Improved modeling of soil organic carbon in a semiarid region of Central East Kazakhstan using EPIC

Hector Causarano, Paul Doraiswamy, Muratova, Pachikin, Gregory Mccarty, Akhmedov, Jimmy Williams

Agron. Sustain. Dev. (2011) 31:275–286

DOI: 10.1051/agro/2010028

Research article

Improved modeling of soil organic carbon in a semiarid region of Central East Kazakhstan using EPIC

Hector J. Causarano[1]*, Paul C. Doraiswamy[2], Nadiya Muratova[3], Konstantin Pachikin[4], Gregory W. McCarty[2], Bakhyt Akhmedov[2], Jimmy R. Williams[5]

[1] Universidad Nacional de Asunción, Facultad de Ciencias Agrarias, Casilla de Correos 1618, San Lorenzo, Paraguay
[2] USDA-ARS Hydrology and Remote Sensing Laboratory, Bldg 007, Rm 104, BARC-West, 10300 Baltimore Avenue, Beltsville, MD 20705, USA
[3] Space Research Institute. Al-Faraby 75, Almaty, Kazakhstan
[4] Research Center of Soil Science and Agrochemistry, Al-Faraby 75, Almaty, Kazakhstan
[5] Blackland Research and Extension Center, 720 E. Blackland Road, Temple, Texas 76502, USA

(Accepted 18 May 2010) (Published online: 9 August 2010)

Abstract – Inappropriate land use and soil mismanagement produced wide-scale soil and environmental degradation to the short-grass steppe ecosystem in the semiarid region of central east Kazakhstan. A limitation for determining the impacts of land use changes on soil organic carbon (SOC) is the dearth of information on SOC stocks under the predominant land uses in the region. Here we used the Environmental Policy Integrated Climate (EPIC) model to study long-term impacts of land use changes and soil management on SOC to a depth of 50 cm during 1955–2030, in degraded agricultural lands of central east Kazakhstan. Simulated land uses were: native rangeland vegetation, wheat (*Triticum aestivum* L.), wheatgrass (*Agropyron cristatum* L.), and abandoned croplands. The EPIC model was initialized with soil properties obtained from a soil map of the study area. Data on crop management, fertilizer application and tillage practices were gathered from local expert knowledge. Simulations were performed for each polygon on a land use classification map, resulting in 4661 simulations. Our results showed that simulated SOC explained 50% of the variation in measured SOC. Of the 1.38 million hectares in the study area, 78% were under native vegetation, 3% cultivated to wheat, 8% on wheatgrass, and 11% were abandoned croplands in 2005. If land use remained constant, total stock of SOC would decrease at an annual rate of 723 kg C ha^{-1}. However, if best management practices are implemented, resulting in reallocation of land use according to the land capability with abandoned croplands being converted to reduced-tillage wheat or wheatgrass, total stock of SOC would increase to an equivalent of 4700 kg C ha^{-1} yr^{-1}. Combining land use classification and soil maps with EPIC, proved valid for studying impacts of land use changes and management practices on SOC; an important aspect of this approach is the ability to scale up site-specific SOC to the region. With the available data, EPIC produced relatively accurate results but more data on spatial and temporal variation in SOC are needed to improve model calibration and validation.

EPIC model / Kazakhstan / steppe / soil organic carbon

1. INTRODUCTION

The former Soviet Union carried out the "Virgin Lands Programme" between 1954 and 1964. With this program cereal production expanded in the steppe region of Kazakhstan, and consequently, large areas of marginal lands were brought into cultivation (McCauley, 1976). Increased cereal production transformed an ecosystem that previously supported nomadic grazing into cropland that supplied over 25% of wheat demand within the Soviet Union (Kaser, 1997). As a result large areas of marginal land were brought into crop production and this led to wide-scale degradation of soils in addition to excess use of fertilizers and large irrigation projects that caused formation of saline soils and water pollution. This problem was exacerbated with the collapse of the Soviet Union and Kazakhstan independence in 1991. The gain of independence destroyed the highly regulated market, and with free-marked grain prices, the cereal-based production system became increasingly unprofitable. Many of the marginal croplands were abandoned, or continue to produce very low grain yields (McCauley, 1976; Meng et al., 2000).

Intensive cultivation, summer fallowing, excessive grazing and resulting degradation of rangelands have been reported to cause depletion of SOC and soil erosion in semiarid regions of central Asia (Lal, 2004). Depletion of SOC causes soil degradation, characterized by breakdown of soil structure,

* Corresponding author: Hector.Causarano@tigo.com.py

Figure 1. Location and delimitation of the World Bank Dryland Management Project in central east Kazakhstan.

compaction and loss of biodiversity. It has been estimated that conversion from natural to agricultural systems may result in SOC losses of 10–40 Mg ha^{-1} in semiarid climates (Lal, 2004).

A limitation for determining the impacts of land use changes on SOC, in the steppe region of central Asia, is the dearth of information on SOC stocks under the predominant land uses in the region. The integration of a properly validated mechanistic model of crop growth and cropping systems with field experiments and a geographic information system database is a sound approach for analyzing interactive effects of climate, soils, land uses, and management practices on SOC at the regional scale (Causarano et al., 2008; Paustian et al., 1995).

The World Bank established the Kazakhstan Dryland Management Project (KDMP), with the aim of the rehabilitation and sustainable utilization of natural resources in marginal cereal growing areas. The project covered 1.38 million hectares of degraded land in the Shetsky Rayon of Karaganda Oblast (central east Kazakhstan). One component of the project was the assessment and monitoring of SOC sequestration under several land use systems (active cereal cropped lands, abandoned croplands, undisturbed rangelands and areas re-vegetated with perennial species). In the initial phase, required information on the spatial distribution of land use systems and measurements of SOC stocks were collected. In the second phase, the EPIC model was used to assess current and potential changes in SOC stocks during the next 25 years.

In this paper we report the outcomes of our EPIC simulation effort. Our objectives were to: (a) scale up site-specific SOC measurements to the KDMP area, (b) assess the impacts of predominant land uses on SOC stocks, and (c) calculate potential C sequestration with increasing adoption of conservation tillage and re-vegetation of abandoned croplands with wheatgrass or wheat.

2. MATERIAL AND METHODS

2.1. Study area

The study area is located in central east Kazakhstan (48.4–49.4° N and 72.0–74.4° E, ~700 m above sea level) covering an area of 1.38 million hectares. It is the area of influence of the KDMP (Fig. 1). The climate is semi-arid. Mean annual temperature vary in response to elevation and latitude, but as a general rule increases from 2.8 °C in the northeast to 4.1 °C in the southwest, with January average of –13.8 °C and July average of 20.1 °C. Mean annual precipitation also varies but in generally decreases from 369 mm in the north to 220 mm in the south. Snow covers the study area from November to March. Mean monthly weather variables in the study area are presented in Table I.

