

# Organic carbon in soils of Central Asia—status quo and potentials for sequestration

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**Abstract** Expectations have been raised that carbon sequestration in soils could provide a short-term bridge to reduce the impacts of increasing carbon emissions until low-carbon technologies are available. To assess the role of Central Asia in this regard, the organic carbon in soils of Central Asia and losses in response to land use were quantified in a spatially explicit way. Based on literature information on soil organic carbon contents and in combination with the FAO-UNESCO Soil Map of the World, the organic carbon stocks in the upper 30 cm of native soils of Central Asia were estimated to amount to  $20,17 \pm 4,03$  Pg. The extent of conversion of native land into agricultural land and the degradation of rangelands was assessed by a land use land cover change map of the region. This type of land use (change) was responsible for a reduction of the soil organic carbon by about  $828 \pm 166$  Tg C, or on average 4.1% of the total stocks. To this reduction, degradation of rangeland (observed on 4.9 Mha) with 50 Tg contributed only 6%. Most of the losses resulted from past conversion of rangelands into rainfed or irrigated agricultural land in the north of Kazakhstan. Hotspots of high soil organic matter depletion were former

wetlands, drained for cultivation during the last decades. Assuming that improved agronomic and grazing management could be put in place and that therewith SOC levels in all of Central Asia's cropland and degraded rangeland could be brought back to native levels in the next 50 years, each year 16.6 Tg C could be sequestered. This is equal to the sizeable amount of 15.5% of the 2004 annual anthropogenic C-emissions of the five Central Asian countries ( $107 \text{ Tg C yr}^{-1}$ ). However, Central Asia contributed only 1.4% of  $\text{CO}_2$  that is set free worldwide by fossil fuel burning. Therefore, the mitigation effect on rising atmospheric  $\text{CO}_2$  levels and climate change of such ambitious sequestration plans, if put into practice, would be hardly notable. The central Asian example shows that, unfortunately, the strategy of soil C sequestration as a stand-alone measure is not a viable bridge to a future in which alternative energy source can substitute fossil fuel burning, but can only be part of a set of mitigating measures.

**Keywords** Soil organic carbon · Soil organic matter · Climate change · Mitigation · CDM

## Abbreviations

FAO	Food and Agriculture Organization of the United Nations
SOC	Soil Organic Carbon
SIC	Soil Inorganic Carbon
UNESCO	United Nations Educational, Scientific and Cultural Organization

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## Introduction

In view of global climate change and possible mitigation strategies, expectations have been raised that a considerable fraction of the amount of carbon that is emitted into the atmosphere as CO<sub>2</sub> by fossil fuel burning could be (re-)sequestered by soils, if properly managed (Batjes 1998; Lal 1999, 2009).

Central Asia, with the five countries Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan and Turkmenistan, got into this focus recently. Some publications have pointed out that soils and agro-ecosystems in this region have a Carbon (C) sequestration potential of global importance (Lal 2004; Gintzburger et al. 2003). However, little is known about the underlying data on carbon in soils of Central Asia. Also, no attempts have been made so far to illuminate carbon sequestration potentials in the light of worldwide C-emissions and major sinks.

This publication tackles this issue. We start with a brief overview of worldwide carbon pools and anthropogenic emissions and the respective share of the Central Asian countries. Estimating the share of CO<sub>2</sub> release from soils in response to land use requires an estimate of carbon stored in soils before and after human interventions. We estimated the amount of organically bound carbon in the upper 30 cm of pristine soils of Central Asia using the FAO-UNESCO (1995) Soil Map of the World and soil/region specific data on soil organic matter from literature. Based on available information of losses of this carbon in response to land use by conversion of native land into rainfed or irrigated agricultural land as well as by degradation of rangeland, in combination with a land use cover (change) map recently released by ICARDA (Celis et al. 2007a, b), we quantified losses of organic carbon in a spatially explicit manner.

### Carbon in soils and world C pools

Carbon in soils can be found in two fractions, (a) organically bound, i.e. as soil organic matter (SOM), and (b) in its inorganic form as carbonate minerals (gypsum, calcite or dolomite).

In case more detailed analyses are unavailable, it is commonly assumed that Soil Organic Carbon (SOC) constitutes 58% of the mass of SOM (Nelson and Sommers 1982), even though use of a single factor

for conversion has been challenged recently (Pribyl 2010).

SOM dynamics of agricultural soils have been studied and described in countless publications. SOM plays a key role for maintaining and improving soil fertility, especially in highly weathered soils of the tropics, but also in poorly developed soils in dry areas (Bot and Benites 2005). Building up and maintaining SOM is crucial for crop-nutrient availability and retention, soil biological activity and health as well as to improve macroporosity, water infiltration and the amount of plant-available soil water.

