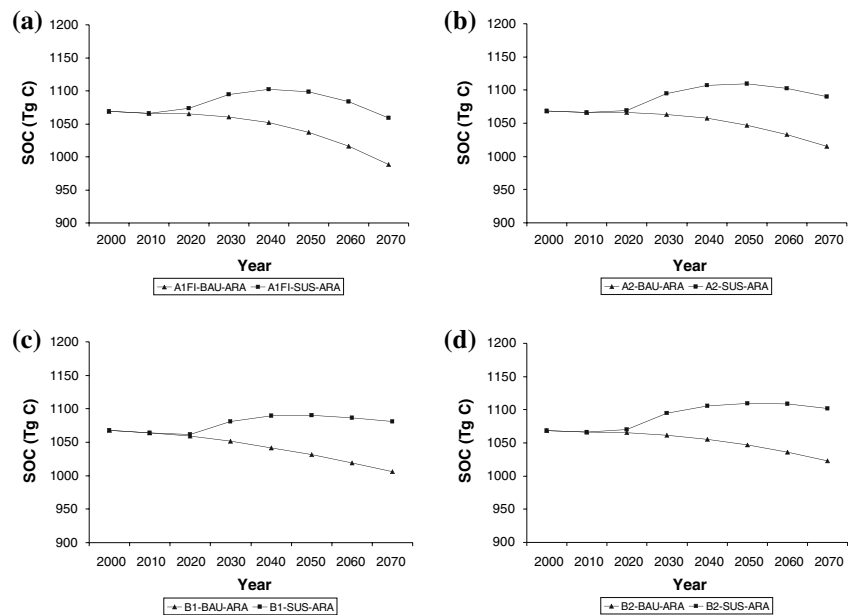


Fig. 7 Change in cropland SOC stock for the area of Russia for which economic data were available to run the SUS scenario, for the BAU and SUS land management scenarios for each climate change scenario; **a** A1FI, **b** A2, **c** B1 and **d** B2 as predicted by RothC (adapted from Smith et al. 2007a)



Results from the model of humus balance

Bearing in mind that, under transient dynamics, models that do not represent the kinetic heterogeneity of SOM are of limited value (Paustian et al. 1997), a comparison was made between the static Model of Humus Balance and the dynamic RothC model for steady-state conditions. The procedure was as follows: climate conditions in the years 2010, 2030 and 2050 were assumed to be constant and the RothC was run to equilibrium under constant (1990–2000) management. The equilibrium SOC predicted under these conditions was then used as the initial C content for

running the Model of Humus Balance, to check null hypothesis that changes in C content (ΔC) will be close to zero under the same climate and management parameters. Those units where podzoluvisols were not predominating were excluded from calculations, since the Model of Humus Balance was developed to simulate C dynamics in these fields.

The projected equilibrium values of SOC from RothC decreased from 2010 to 2050 under a B1 climate, but increased from 2010 to 2030 before decreasing again by 2050 in the A1FI climate (Table 5). The absolute changes predicted by the model of humus balance are quite close to

Table 6 Comparison of yearly SOC change, 2000–2070 as estimated by Candy, RothC and the Model of Humus Balance, in three areas within European Russia and the Ukraine for the A1FI and B1 climate scenarios, for three management scenarios

Climate Scenario	Management Scenario	Model	Change in SOC for the area, 2000–2070 (Tg C)		
			Chernozem region of European Russia	European Russia	European Russia and the Ukraine
A1FI	BAU	CANDY		+2	
		RothC	-88	-796	-1,098
	OPT	CANDY		+1,327	
		RothC		-608	-774
	SUS	CANDY			
		RothC	+5		
B1	BAU	CANDY		+157	
		RothC	-60	-573	-778
	OPT	CANDY		+1568	
		RothC		-385	-434
	SUS	CANDY			
		RothC	+57		

zero; however, the regression model always gives higher estimates of equilibrium SOC concentrations than comparable RothC runs. It can be demonstrated by positive values of mean changes and skewness (Fig. 6), though mean changes are not significant in any case, and most of the predicted changes are close to zero, as shown by high kurtosis (Fig. 6). In absolute terms, however, differences between C stocks predicted by the two models are not more than 0.5–0.9% from the initial content and within expected yearly percentage changes in SOC under cereal straw or ley-arable farming from long-term European field experiments (Smith et al. 2000) (Fig. 8).

For all runs soils that have equilibrium SOC content <1.2% demonstrated zero C changes. For light textured soils with smaller SOC content, estimates of the both models are close. Differences increase for soils with higher SOC contents, and in most cases the Model of Humus Balance suggested greater C accumulation in soils than RothC. It is therefore likely that for soils with higher clay content, RothC may slightly underestimate C accumulation in podzoluvisols, since the static model was developed from long-term experiments on these soils and is likely to accurately describe the SOC dynamics of these soils.