The dominant vegetation is a short-grass steppe with *Stipa* sp. and *Festuca* sp. as dominant species, and abundance of *Artemisia* sp. on saline soils. Dominant soils were classified in the Russian system of soil classification as Chestnut (order mollisols, great group argiustolls in the US Soil Taxonomy). These soils are deep, well drained, and moderately slow permeable, developed in loess, and have accumulation of secondary carbonates within 100 cm of the soil profile. Chestnuts have a high nutrient concentration, with a cation exchange capacity of 25–30 cmol$_c$ kg^{-1} soil. The soil-pH is slightly alkaline. According to SOC content in the top horizons, these soils are sub-classified as Dark Chestnuts, Normal Chestnuts or Light Chestnuts. Dark Chestnuts are located in the northeast section and occupy 21% of the study area; containing 2.0–2.6% SOC. Light Chestnuts are located in the southwest section, occupy 11% of the study area, and contain 0.9–1.5% SOC. Between Dark Chestnuts and Light Chestnuts extend Normal Chestnuts, which occupy 42% of the study area and have intermediate SOC contents. The remaining area is occupied by Meadow soils (order mollisols, great groups

Table I. Mean monthly weather variables in central east Kazakhstan.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max. temperature, °C*	–8.8	–7.3	–1.6	11.5	19.7	25.1	26.7	25.3	19.3	10.2	–0.1	–6.5
Min. temperature, °C*	–18.8	–18.5	–12.6	–0.8	6.1	11.1	13.4	11.3	4.6	–1.8	–10.1	–16.4
Mean temperature, °C*	–13.8	–12.9	–7.1	5.3	12.9	18.1	20.1	18.3	11.9	4.2	–5.1	–11.4
Precipitation, mm*	20.4	19.9	23.4	23.8	32.1	31.4	36.1	22.5	14.8	24.0	25.2	22.4
Solar radiation, MJ m^{-2}**	6.2	10.3	14.8	19.4	24.7	26.1	21.6	20.8	15.8	8.8	5.3	4.5
Relative humidity**	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8
Wind speed, m s^{-1}**	3.1	3.9	4.0	3.9	3.7	3.7	3.3	2.8	3.3	3.6	3.7	3.5

* Calculated from 11 years (1995–2005) daily data at Jarik and 21 years (1985–2005) decadal data at Bes-Oba, Akcy-Auli, Agadir, and Jana-Arka.
** Calculated from 45-km daily AGRMET data (Agricultural Meteorology Modeling System of the US Air Force Weather Agency) closest to the ground stations where temperature and precipitation data were obtained.

argiaquols and natraquols)(21%), Solonetz (order aridisols, great group natrargids)(2.9%), and Solonchak (order aridisols, great group haplosalids) (0.1%).

2.2. Model description

Environmental Policy Integrated Climate (EPIC) is a process-based model developed in early 1980's (Williams, 1990) to simulate erosion impacts on crop productivity. Since then, it has been widely tested and adapted to simulate the effects of climate, soil and management on crop production and SOC (Gassman et al., 2004). We used EPIC v3060, a version that recently received modifications in the SOC routine by including algorithms from the Century model (Izaurralde et al., 2006). The EPIC model operates on a daily time step, and can execute simulations over periods spanning hundreds of years, on catchments up to 100 ha. Twelve plant species can be modeled at the same time, allowing inter-crop and cover-crop mixtures. Simulated processes include tillage effects on crop residues and bulk density, wind and water erosion, hydrology, soil temperature and heat flow, C, N and P cycling, fertilizer and irrigation effects on crops, pesticide fate, and economics.

In EPIC, simulations are driven by daily weather variables (input or simulated from long-term weather statistics) including temperature, radiation, precipitation, relative humidity and wind speed. Daily crop growth is simulated by functions that convert a fraction of solar radiation into plant biomass and is modified by ambient water vapor pressure, CO_2 concentration, and stresses (water, temperature, N, P, aeration); root growth is affected by soil strength, aluminum content and temperature. Soil organic C is simulated by functions that convert crop residues, roots and organic amendments added to the soil into three compartments with different turnover times: microbial biomass (days or weeks), slow humus (few years) and passive humus (hundreds of years). Carbon can also be lost in the form of leachates, eroded sediments or CO_2 emission.

2.3. Model inputs

For accurate simulations, EPIC requires local information on weather, soil, and management. Although EPIC was developed for field simulations, geographical information systems (GIS) techniques have been applied for upscaling field simulations (Causarano et al., 2008; Izaurralde et al., 2003; Priya and Shibasaki, 2001; Rao et al., 2000; Tan and Shibasaki, 2003). First, we developed a general land use classification map (Fig. 2) and a soil map of the study area. Then, we overlaid the land use and the soil map to assign soil properties to each land use polygon (Fig. 3). The basic units for EPIC simulations were land use polygons; where weather, soil, and management were assumed uniform. There were 4661 polygons resulting in equal number of simulations. The large number of simulations was facilitated by i_EPIC (Version 1.1, 2008, Center for Agricultural and Rural Development, Ames, Iowa, USA), a public domain software that manages input and output of multiple EPIC simulations within a single database.

We simulated crop yields and SOC at the 0–50 cm depth. Weather, soil and management input files were prepared to conduct 76-yr simulations (January 1955–December 2030). It was assumed that native vegetation was in a steady-state equilibrium with regard to SOC (inputs through biomass is balanced by losses); and under this assumption we initialized the model in 1955 with soil properties measured in 2004 under native vegetation conditions.

2.4. Weather

The EPIC model simulates daily weather from monthly climate statistics: averages and standard deviation of maximum and minimum temperature, precipitation, radiation, relative humidity, and wind speed. For realistic daily precipitation simulation, skewness, average days of rain per month, probability of a wet day after a dry day, and probability of a wet day after a wet day are also necessary. We obtained monthly climate statistics of maximum and minimum temperature, and precipitation, from 11 years (1995–2005) of measured daily data at Jarik, located central west of the study area (49.0° N, 72.6° E); and 21 years (1985–2005) of measured decadal data at other four stations: Bes-Oba (northeast, 49.4° N, 74.5° E), Akcy-Aulyi (southeast, 48.8° N, 73.7° E), Agadir (south, 48.3° N, 72.9° E), and Jana-Arka (west, 48.7° N, 71.7° E). Monthly statistics for solar radiation, relative humidity and wind speed, were calculated from the 45-km grid daily data acquired from the Agricultural Meteorology modeling System (AGRMET) of the US Air Force Weather Agency.