Soil inorganic carbon (SIC), though abundant in some soils particularly in dry areas, in comparison got much less attention in literature, as its influence on the fertility of soils is limited. It is however a potential source or sink of carbon and hence should be included in the soil-carbon sink debate. On the one hand, primary SIC from parental materials (rocks) might be set free as CO<sub>2</sub> in response to naturally occurring soil weathering, a process that is accelerated by any additional (human induced) soil disturbance. On the other hand, the reverse process might occur, when atmospheric CO<sub>2</sub> diluted in the soil water reacts with dissolved calcium and/or magnesium ions and precipitates as so called secondary carbonate. Particularly soils in arid regions might potentially be important sinks of secondary carbonate.

This article focuses on SOC and its release in response to agricultural management. An assessment of SIC is still due, but requires site-, soil-, climate- and land-use specific information, which is currently not sufficiently available to allow reliable estimates.

Looking at the predominant global C-pools, the importance of carbon in soils becomes obvious (Table 1). The amount of C in soils is for instance around three times higher than the amount of carbon bound in plants and animals. It is assumed that about a third of SOC occurs in forest soils, another third in grassland and savannah soils and the rest in wetlands, cropland and other biomes (Janzen 2004).

Carbon in the upper meter of soil, and to some extent even also in the deeper soils (see e.g. Sommer et al. 2000 on this issue), is not inert. Land use change and soil cultivation—often linked to deforestation and an additional release of carbon from biomass—has lead to a tremendous loss of SOC in the past. Houghton (2003) estimated that the net cumulative emission of CO<sub>2</sub> (soil and aboveground) from the

**Table 1** World C pools

Pool	Amount (Pg C) <sup>a</sup>	Source
Ocean	38–39000	IPCC 2001
Atmosphere	785	Janzen 2004
Biotic	466–835	Janzen 2004; Sombroek et al. 1993
Geologic (coal, gas, oil)	4–5000	IPCC 2001
Soil, SOC <sup>b</sup>	1220–1550	Batjes 1996; Eswaran et al. 1995; Post et al. 1982
Soil, SIC <sup>c</sup>	750–950	Lal and Kimble 2000
Soil, total (1 m depth)	2000–2500	Janzen 2004; Amundson 2001; Eswaran et al. 2000

<sup>a</sup> 1 Pg = 1 peta gram = 1000

Tg = 10<sup>15</sup> g = 1 billion tons

<sup>b</sup> SOC = soil organic carbon

<sup>c</sup> SIC = soil inorganic carbon

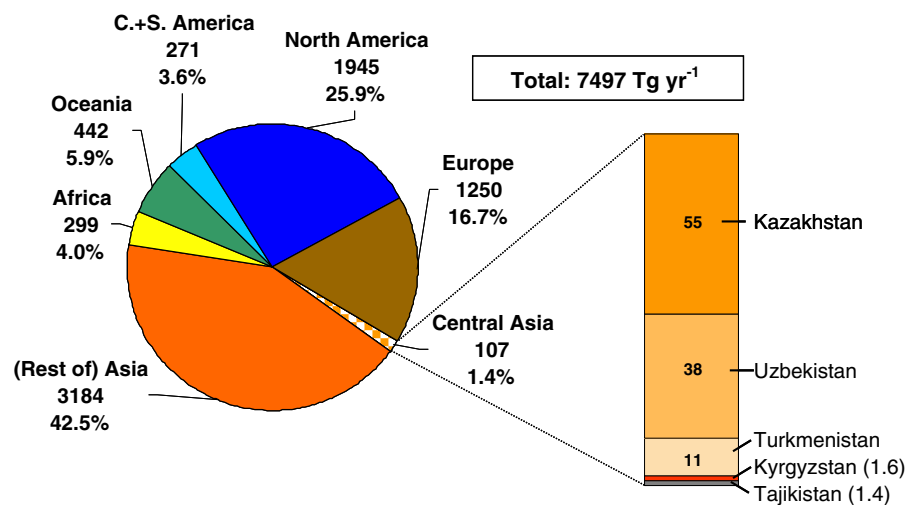
year 1850 to 2000 in response to human-induced land use change amounts to 156 Pg C. Nowadays, each year another ~2 Pg C is set free as CO<sub>2</sub> in response to land use change. Deforestation and rainforest burning in the tropics contributes the biggest part (Fearnside 2000; Houghton et al. 2000).

#### Anthropogenic CO<sub>2</sub> emissions

Rating carbon in soils and potentials to mitigate human-induced CO<sub>2</sub> emissions, it is necessary to consider C-emissions from fossil fuel burning (coal, gas, oil).

Worldwide in 2004 around 7.5 Pg C was emitted by fossil fuel burning (Fig. 1). This is almost four times higher than the rate of CO<sub>2</sub> emission from land use change (~2 Pg, s. above). With 107 Tg C yr<sup>-1</sup>, the Central Asian countries contributed only around 1.4% of CO<sub>2</sub> that was set free worldwide by fossil fuel burning.