This study has shown that RothC and the Model of Humus Balance provide similar estimates of SOC dynamics over the next 50 years at the regional scale. As both are based on long-term experimental data, this test demonstrates possibilities to extend experimental information to other climatic and management regimes. For the

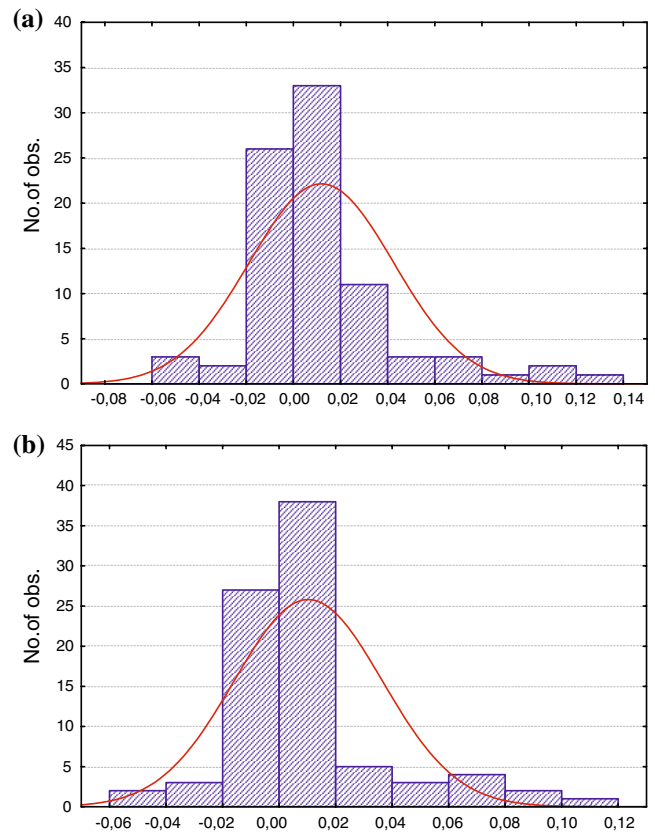


Fig. 8 Histogram of the empirical distribution and corresponding normal density for change in C content under BAU management estimated by the Model of Humus Balance with C equilibrium values derived from RothC model, BAU management; **a** A1FI climate scenario, 2050; **b** B1 climate scenario, 2030

static model though, extrapolation should not be made for cases where the value for any parameter falls outside the range for that parameter in the dataset from which the model was derived. This comparison assumes steady-state conditions, and a more detailed study is needed to test possible differences between RothC and the Model of Humus Balance under non-equilibrium conditions.

Discussion

Climate impacts on cropland mineral SOC in European Russia and the Ukraine

Only two dynamic models, RothC and CANDY, can examine the impact of climate change since only these respond to changes in the climatic driving variables. The Model of Humus balance is a static model and cannot be used for climate change impact assessment; we therefore consider only CANDY and RothC in this section. When considering only climate impacts on cropland mineral soil

carbon in European Russia and the Ukraine (i.e. under BAU) over the next 70 years, RothC predicts that SOC will be lost due to climate change under all climate scenarios, but CANDY predicts a small accumulation of SOC under future climate. RothC predicts a loss since higher temperatures speed decomposition in the model, whereas CANDY predicts an increase due to increased C reproduction flow in the model. For RothC, the loss was equivalent to an average of 6.2–15.7 Tg C per year. With the CANDY model, the smallest carbon accumulation is found for both management scenarios under the A1FI climatic scenario and the highest under the B1 climatic scenario. The difference between the smallest and highest accumulation amounts to 156 Tg C (2.4 Tg per year) under the BAU scenario, and 240 Tg C (3.4 Tg per year) under the OPT scenario.

At first sight, the model results seem very different. The general problem arising in the CANDY model comes from using and calculating the inert carbon pool (C_i). Using the C_i pool size and assuming a given C_{org} -value, the dynamic range of the total carbon content is restricted or expanded, affecting the initial size of the decomposable part of SOM. This has a strong impact on the direction of further development of carbon storage. The choice of the start parameter is therefore of critical importance, and all approaches using an IOM pool can lead to this problem. Puhmann et al. (2006) show the significance of the chosen method of C_i estimation for model outputs, with a clear improvement if a method that includes soil structure is used. Results from CANDY suggest that this should be included in the development of the next generation of SOM models, as recent research activities have concluded that soil structure plays a significant role in controlling the long-term carbon storage in soil (K. Kuka et al., unpublished results).