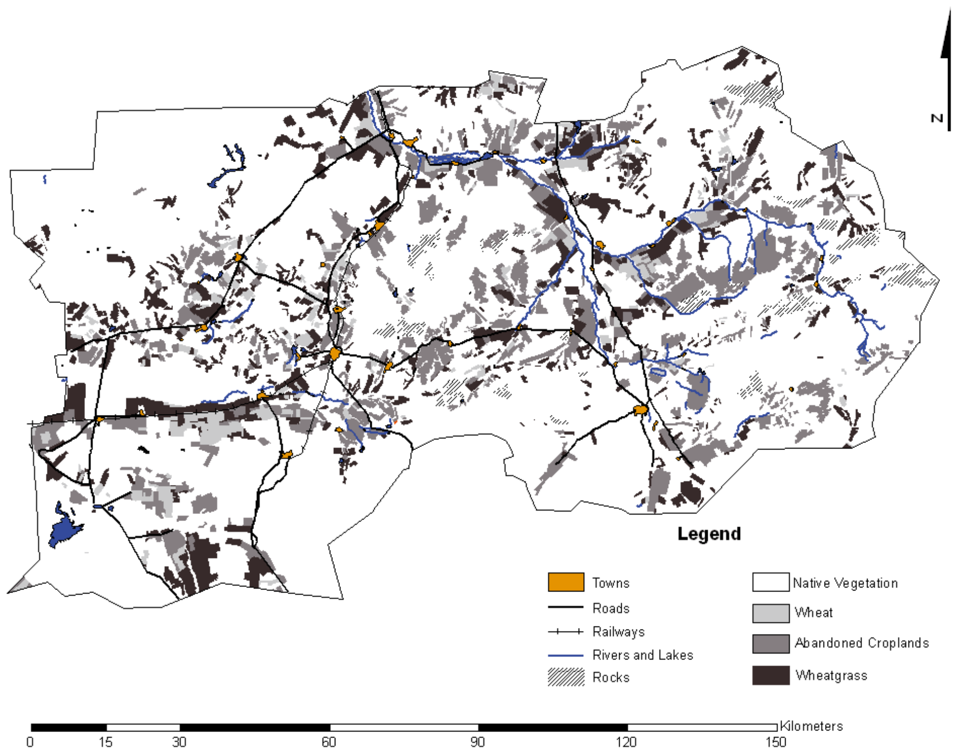

Figure 2. Types and distribution of land uses (year 2005) in the area of influence from the World Bank Dryland Management Project (central east Kazakhstan).

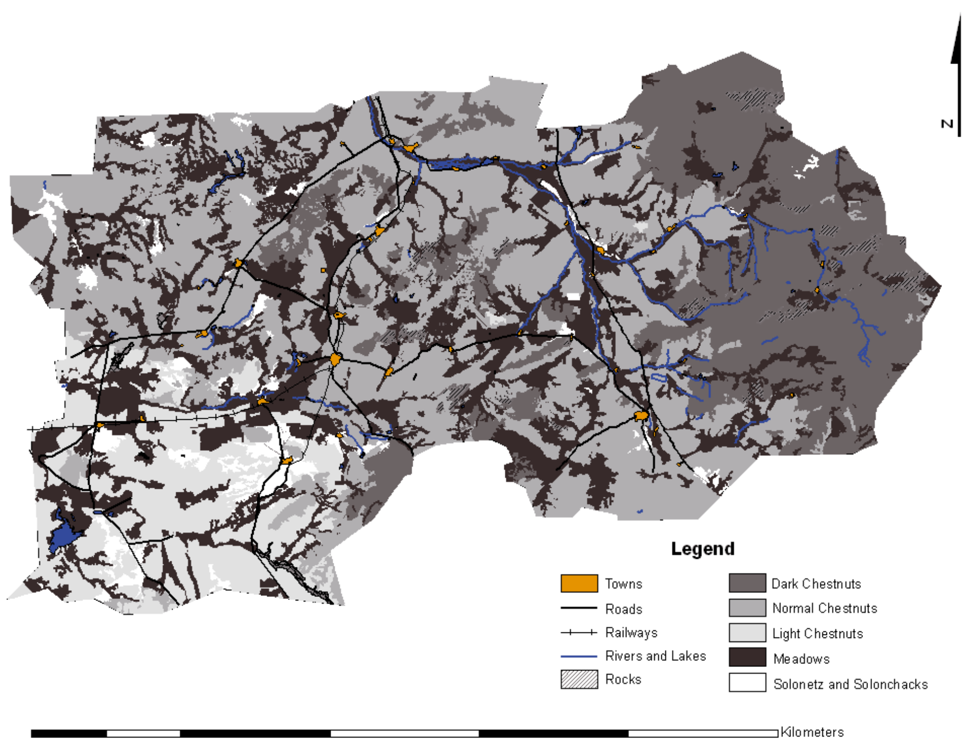

Figure 3. Main soil groups in the World Bank Dryland Management Project area of influence (central east Kazakhstan).

Table II. Selected soil properties and depths of representative soil profiles in east central Kazakhstan.

Soil properties	0–0.1 m	0.1–0.2 m	0.2–0.3 m	0.3–0.4 m	0.4–0.5 m
			Dark Chestnut		
Bulk density, Mg m^{-3}	1.2	1.3	1.3	1.4	1.4
Sand, %	35.7	28.2	38.7	33.0	15.1
Clay, %	25.7	32.9	28.7	35.2	49.7
Soil organic C, %	3.7	2.0	1.3	0.8	0.4
pH	6.7	7.3	8.2	8.6	8.7
Sum of bases, cmol$_c$ kg^{-1}	29.0	31.7	29.2	25.0	20.2
			Normal Chestnut		
Bulk density, Mg m^{-3}	1.2	1.3	1.3	1.3	1.4
Sand, %	49.6	51.2	50.9	55.0	54.2
Clay, %	19.1	18.4	21.2	21.8	22.0
Soil organic C, %	1.6	1.6	1.3	0.9	0.7
pH	7.5	7.4	7.6	8.1	8.6
Sum of bases, cmol$_c$ kg^{-1}	20.6	21.7	23.7	23.6	18.9
			Light Chestnut		
Bulk density, Mg m^{-3}	1.3	1.3	1.3	1.3	1.3
Sand, %	64.6	66.8	70.4	69.2	69.2
Clay, %	16.8	16.8	17.0	20.6	20.6
Soil organic C, %	1.2	0.9	0.6	0.4	0.2
pH	7.0	7.0	7.7	8.4	8.4
Sum of bases, cmol$_c$ kg^{-1}	8.5	9.2	10.5	10.0	9.8
			Dark Meadow		
Bulk density, Mg m^{-3}	1.0	1.2	1.2	1.2	1.3
Sand, %	8.1	6.3	6.6	7.4	6.4
Clay, %	59.9	64.7	66.8	67.9	68.2
Soil organic C, %	8.2	4.4	2.9	2.0	1.5
pH	7.8	7.8	7.9	8.0	7.9
Sum of bases, cmol$_c$ kg^{-1}	77.4	59.7	52.4	48.5	42.6
			Steppe Solonetz		
Bulk density, Mg m^{-3}	1.2	1.3	1.4	1.4	1.5
Sand, %	58.7	57.8	48.8	53.1	49.9
Clay, %	16.3	20.6	32.2	32.8	34.7
Soil organic C, %	1.0	0.7	0.4	0.2	0.2
pH	8.8	9.4	9.6	9.8	9.9
Sum of bases, cmol$_c$ kg^{-1}	21.3	19.8	23.4	21.6	20.0
			Common Solonchak		
Bulk density, Mg m^{-3}	1.1	1.2	1.2	1.3	1.3
Sand, %	56.0	31.4	21.6	25.4	35.5
Clay, %	18.8	29.7	37.7	38.3	37.6
Soil organic C, %	0.4	0.2	0.1	0.1	0.1
pH	10.5	10.6	10.6	10.6	10.6
Sum of bases, cmol$_c$ kg^{-1}	23.0	17.8	21.6	27.4	25.5

Each polygon used weather data from the station that best represented its climatic condition based on closest distance and/or similar altitude.