**Fig. 1** CO<sub>2</sub> emissions (Tg C yr<sup>-1</sup>; % of total) from fossil fuel burning in 2004 worldwide as well as in detail for Central Asia (adapted from various sources provided by the Carbon Dioxide Information Analysis Center <http://cdiac.ornl.gov/>); 1 Tg = 1 tera gram = 10<sup>12</sup> g = 1 million tons; Central and South America also includes the Caribbean countries; Oceania comprises Japan, Australia and New Zealand as major emitters (99.6% of Oceania's total) and twelve other states in the Pacific

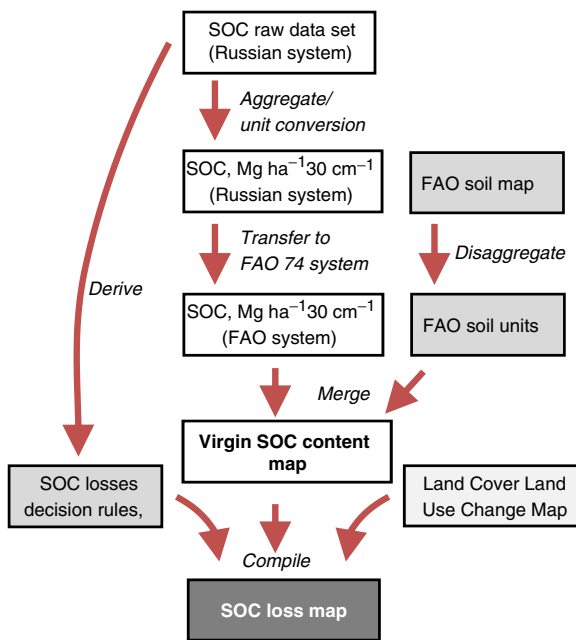


To this share Kazakhstan alone with an emission of 55 Tg C yr<sup>-1</sup> added roughly one half, followed by Uzbekistan and Turkmenistan. Kyrgyzstan and Tajikistan only contributed a very minor fraction to the overall C-emissions from fossil fuel burning of Central Asia.

#### Material and methods

To obtain spatially explicit SOC estimates for Central Asia the step-wise approach outlined in Fig. 2 was used.

Main data sources for the compilation of raw data set were Nasyrov et al. (2004) for Uzbekistan, Saparov et al. (2007) for Kazakhstan, and Mamitov (1968) for Kyrgyzstan. For some soils, information on SOC was extracted from the ISRIC-WISE (2009) global soil profile database. In such cases, i.e. when region-specific information was unavailable, SOC



**Fig. 2** Method for obtaining spatially explicit SOC estimates (see “Material and methods” chapter for detailed description)

contents were adjusted based on climatic factors (aridity index) to take into consideration the clearly visible gradient along a change in climate, as was observed for other soils.

The SOC levels obtained at different depths from these sources were aggregated to 0–30 cm, representing the soil depth where land use change or management would have the most influence on the native SOC level.

The native SOC levels for the different soil types, classified according to the Russian soil classification system, were transferred into their counterparts of the FAO-UNESCO Soil Map of the World (1974) classification system. As the two classification systems have a different philosophy, with the Russian system being more based on soil genesis and ecology, and the FAO system relying more on soil morphology, there is no perfect matching of soil units between the two systems. In cases where no clear-cut equivalents could be identified, expert judgment was used for gap-filling and obtaining SOC levels ( $\text{Mg ha}^{-1}$ ) over a standard 0–30 cm depth for each FAO soil unit.

These SOC estimates were linked to the soil map of Central Asia, extracted from the FAO-UNESCO Soil Map of the World (1995) and represented in a GIS system at a spatial resolution of 30 arc-seconds (roughly 900 m at the equator). The FAO-UNESCO Soil Map (1995) in total contains 1,204 soil

polygons (soil mapping units) for Central Asia distinguishing 247 different soil associations. Using the information on the percentage share of the dominant soil unit and the component soil units (=associated soils or soil inclusions of comparably minor coverage), which are provided as name-codes for each soil mapping unit, soil units could be mapped and the area quantified.

Subsequently, to account for the impact of rainfed and irrigated agriculture on SOC, the native SOC content map was intersected with the land cover/land use map developed by Celis et al. (2007a) on the basis of 1-km resolution AVHRR data for Central and West Asia and North Africa (base year 1993). To consider the impact of destructive overgrazing (visible by land degradation) on SOC of rangelands, related spatial information was extracted from the (follow-up) study of Celis et al. (2007b), in which land cover/land use change during the period 1982–2000 was quantified on the basis of 10-daily composites of 8-km AVHRR satellite images. Both studies (Celis et al. 2007a, b) built on the seasonal dynamics of the Normalized Difference Vegetation Index (NDVI), as an index that describes the greenness of vegetation. Considering the regular seasonal NDVI dynamics of different types of vegetation in the different agro-climatic zones in the region and applying regression tree analyses, Celis et al. (2007a, b) could distinguish the following six different LCLU classes: 1) irrigated cropland, 2) forest/tree crops, 3) rainfed cropland, 4) Savannah (not found in central Asia), 5) grassland, 6) sparsely vegetated land.