Soil organic carbon losses from croplands in the recent past have been recorded elsewhere in Europe (Sleutel et al. 2003; Bellamy et al. 2005; Janssens et al. 2003, 2005), but it is unclear whether this is due to climate (as suggested by Bellamy et al. 2005), management change (as suggested by Sleutel et al. 2003) or a combination of factors (Janssens et al. 2003). Both models showed the same pattern of response to the climate scenarios, with B1 most favourable for SOC and A1FI least favourable. Both models reveal considerable regional variation in response to climate change, but both RothC and CANDY show similar regional patterns (Figs. 1, 2; Table 6). The UNFCCC and its Kyoto Protocol aim to stabilise and then reduce GHG emissions. If successfully implemented, this could benefit SOC stocks and could thereby reduce climate forcing. Land management could have a significant impact in reducing the adverse effects of climate change on SOC as discussed below.

Management impacts on cropland mineral SOC in European Russia and the Ukraine

All models suggest that optimal management can increase SOC stocks in the cropland mineral soils of European Russia and the Ukraine relative to BAU. RothC suggests that the SOC loss predicted under BAU is reduced by between 324 and 345 Tg, which is a reduction of the SOC loss of between 30 (A1FI) and 44% (B1). Compared to BAU, the CANDY model calculated an increased carbon accumulation for the OPT scenario of 1,325 Tg C (18.9 Tg per year) under A1 conditions and 1,410 Tg C (20.1 Tg per year) with the B1 climatic scenario. Both CANDY and RothC suggest that this impact is larger than the variation between climate scenarios, implying that improved agricultural soil management will have a significant role to play in the adaptation to and mitigation of climate change (Smith 2004a, b). The economically and environmentally SUS could only be simulated by the RothC model and the Model of Humus Balance, and even for these models could only be applied for a limited area within the total region. Both models show an increase in SOC relative to BAU, which suggests that much of the adaptation in management practices could be realised without damaging profitability for the farmers, a key criterion affecting whether optimal management can be achieved in reality.

Comparison with previous estimates of cropland SOC change in Russia and the Ukraine

Despite some differences among scenarios, simulated soil organic C was not particularly sensitive to climate and management scenarios for the central and the south-eastern part of European Russia (Figs. 1, 2, 4). Both CANDY and RothC predict that the main focus of carbon accumulation will be in the northern part of the study area. These results support findings of Kozlovsky (1998) about the potential for agricultural soils to be a sink for CO_2 during the transition to more C-conserving practices, which suggested a higher potential for the northern part of the Russian Plain with the southern border at forest steppe natural zone. For more arid conditions, it is possible only to decelerate SOC loss or preserve current levels.

Based on a survey of arable land between 1960 and 1995 in the Russian Federation and a calculation of SOC dynamics during this period, C sequestered by arable lands has increased, interrupted by adverse changes following 1990, with average cereal crop yield falling from 1.6 t ha⁻¹ in 1986–1990 to 1.18 t ha⁻¹ in 1995 (in 1967–1971 it was 1.29 t ha⁻¹; Rodin and Krylatov 1998). Increased primary production has provided a 30% reduction of the SOC loss compared with current figures. This corresponds well with our estimates for the optimal management scenario.

Potential benefits from the introduction of C sequestering management practices depend on the initial SOC status of a particular site, and assuming depletion of SOC stocks in 1990–2000, gains in SOC are a function of the net increase of C inputs, with increasing potential yield productivity in the OPT and SUS scenarios. In 1980–1990, the north, north-west and part of the central region of the Russian Plain were a SOC sink, and this trend can be maintained for these territories under SUS and OPT scenarios in the future. It is important to note that despite a 5–20% rise of perennial grass in crop rotations on podzoluvisols during last 10 years, this region has the potential for C gain in the future, as the soils have previously been depleted in SOC and have significant potential to store more C (Fig. 4). The possibilities for SOC gain under the OPT scenario in the Ukraine have yet to be fully realised, as the C balance was negative for the last 30 years in Russian chernozem arable soils and was most pronounced for all climate scenarios without adaptation in the Ukraine (Rodin and Krylatov 1998; Figs. 2, 4).

Previous estimates of SOC loss for Russian arable land by Orlov et al. (1996) using a compilation of all data available to 1996 suggested SOC losses in 0–20 cm layer, based on 128 mha arable lands, of 751–1,984 Tg by 2010, 1,414–3,734 Tg by 2025 and 2,519–6,651 Tg by 2050. Other studies have suggested that future SOC losses are likely to be lower than SOC losses in the past due to significant losses of SOC from these soils historically (sometimes referred to as dehumification; Stolbovoi 2002). The rate of SOC loss in RothC does slow as the soil carbon stock is depleted (Coleman and Jenkinson 1996) and therefore reflects the dehumification effect suggested by Stolbovoi (2002). Indeed, the SOC losses projected by 2050 in this study are lower than those suggested by Orlov et al. (1996) after recalculation for European Russia, perhaps reflecting the slowing loss of SOC as soils become more SOC-depleted. Nevertheless, our results suggest that despite these historical losses, the cropland mineral soils of Russia and the Ukraine have the potential to lose still more.