We used the Hargreaves method (Hargreaves and Samani, 1985) for estimating evapotranspiration.

2.5. Soil

Selected soil properties of representative soil profiles used for model initialization are shown in Table II. Weighted averages for each soil property were calculated for 0–10, 10–20, 20–30, 30–40, and 40–50 cm depths within each component of a map unit; then, all components of a map unit were aggregated by computing weighted averages based on the percentage of a map unit occupied by each component.

Because simulations were run on land use polygons, we intercepted the soil map with the land use map to determine the soil that best represent each land use polygon.

The slope representing each land use polygon was calculated from a 73-m digital elevation model (DEM) obtained from the United States Geological Survey (2007). Slope lengths were assumed to be 100 m. We also assumed soils were adequately drained.

2.6. Management operations

Tillage, planting, fertilization, harvesting, and associated operation dates and quantities were based on expert knowledge (Ruskali Saduakas, pers. commun.).

Native vegetation was simulated as composed of two perennial species, belonging to the taxonomic families of Poaceae and Fabacea, respectively, and being grazed (10 cows ha^{-1}) during 155 days of each year.

Cropland was simulated as wheat seed on the 20th May and harvested on the 1st September. From 1955 to 1970, soil preparation consisted of moldboard plow in late September, followed by harrowing disk late April, and field cultivator early May. After 1970, moldboard plow and harrowing disk were substituted with paraplow (vertical implement that loosens compacted soil layers). The crop received no fertilization from 1955 to 1970; but 90 kg ha^{-1} of ammonium nitrate was applied at seeding after 1970. With regards to wheat residues, from 1955 to 1990 crop residues in excess of 15 cm height were cut and removed for animal feeding; and after 1990 all crop residues were left on the field. For simulations representing best management practices (from 2006 to 2030) wheat was no-tilled. The timelines used for these practices was based on the local knowledge of practice history.

Wheatgrass simulations began in 1990 (i.e. between 1955 and 1989 wheat cropland was simulated). The pasture was fertilized with 100 kg ha^{-1} ammonium nitrate and was harvested for animal feeding each year (cutting height was 5 cm). No tillage was used for seeding wheatgrass. For simulations representing best management practices (from 2006 to 2030), wheatgrass was fertilized and harvested every second year.

Abandoned cropland simulations also began in 1990 (i.e. between 1955 and 1989 wheat cropland was simulated). It was assumed that abandoned croplands were populated with perennial weed species. Abandoned croplands were not simulated on best management practices scenarios.

2.7. Model calibration and validation

The calibration process focused on the crop growth and SOC modules. There were no time series data on biomass production or crop yields in the study area, therefore we relied on expert knowledge (Ruskali Saduakas, pers. commun.) for calibration of the crop growth module. The SOC module was calibrated against one set of measured data on a Normal Chestnut soil in 2004. For this, we initialized the model in 1955 assuming at this time the field was covered by native vegetation, then we simulated four land uses with the same soil and climatic condition: native vegetation, wheat croplands, wheatgrass, and abandoned croplands; and compared simulated SOC at the 0–50 cm against measured SOC at the same depth.

The validation process consisted of comparing simulated SOC against measured SOC for a variety of soil, climatic conditions and land uses. The slope and intercept of the regression line, the coefficient of determination (R^2), the root mean square error (RMSE), and a t test of the hypothesis of no model bias were used to judge simulations accuracy.

The RMSE is the average percentage error and expresses the total difference between measured and simulated values; it was defined (Smith et al., 1997) as:

$$\mathrm{RMSE} = \frac{100}{\bar{\mathrm{M}}}\sqrt{\sum_{i=1}^{n}(\mathrm{S_i} - \mathrm{M_i})^2/n}$$

where M and S are measured and simulated values, respectively.

The statistic t was calculated (Smith et al., 1997) as:

$$t = \frac{\sum_{i=1}^{n}(\mathrm{M_i} - \mathrm{S_i})/n}{\sqrt{\dfrac{\sum_{i=1}^{n}\left(\mathrm{M_i} - \mathrm{S_i} - \sum_{i=1}^{n}(\mathrm{M_i} - \mathrm{S_i})/n\right)^2}{n-1}} \Bigg/ \sqrt{n}}.$$

3. RESULTS AND DISCUSSION

3.1. Model calibration

The EPIC model has a set of crop parameters that control plant growth responses to their environment. Crop parameters we modified are presented in Table III. The biomass energy ratio and temperature parameters for wheat and wheatgrass are from Kiniry et al. (1995). Other parameters were adjusted based on expert knowledge (Ruskali Saduakas, pers. commun.). We modified a generic crop file (FALW) to simulate weeds species growing on abandoned croplands, and two others (RNGE and NEW) to simulate mixed species growing on native vegetation.

Adjusted parameters in the SOC module and their values were as follows: slow humus transformation rate, 0.00041 d^{-1}; passive humus transformation rate, 0.0000082 d^{-1}; microbial activity in top layer, 0.5; and residue decay tillage coefficient, 5.0. Sensitivity analyses have indicated these EPIC parameters are influential on SOC simulations (Causarano et al., 2007; Wang et al., 2005).

Simulated wheat yields on a Normal Chestnut soil during the period 1955–2005 are presented in Figure 4. There is a dearth of published information on historical wheat yields in our study area, but our results were consistent with expert knowledge (Ruskali Saduakas, pers. commun.). Wheat yields ranged from 0.20 to 2.39 Mg ha^{-1}, with average plus standard deviation of 0.82 ± 0.51 Mg ha^{-1}. Meng et al. (2000) provided an overview of wheat production systems in Kazakhstan; according to their report, average wheat yields in Kazakhstan varied from 0.3 to 1.4 Mg ha^{-1} during 1960–1995. Rainfall distribution during the cropping season was the major factor in yield variation. Low yields resulted from dry periods during tillering, head development or flowering; which is consistent with the explanation for wheat yield variations given by Meng et al. (2000).

Simulated SOC (0–50 cm) under several land uses during 1955–2005 are presented in Figure 5. Soil organic carbon under native vegetation remained fairly constant with an average

Table III. Parameters in EPIC crop sub-model adjusted during the calibration phase for simulation of wheat, wheatgrass, abandoned croplands, and native vegetation in central east Kazakhstan.