For the quantification of SOC contents in response to these types of land use, a number of decision rules were implemented using GIS calculator scripts. These decision rules were based on information from literature on the impact of land use (rainfed, irrigated or intensive grazing). The rules were as follows—underlying source in parentheses:

- If land use is ‘irrigated’ and the climate is ‘very arid’ (characterized by an annual aridity index  $>0.14$ ), the SOC levels of sandy soils were increased by 20% (Nasyrov et al. 2004).
- If land use is ‘irrigated’ and the climate is ‘very arid’, the SOC levels of non-sandy soils were increased by 60% (Nasyrov et al. 2004).
- If land use is ‘irrigated’ and the climate is not ‘very arid’, the OC levels of all soils except Histosols were decreased by 30% (Nasyrov et al. 2004).

- d) If land use is ‘irrigated’ and the soils are Histosols, the SOC levels were decreased by 80% (expert estimation).
- e) If land use is ‘rainfed’, the SOC levels were reduced by deducting 12.2 Mg ha<sup>-1</sup> as compared to native land (Mamitov 1968; Nasyrov et al. 2004; Saparov et al. 2007).
- f) If during the period 1982–2000 land use changed from ‘grassland’ to finally ‘barren/sparsely vegetated’, SOC levels were decreased by 35% (Han et al. 2008)
- g) If land use is not ‘irrigated’ or ‘rainfed’, or did not changed from ‘grassland’ to ‘barren’, the SOC levels remained unchanged.

The underlying data sets that led to these rules are explained in more details in the results.

All raw data are available for download under [ftp://ftp.cgiar.org/icarda/icarda-gisu/Central\\_Asia/](ftp://ftp.cgiar.org/icarda/icarda-gisu/Central_Asia/) (authors to be contacted for login and password).

### Statistical analysis

A true statistical analysis was difficult for the following reasons:

- a) The number of sample data available in the English-language literature from soils of Central Asia was very limited;
- b) for many soils of Central Asia, having the same classification, the SOC content is furthermore graduated by the climatic zone in which soils occur, particularly by the degree of aridity, and the effect of the landscape-level runoff-runon relationships on soil moisture availability. This is for example the case for the so-called ‘intra-zonal soils’, such as Solonetz, Solonchaks, Fluvisols and Cambisols, but SOC contents at this level of detail are not available for Central Asia;
- c) the sample data available in international public-access soil databases, such as WISE, include very few comparable profiles from soils outside Central Asia. The ranges of variation are therefore not necessarily representative for soils of Central Asia, and under these circumstances it appeared wiser to interpret the few available profile data from the region rather than making extrapolations from remote regions.

For these reasons only a rough indication of variability within the classification units (FAO or Russian) can be given. The available sample data showed an average dispersion from the mean value of  $\pm 20\%$ , and a maximum dispersion from the mean of  $\pm 40\%$ . The SOC content of about 67% of the soils fell within  $\pm 20\%$  of the sample mean, which we use in the remainder of the paper as measure of uncertainty.

## Results

### Soils of Central Asia

Xerosols and Yermosols, followed by Kastanozems, Solonetz and Lithosols with rock outcrops occupy the largest area in Central Asia (Fig. 3). Kastanozems are the dominant soils of many soil associations and therefore predominate when only those, but not associated soils or inclusions, are displayed, such as in Fig. 3. Sand dunes prevail in the Kyzylkum and Karakum deserts of the south.