A comparison between projected SOC losses in the chernozem region with literature values of past losses shows good agreement. Rodin and Krylatov (1998) reported annual soil C losses for the 1967–1995 period of 0.46 t C ha⁻¹ in the Central Chernozem economic region and 0.51 t C ha⁻¹ in the North Caucasus region, decreasing slightly at the end of the 1980s, but increasing again to 0.4 and 0.55 t C ha⁻¹, respectively, by 1995. Average annual soil C losses in 1950–1982 were 0.62 t C ha⁻¹. During the 29 years between 1967 and 1995, soil C losses in the arable soils of Russia were as high as 13% of the total stock in the plough layer. These figures represent losses comparable to the historical losses suggested by Stolbovoi (2002), suggesting that soils were still losing significant quantities of

SOC in the recent past, despite significant historical losses (150–200 years ago). Moreover, RothC predicts a loss of SOC between 2000 and 2060 of 10 t C ha⁻¹, which is 0.17 t C ha⁻¹ year⁻¹ for most of the chernozem zone (for the business-as-usual economic scenario and the most extreme climate scenario; A1FI). For other arable lands, this figure does not exceed 5 t C ha⁻¹ (0.08 t C ha⁻¹ year⁻¹). This rate of SOC loss is lower than current C loss rates, providing further evidence that the “dehumification effect” is replicated by RothC, and that significant future SOC losses are still possible.

Uncertainties and limitations

In terms of potential sinks and sources of carbon omitted from this study, we have not addressed the growth of abandoned lands since 1990. These lands, no longer under cultivation, occupied more than 34 mha in 1990–1995 and intergrade to grassland or forest land (Larionova et al. 2003). With the absence of a spatially resolved database of set-aside lands, this very potentially important sink for C is not included in our SOC stock estimates. Similarly, information on no-till and reduced tillage agriculture in the Russia and Ukraine is not available; so, reduced tillage is not included in the suite of management options in this study. In terms of potential sources of C, organic soils were not included despite being prevalent in 27% of polygons in the region, since a suitable model for representing C turnover in organic soils is not available for this region and the model we used has not been parameterised for highly organic soils (Coleman and Jenkinson 1996). However, in total arable land of the European Russia, organic soils play only a minor role. For example, in the south taiga, where C accumulation takes place mainly in organic soils (37,300 Tg), the total C stock in arable mineral soils is 3,600 Tg, while organic soils that are used as agricultural land contain only 99 Tg (Orlov et al. 1996). Despite these necessary limitations, this study shows large potential losses of C from mineral soils under future climate in European Russia and the Ukraine and the significant potential to mitigate this loss by agricultural management.

Uncertainty is high in the level of implementation of the management practices represented in the scenarios, and probably larger than uncertainties due to individual model inputs such as initial SOC content and internal parameters such as decomposition rates. Further uncertainty is introduced by the use of a single climate model, with change in SOC shown to differ according to the climate model used to project future climate (Smith et al. 2005, 2006), and uncertainty in the impact in changes in technology, not explicitly simulated here, but found to be important in projections of SOC change in western Europe (Smith et al. 2005).

Policy implications

Modelling studies such as this one help to identify where current climate policy will encourage good soil management and where it may fail to do so. Results from RothC suggest that Russia might not benefit from carbon credits from carbon sequestration under cropland management, as SOC levels are projected to decline under climate change (Smith et al. 2007a). CANDY, however, predicts a slight increase in SOC, in which case cropland management would be more attractive. Whether or not carbon credits can be gained from cropland management to improve soil carbon stocks, preserving SOC levels remains a highly desirable objective, since soil organic matter is of central importance for multiple aspects of soil fertility (Lal 2004), sustainability (Smith and Powlson 2003) and quality (Sparling et al. 2003). To this end, an accounting system that provides incentives to preserve SOC stocks relative to BAU would be more effective in preserving SOC stocks in the future, than the current accounting system that compares current losses with losses at the 1990 baseline. Since incentives to maintain SOC stocks for climate mitigation may be weak (due to SOC losses in the future or only very slight increases in SOC), other non-climate policies may be required to encourage practices that maintain or enhance SOC. Studies such as this one provide information to help identify the relative merits of changes in agricultural management systems, set aside policies and afforestation activities. Some of these activities are occurring without policy or economic incentives, but might be further enhanced by implementation of specific socio-economic programmes in Russia and the Ukraine.

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