Parameters	Wheat	Wheatgrass	Abandoned croplands	Native vegetation	
EPIC code	SWHT	CWGR	FALW	RNGE	NEW*
Duration	Annual	Perennial	Perennial	Perennial	Perennial
Type	Row crop	Pasture	Pasture	Pasture	Legume
Biomass energy ratio, kg ha^{-1} Mj^{-1}	35	35	10	25	10
Harvest index	0.45	0.9	0.1	0.5	0.95
Optimal temperature, °C	18	25	18	25	25
Minimum temperature, °C	0	8	5	8	8
Maximum leaf area index	4	5	4	5	3
Maximum crop height, m	0.5	0.7	1	1	0.5

* Generic plant in EPIC crops file, created to simulate a legume plant grown at the same time as RNGE on native vegetation.

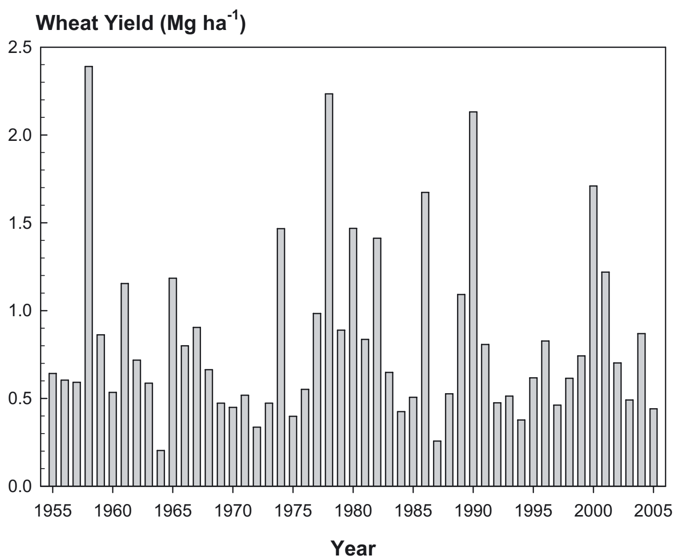

Figure 4. Simulated wheat yields on a Normal Chestnut soil during 1955–2005 in central east Kazakhstan.

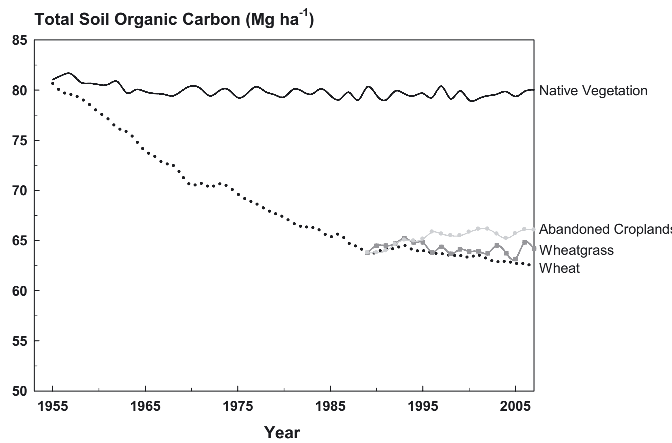

Figure 5. Simulated soil organic C stocks (0–50 cm) during 1955–2005 under native vegetation, wheat, wheatgrass, and abandoned croplands, in central east Kazakhstan.

Table IV. Comparison of measured and simulated soil organic C (0–50 cm) under four soil land uses on a Normal Chestnut soil in central east Kazakhstan during 2004.

Land use	Soil organic carbon (Mg ha^{-1})	
	Measured	Simulated
Native vegetation	83.9	82.0
Wheat	63.8	58.5
Wheatgrass	66.8	58.5
Abandoned Croplands	63.6	62.7

plus standard deviation of 82.0 ± 0.5 Mg ha^{-1}. Wheat cultivation had a negative impact on SOC, which decreased at a rate of 0.87 Mg ha^{-1} yr^{-1} during 1955–1970 (moldboard plow, no fertilizer use, residues removed), 0.58 Mg ha^{-1} yr^{-1} during 1971–1990 (paraplow, fertilizer use, residues removed), and 0.11 Mg ha^{-1} yr^{-1} during 1991–2005 (paraplow, fertilizer use, residues not removed). The abandonment of croplands and the introduction of wheatgrass impacted positively on SOC, the rate of carbon sequestration was lower under wheatgrass because forage was removed for animal feeding, as opposed to no biomass removal on abandoned croplands populated with weeds.

With the scenarios presented in Figure 5, stocks of simulated SOC under native vegetation in 2004 agree well with measured SOC in the same year (Tab. IV). The EPIC model simulated wheat and wheatgrass production resulting in less SOC than in abandoned croplands while measured data showed the opposite results. It is reasonable to assume that grain and forage removal on wheat and wheatgrass fields would result in lower SOC content than in abandoned croplands, where plant residues are not removed; for this reason and because of the uncertainties related to measured values, we considered EPIC simulations were satisfactory.

3.2. Model validation

Measured and simulated SOC are compared in Figure 6. The EPIC model adequately simulated SOC stocks (0–50 cm) at 23 locations varying in land use, distributed within the study area. Simulated SOC explained 50% of the variation in

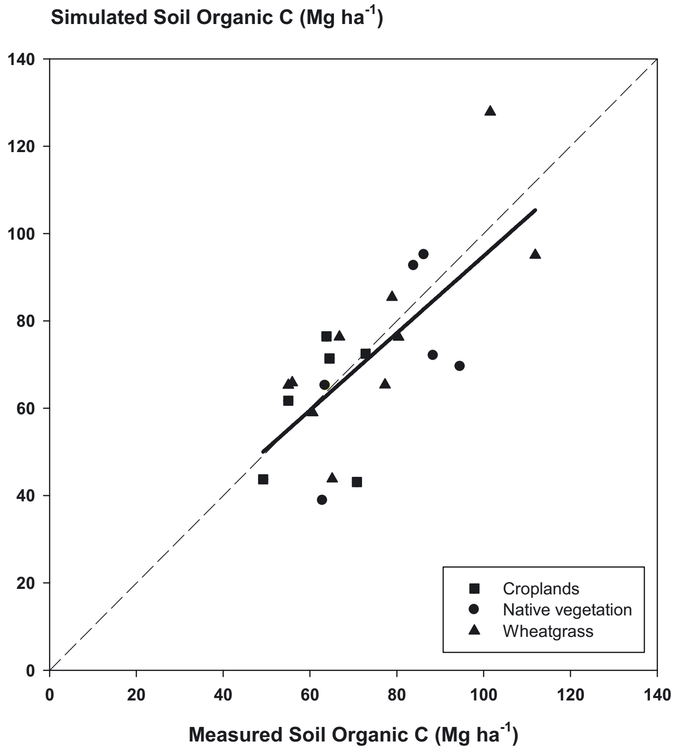

Figure 6. Comparison of measured and simulated soil organic C (0–50 cm) in central east Kazakhstan during 2004. Regression equation: y = 6.56 + 0.88x, R2 = 0.50, root mean square error = 19.47%. The slope and intercept of the regression line are not significantly different from 1 and 0, respectively.

measured SOC. The slope and intercept of the regression relating simulated to measured values were not significantly different from 1 and 0, respectively. On a long-term experiment with relative uniform landscape in Alberta, Canada, Izaurralde et al. (2006) reported an R^2 of 0.89. On a site-specific experiment in central Alabama, USA, to evaluate EPIC as a predictor of SOC on varying topography, Causarano et al. (2007) reported R^2 of 0.40.