### Organic carbon in native soils of Central Asia

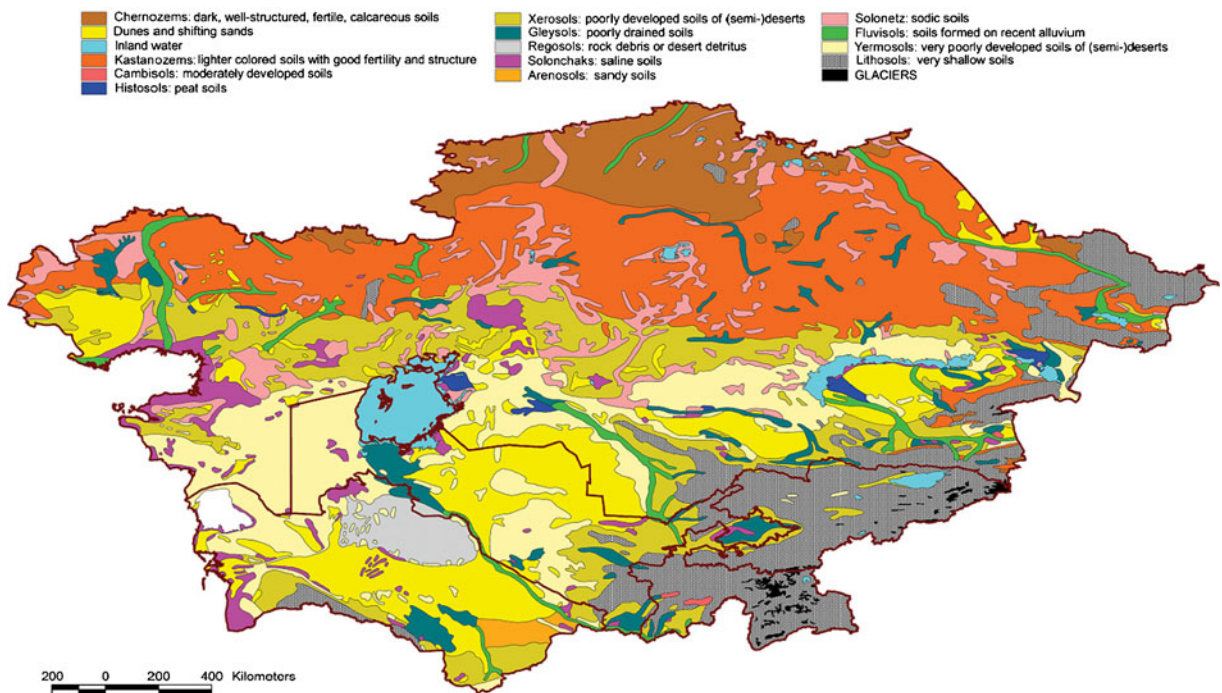
We estimate the OC stocks of native soils of whole Central Asia in the upper 30 cm to amount to 20.172 Pg. About 48% of this SOC can be found in ten soils (Table 2).

Clearly, (Eutric) Histosols, i.e. wetland (peat) soils, contain the highest SOC per hectare, but the area covered is limited. Nevertheless, together with Orthic Solonetz’, Luvic Kastanozems, Haplic Kastanozems, Lithosols, Mollic Gleysols, Luvic Xerosols, Calcic Chernozems, Calcic Xerosols and Haplic Chernozems they belong to the ten most important soils when SOC per hectare and area coverage is combined, i.e. when stocks are calculated (Table 2).

The north to southwest gradient of SOC is clearly visible in Fig. 4.

### Soil organic carbon losses in response to land use

Saparov et al. (2007) provide an overview of SOC of the steppe of northern Kazakhstan, an area they depict to cover 126.2 Mha which is 42.6% of the total area of Kazakhstan. In this area the most predominant soils are slightly developed, normal, alkaline, calcareous, and



**Fig. 3** Soil map (major units) of Central Asia (redrawn from data of FAO-UNESCO 1995)

meadow Chernozems or Kastanozems. Carbon of these soils steadily decreased with increasing average annual temperatures and decreasing rainfall and latitude (Fig. 5).

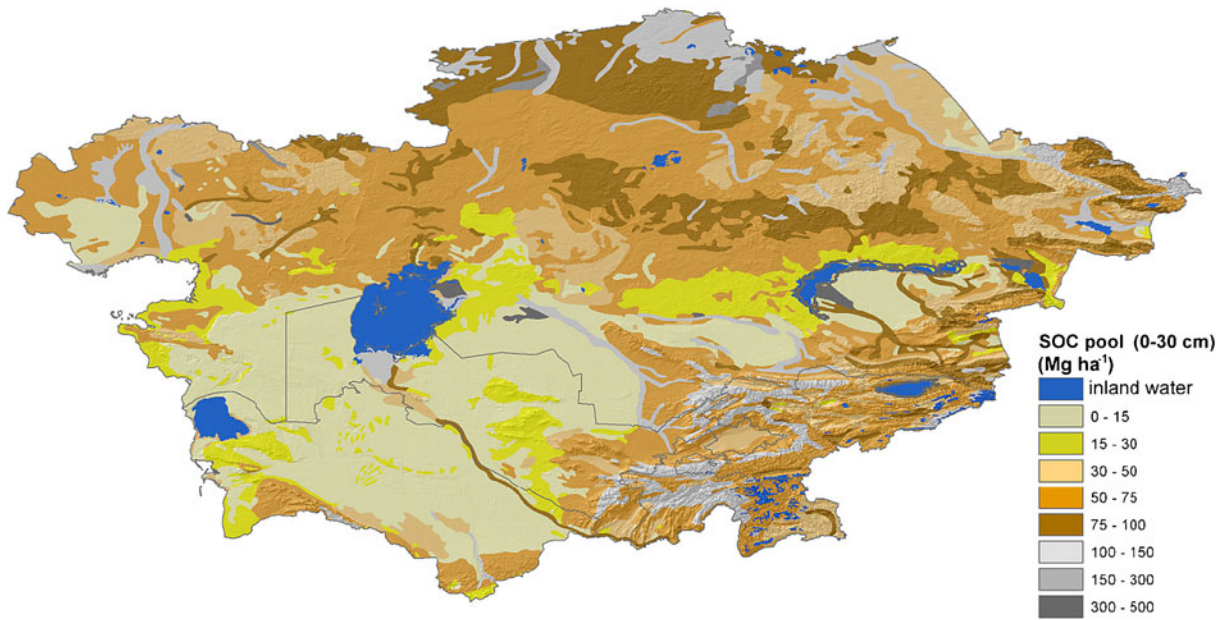
According to Saparov et al. (2007) conversion from native to arable land triggered a loss of soil carbon between 9% and 21% (average 16%) corresponding to 5.0–15.5 (average 8.5) Mg C ha<sup>-1</sup> in the top 20 cm