Two other indices that express the quantitative relationship between measured and simulated SOC are presented in Figure 6: RMSE and Pr > t. The RMSE indicates that simulated SOC has 20% average percentage error. Falloon and Smith (2003) reported average errors for regional-level application of 12% using ROTHC and 34% using the CENTURY model at several locations in Europe. Causarano et al. (2008) reported average errors of 26–30% for regional-level simulations in Midwestern USA. Although our calculated RMSE is lower than other published values, a significant reduction in the uncertainty is needed to detect differences in SOC among land uses. To reduce the uncertainty, more information on initial soil conditions and management practices are needed. The statistic t tested the hypothesis that simulated SOC accurately represented measured SOC (no model bias), and the results (Pr > t: 0.26) indicated that EPIC was accurate (Fig. 6). Overall, simulation results in this study were adequate given the fact that high variation in soils, history of land use and management, and topography exist.

Table V. Estimated area under different land uses in 1955, 2005, and 2030, in central east Kazakhstan. Corresponds to the area of influence from the World Bank Dryland Management Project.

Land use	Area (million ha)			
	Year 1955	Year 2005	Year 2030 a*	Year 2030 b**
Native vegetation	1.383	1.075	1.075	0.933
Wheat	0	0.044	0.044	0.167
Wheatgrass	0	0.114	0.114	0.284
Abandoned croplands	0	0.149	0.149	0
Total	1.383	1.383	1.383	1.383

* Scenario "business as usual", same land use as in year 2005.

** Scenario "best management practices", land use based on a Land Capability Map.

3.3. Effects of land use change on soil organic C (0–50 cm)

We initialized our simulation in 1955 coinciding with the beginning of land use change from native rangeland vegetation to wheat croplands. It was assumed that areas under native vegetation described in 2005 (Fig. 1) remained the same since 1955, and the rest of the study area changed to wheat production during the period 1955–1990. In 1991, low yields and economical difficulties resulted in some wheat production areas being abandoned or being converted to wheatgrass (perennial grassland). These land uses continued until 2005, when our simulations followed two scenarios. One scenario represented business as usual; i.e., land uses continue under native vegetation, wheat, wheatgrass or abandoned croplands. The other scenario represented best management practices; in which soil information was considered for determining each simulation unit's best use. In other words, we determined the ability of each land use polygon to sustain certain types of use without causing degradation. Under the best management practices scenario, native vegetation, wheat or wheatgrass where simulated during 2005–2030.

Land use area changes are presented in Table V. The 1.383 million ha of native vegetation in 1955 reduced to 1.075 million ha in 2005, being 0.044 million ha converted to wheat, 0.114 million ha to wheatgrass, and 0.149 million ha being abandoned. Under the business as usual scenario the four land uses areas were maintained until 2030 but under the best management practices scenarios abandoned croplands were converted to wheatgrass or wheat, and some native vegetation lands were also reduced for the same reason. As a result, wheat croplands increased 4-fold and wheatgrass areas increased 2.5-fold. This land use distribution indicates the potential expansion of wheat and wheatgrass based on the best use of soils; however, final decision should take policy and economical factors into consideration.

The impacts of land use changes on SOC stocks (0–50 cm) are presented in Table VI. Soil organic carbon stocks in 2005

Table VI. Simulated soil organic C stocks (0–50 cm) under different land uses, in 1955, 2005, and 2030, in central east Kazakhstan. Corresponds to the area of influence from the World Bank Dryland Management Project.

Land use	Soil organic carbon stocks (Tg)			
	Year 1955	Year 2005	Year 2030 a*	Year 2030 b**
Native vegetation	105.4	71.7	70.6	64.0
Wheat	0	2.3	2.2	11.3
Wheatgrass	0	5.5	5.6	18.8
Abandoned croplands	0	8.1	8.2	0
Total	105.4	87.6	86.6	94.1

* Scenario "business as usual", same land use and tillage management as in year 2005.

** Scenario "best management practices", land use based on a Land Capability Map and reduced tillage and wheatgrass harvest operations.

can be seen as the baseline; in this sense our approach allowed the conversion of coarse resolution soil data to a much finer resolution soil data. The rational for this assertion is that profile descriptions under undisturbed vegetation were used to create the soil map, and the EPIC model simulations allowed estimating soil properties for other land uses (i.e., wheat croplands, wheatgrass, abandoned croplands).

Considering the business as usual scenario during 2005–2030, there was a decrease of 0.1 Tg SOC under wheat (Tab. VI), which is equivalent to 87 kg C ha^{-1} yr^{-1}. However, there was an increase under wheatgrass (34 kg C ha^{-1} yr^{-1}). The decrease under wheat suggests this production system would have a negative impact on SOC in the long term. In the whole KDMP area, SOC would decrease from 87.6 Tg in 2005 to 86.6 Tg in 2030 (723 kg C ha^{-1} yr^{-1}).

Using best management practices, SOC would increase from 87.6 Tg in 2005 to 94.1 Tg in 2030, corresponding to a SOC sequestration rate of 4700 kg C ha^{-1} yr^{-1}. This positive influence on SOC is appealing because it indicates soil quality improvements and mitigation of environmental problems by causing a net sink for atmospheric CO_2, even when grain and forage production areas have been increased.

3.4. Spatial distribution of soil organic C (50 cm)

Simulated spatial distributions of SOC in 1955 and 2005 are shown in Figure 7. Soil properties determined during the soil survey in 2005 (when soil profiles under native vegetation were characterized) were used to initialize EPIC in 1955 (beginning of cultivation), under the assumption that SOC under native vegetation is in a steady-state equilibrium. The 1955 map shows Dark Chestnut soils having the highest contents of SOC, Normal Chestnuts with medium contents, and Light Chestnuts with the lowest contents.

The 2005 SOC map represents the baseline or prevailing SOC conditions at the beginning of the KDMP. Clearly, changes in land use brought about reductions in SOC stocks, with the largest changes on steep slopes and Dark Chestnut soils located on the eastern section of the study area; and the smallest changes, on relatively plane topography on Normal and Light Chestnut soils located on the southwestern section of the study area. Increments of SOC stocks during 1955–2005 were estimated on low relief topography areas with Solonetz soils, where native vegetation was maintained, yet this soil occupied only 3% of our study area.