**Table 2** Area covered and average native soil organic carbon contents of the ten most important soils in Central Asia according to FAO-74 and corresponding Russian soil classification system; source for estimation of SOC provided in the last column

Soil unit		Land coverage	Soil organic carbon	Source
FAO-74	Russian system	(km <sup>2</sup> )	(Mg ha <sup>-1</sup> 30 cm <sup>-1</sup> )	
Orthic Solonetz	Normal solonetzic soil	334,068	21–66	Variable following aridity gradient
Luvic Kastanozem	Normal dark Chestnut soil	278,968	68.7	Saparov et al. (2007) <sup>a</sup>
Haplic Kastanozem	Normal Chestnut soil	407,428	44.0	Saparov et al. (2007) <sup>a</sup>
Lithosol	Lithosol	216,211	76.6	Mamitov 1968 <sup>b</sup>
Mollic Gleysol	Typical meadow-chernozemic soil	86,754	153.3	Saparov et al. (2007) <sup>a</sup>
Luvic Xerosol	Alkali steppe soil	199,123	55.3	Saparov et al. (2007) <sup>a</sup>
Calcic Chernozem	Calcareous Chernozem	122,120	85.2	Saparov et al. (2007) <sup>a</sup>
Calcic Xerosol	Alkali steppe soil	179,166	55.3	Saparov et al. (2007) <sup>a</sup>
Eutric Histosol	Bog soil	18,812	479.0	ISRIC-WISE (2009)
Haplic Chernozem	normal Chernozem	74,487	120.3	Saparov et al. (2007) <sup>a</sup>
Total		1,917,136		
Percent of total		48		

<sup>a</sup> recalculated for 0–30 cm from original soil layers differing in thickness

<sup>b</sup> calculated based on percentage SOC data using a default soil bulk density of 1.25 g cm<sup>-3</sup>

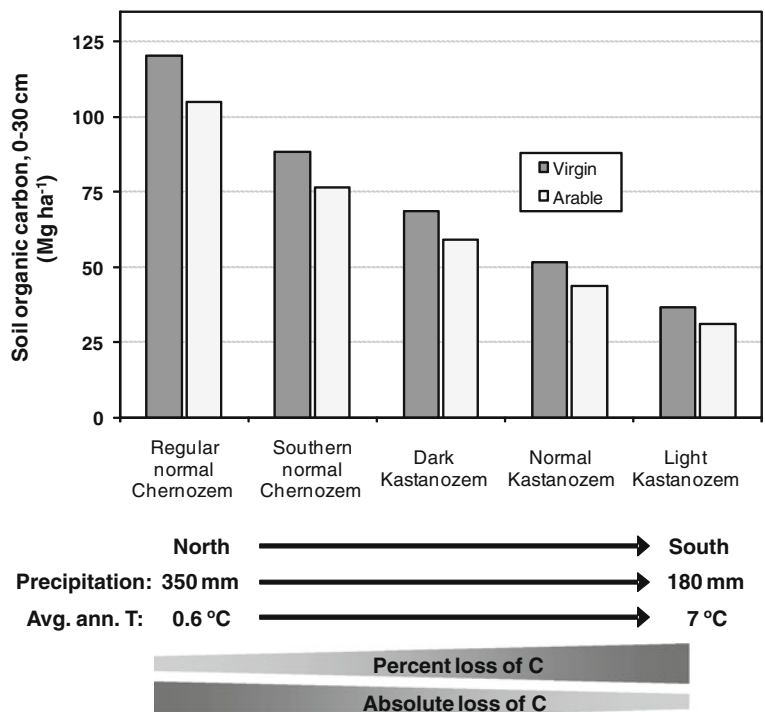


**Fig. 4** Pristine (virgin) soil organic carbon content of soils in Central Asia

depending on chemical composition and eco-zone. Soils in dryer and hotter southern regions lost comparably less C in absolute terms than soils in the wetter and colder north of Kazakhstan, while percentage losses behaved vice-versa. In 20–50 cm depth losses were lower with on

average 6%, corresponding to  $3.2 \text{ Mg C ha}^{-1}$ , but larger overall variation (range:  $-8\%$  to  $+16\%$ ). Aggregating this information for 0–30 cm soil depth, cropping of soils in the steppe of northern Kazakhstan triggered a loss of on average  $10.0 \text{ Mg C ha}^{-1} \text{ } 30 \text{ cm}^{-1}$ .