3.5. Estimated spatial changes in SOC (50 cm) during the period 2005–2030

Gain or losses in SOC stocks (50 cm) during the period 2005–2030 for the business as usual and the best management practices scenarios are presented in Figure 8. If land use continues the same, most gains in SOC are estimated to occur under native vegetation and Normal Chestnuts or Light Chestnuts with relative plane topography, on the central and western section of the study area (Fig. 8a).

With best management practices, gains occur on most of the study area (Fig. 8b). Steep slopes, which accelerate the negative impacts of soil erosion on SOC, was the major factor causing SOC decreases. The regionalization of SOC gain or losses portrayed in Figure 8, must be considered for planning croplands and cultivated pasture expansion. Additional soil conservation practices (e.g., terraces, strip cropping) need to be considered at locations with steep slopes.

3.6. Simulated wheat yields during 2006–2030

With conservation tillage and relocation of wheat croplands based on land capability, wheat yields in the KDMP area during 2006–2030 would vary from 0.7 to 3.7 Mg ha^{-1}, with average and standard deviation of 1.48 ± 0.63 Mg ha^{-1}. Thus, our simulation results predict significant increase in grain yields (compared to the period 1955–2005) if best management practices are adopted.

4. CONCLUSIONS

Combining land use classification and soil maps with EPIC proved valid for studying impacts of land use changes and management practices on SOC in the short-grass steppe region of Kazakhstan. An important aspect of this approach is the ability to scale up site-specific SOC to the region.

With the available data, EPIC produced relatively accurate results but more data on spatial and temporal variation in SOC are needed to improve model calibration and validation in semiarid environments.

Our model outputs indicated that currently, SOC in the KDMP area is acting as a net source for atmospheric CO_2, and suggest that the conversion of abandoned croplands to wheat or wheatgrass, and the adoption of conservation tillage would impact positively on SOC sequestration, resulting in a net sink of 6.5 Tg (6.5 million metric tons) SOC to a depth of 50 cm during a period of 25 years.

The impacts of best management practices are highest in the western section of the study area, where gentle topographic slopes predominate.

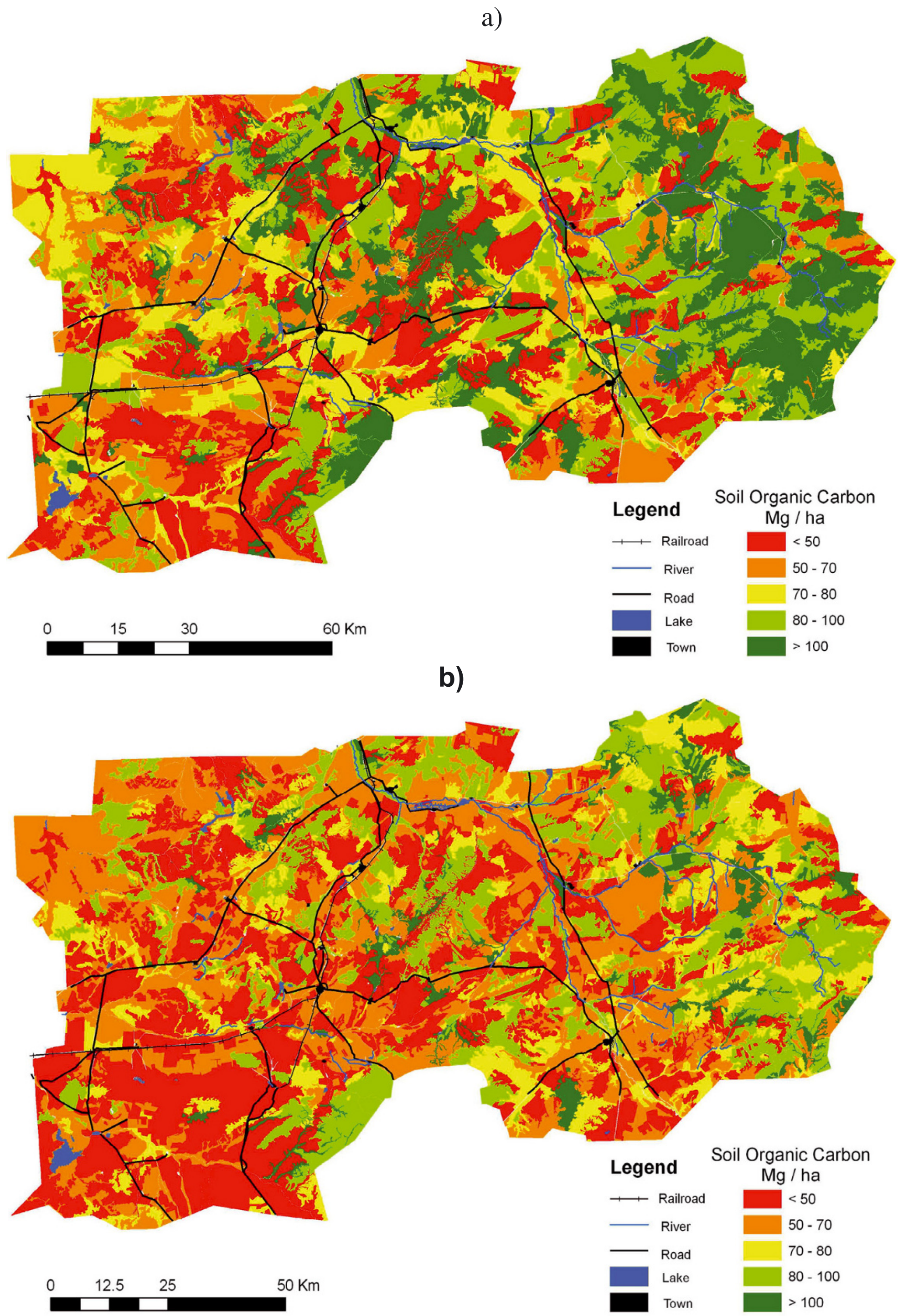

Figure 7. Spatial distribution of soil organic C (0–50 cm) in (a) 1955 and (b) 2005, in the area of influence from the World Bank Dryland Management Project (central east Kazakhstan).

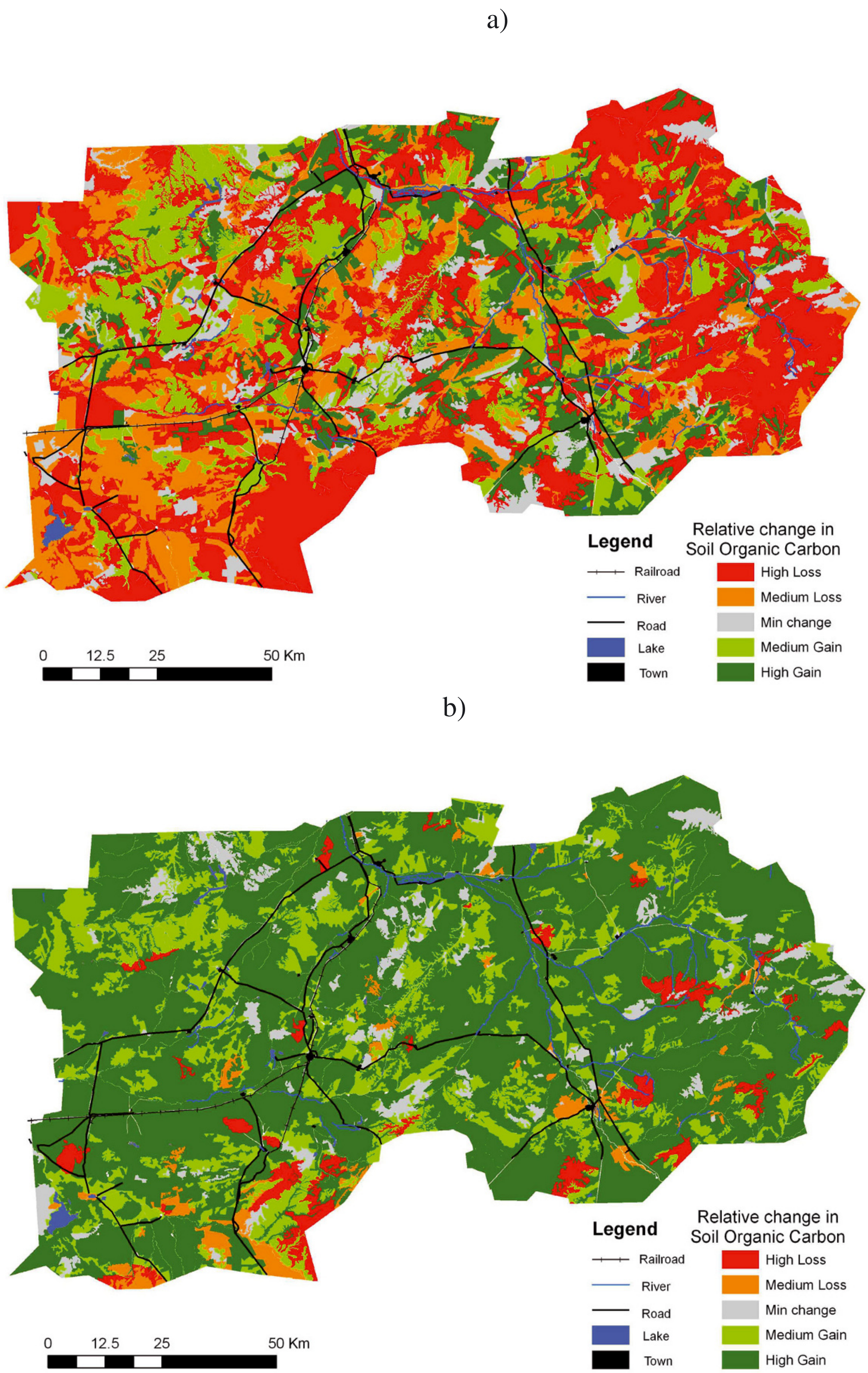

Figure 8. Simulated relative change in soil organic C (0–50 cm) between 2005 and 2030, for (a) the business as usual scenario, and for (b) the best management practices scenario, in the area of influence from the World Bank Dryland Management Project (central east Kazakhstan).

REFERENCES

Causarano H.J., Doraiswamy P.C., McCarty G.W., Hatfield J.L., Milak S., Stern A.J. (2008) EPIC modeling of soil organic carbon sequestration in croplands of Iowa, J. Environ. Qual. 37, 1345–1353.

Causarano H.J., Shaw J.N., Franzluebbers A.J., Reeves D.W., Raper R.L., Balkcom K.S., Norfleet M.L., Izaurralde R.C. (2007) Simulating field-scale soil organic carbon dynamics using EPIC, Soil Sci. Soc. Am. J. 71, 1174–1185.

Falloon P., Smith P. (2003) Accounting for changes in soil carbon under the Kyoto protocol: need for improved long-term data sets to reduce uncertainty in model projections, Soil Use Manage. 19, 265–269.

Gassman P.W., Williams J.R., Benson V.W., Izaurralde R.C., Hauck L.M., Jones C.A., Atwood J.D., Kiniry J.R., Flowers J.D. (2004) Historical development and applications of the EPIC and APEX models (ASAE Paper No.042097), ASAE, St. Joseph, MI.

Hargreaves G.H., Samani Z.A. (1985) Reference crop evapotranspiration from temperature, Appl. Eng. Agric. 1, 96–99.

Izaurralde R.C., Rosenberg N.J., Brown R.A., Thomson A.M. (2003) Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States: Part II. Regional agricultural production in 2030 and 2095, Agric. For. Meteorol. 117, 97–122.

Izaurralde R.C., Williams J.R., McGill W.B., Rosenberg N.J., Jakas M.C.Q. (2006) Simulating soil C dynamics with EPIC: Model description and testing against long-term data, Ecol. Model. 192, 362–384.

Kaser M. (1997) The economics of Kazakhstan and Uzbekistan. London: The Royal Institute of International Affairs.

Kiniry J.R., Major D.J., Izaurralde R.C., Williams J.R., Gassman P.W., Morrison M., Bergentine R., Zentner R.P. (1995) EPIC model parameters for cereal, oilseed, and forage crops in the northern Great Plains region, Can. J. Plant Sci. 75, 679–688.

Lal R. (2004) Carbon sequestration in soils of central Asia, Land Degrad. Dev. 15, 563–572.

McCauley M. (1976) Khrushchev and the development of Soviet agriculture: The Virgin Land Programme, Holmes & Meier, New York, pp. 1953–1964.

Meng E., Longmire J., Moldashev A. (2000) Kazakhstan's wheat system: priorities, constraints, and future prospects, Food Policy 25, 701–717.

Paustian K., Elliott E.T., Collins H.P., Cole C.V., Paul E.A. (1995) Use of a network of long-term experiments in North America for analysis of soil C dynamics and global change, Aust. J. Exp. Agric. 35, 929–939.

Priya S., Shibasaki R. (2001) National spatial crop yield simulation using GIS-based crop production model, Ecol. Model. 136, 113–129.

Rao M.N., Waits D.A., Neilsen M.L. (2000) A GIS-based modeling approach for implementation of sustainable farm management practices, Environ. Modell. Software 15, 745–753.

Smith P., Smith J.U., Powlson D.S., McGill W.B., Arah J.R.M., Chertov O.G. (1997) A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments, Geoderma 81, 153–225.

Tan G., Shibasaki R. (2003) Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration, Ecol. Model. 168, 357–370.

United States Geological Survey (2007) Seamless Data Distribution System [Online]. Available at http://seamless.usgs.gov (verified 23 July 2007).

Wang X., He X., Williams J.R., Izaurralde R.C., Atwood J.D. (2005) Sensitivity and uncertainty analyses of crop yields and SOC simulated with EPIC, Trans. ASAE 48, 1041–1054.

Williams J.R. (1990) The erosion-productivity impact calculator (EPIC) model: a case history, Philos. Trans. R. Soc. Lond. 329, 421–428.