**Fig. 5** Influence of agromonic land use on SOC pools in 0–30 cm depth in the predominating soils of the northern Kazakh steppe zone (recalculated from % data of SOC in 0–20 cm and 20–50 cm depth of Saparov et al. (2007) assuming homogenous distribution of C in the second layers); percent or absolute loss of C is related to the influence of land use (virgin vs. arable)



As was observed for soils in the Kazak steppe, land use led to a loss of organic carbon in the Sierozems ( $\cong$  Calcisols or Cambisols) of Uzbekistan (Nasyrov et al. 2004; Fig. 6). But compared to the Kazak steppe soils, losses in 0–30 cm in the Uzbek soils were higher and accounted for on average 35% (14.7 Mg C ha<sup>-1</sup>) of the SOC under irrigated conditions and even 55% (25.7 Mg C ha<sup>-1</sup>) under rainfed conditions.

For the predominant soils under rainfed conditions a loss of on average 12.2 Mg ha<sup>-1</sup> was observed with only a minor, statistically insignificant, influence of initial levels. Former wetlands (Histosols) nowadays drained and under irrigated production, lost by far more SOC. Our expert estimate is a reduction by at least 80%. Irrigation of soils in desert regions (Takyr and Grey Brown soils), on the other hand, led to an increase of SOC (20–60%), most likely because of an increased biomass production and input of crop-residues/roots into the soil as compared to desert conditions.

The impact of livestock grazing on SOC of rangelands requires special attention, simply because of the vast area rangelands cover in Central Asia (~261 Mha, Table 3).

There are a number of studies on the effect of grazing on SOC elsewhere in the world (see “Discussion”), but comparable studies done in Central Asia are scarce. Given the closeness between the Central Asian Rangelands and those in neighboring Inner Mongolia, we selected the study of Han et al. 2008 as baseline. They monitored the

impact of 30 years of light, medium and heavy grazing on organic carbon contents of a light brown Chernozem in the steppe of Mongolia. As compared to light grazing, the upper 30 cm soil under heavy grazing had lost 29.6 Mg C ha<sup>-1</sup> or 32.4%.

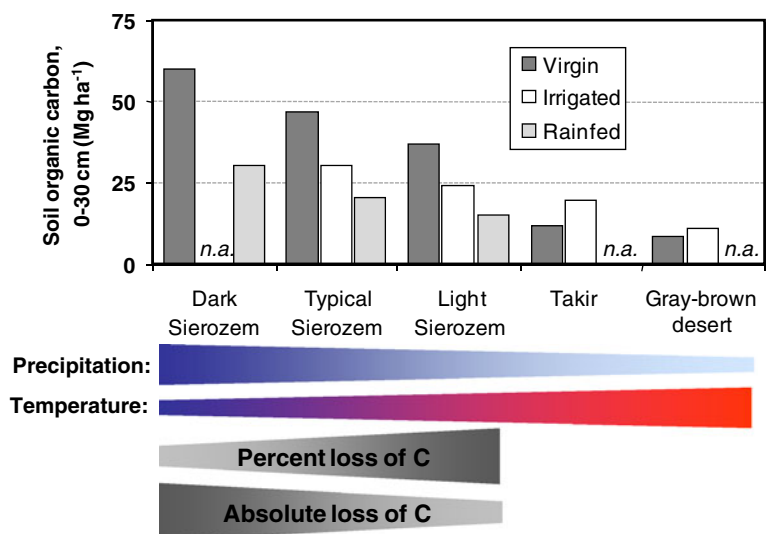
#### Land cover and land use change in Central Asia

For the year 1993 and Central Asia, Celis et al. (2007a) could identify 7.3 million hectares forest, 167.9 Mha grassland and 93.6 Mha sparsely vegetated steppe land (Fig. 7, Table 3).

Rangelands, i.e. grassland plus sparsely vegetated land, of Kazakhstan alone with 191.7 Mha contributed almost 50% of the area of Central Asia. Annual crops were produced on altogether 85.3 Mha. Irrigated agriculture in 1993 was practiced in 6.5% of the area. With 8.8 Mha Uzbekistan had the comparably highest share of land under irrigation.

Over the period 1982 to 2000, Celis et al. (2007b) revealed that land use changed on 12% of the land in Central Asia. In some cases there was astoundingly balanced, “back-and-forth” of land use. For instance, in total 8.4 Mha of land under rainfed agriculture were abandoned and turned into grassland, but during the same period almost the identical area (8.6 Mha) of grassland was taken into rainfed agriculture (Fig. 8). On the other hand, significant deforestation (‘Trees to Rainfed’) was detected in Kazakhstan, Uzbekistan and Tajikistan. More than double the size of sparsely

**Fig. 6** The influence of rainfed or irrigated agriculture on soil organic carbon in predominant soils of Uzbekistan (0–30 cm depth; recalculated from percent data of Nasyrov et al. 2004, assuming a soil bulk density of 1.25 g cm<sup>-3</sup>); n.a. = not applicable; Dark Sierozem  $\cong$  Calcic Cambisol; Typical Sierozem  $\cong$  Calcisol; light Sierozem  $\cong$  Calcic Solonchak or Calcisol; Takir  $\cong$  Takyric Calcisols; Gray-brown desert  $\cong$  Calcic or Yermic Leptosol, Solonchak or Solonetz according to FAO (1998) soil classification





**Table 3** Land cover/land use in central Asia in the year 1993 (data from Celis et al. 2007a); Trees = forest and/or tree crop, Sparse = sparsely vegetated land (including deserts), Not defined = remote sensing data did not allow for an unambiguous detection (of change)

	Total Mha	Trees	Grass-land	Sparse	Rainfed	Irrigated	Inland water	Not-defined
Kazakhstan	269.2	6.0	151.6	40.1	43.8	6.4	1.7	19.8
Kyrgyzstan	20.0	1.0	6.6	0.5	8.2	1.0	0.4	2.4
Tajikistan	14.1	0.2	2.2	3.4	1.8	4.0	0.0	2.4
Turkmenistan	48.8	0.03	3.2	29.6	3.6	5.7	1.4	5.3
Uzbekistan	42.5	0.1	4.2	20.0	2.1	8.8	5.0	2.2
Total	394.6	7.3	167.9	93.6	59.5	25.8	8.4	32.1
% of total		1.9%	42.5%	23.7%	15.1%	6.5%	2.1%	8.1%

vegetated land turned into grassland (11.5 Mha) than vice-versa (4.9 Mha).

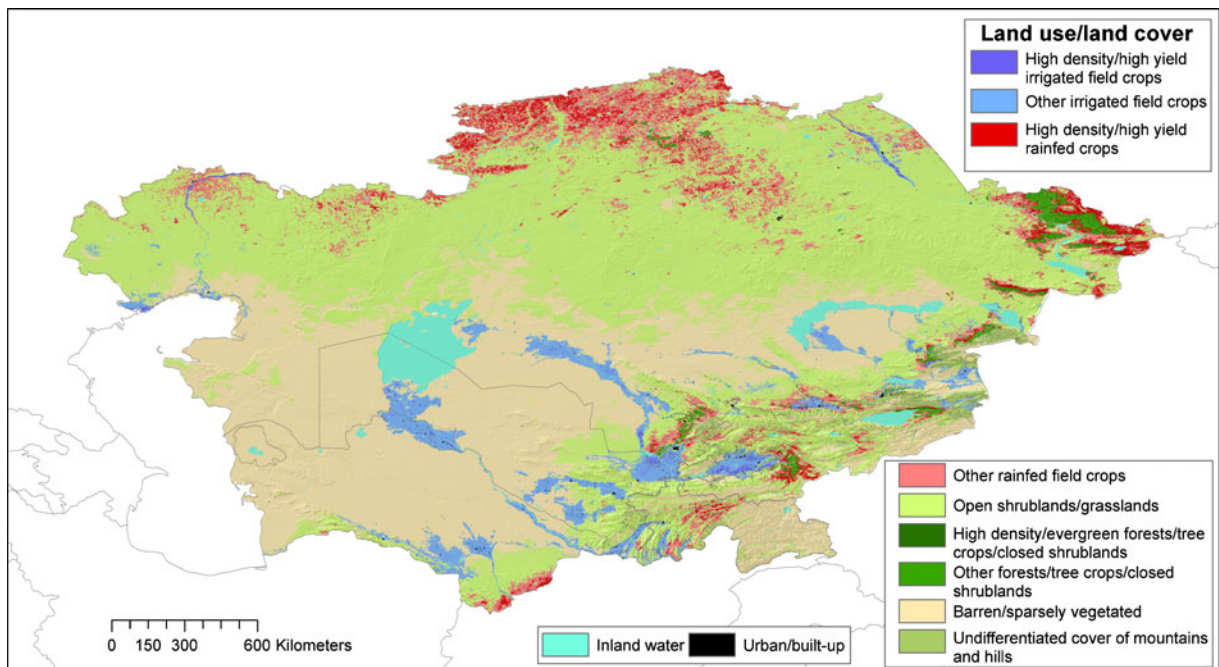
Resulting losses of SOC in Central Asia in response to land use

Conversion of native rangelands in the north of Kazakhstan into rainfed or irrigated agricultural land—given the vast areas affected—was responsible for most of the losses of SOC in response to land use (Fig. 9). Hotspots of high SOC depletion are former wetlands with SOC-rich soils nowadays drained for

cultivation, such as for instance land around the shrinking Lake Balkhash in eastern Kazakhstan or some areas along the Syr Darya or east of the Aral Sea, the southern part of which by now has almost completely disappeared.

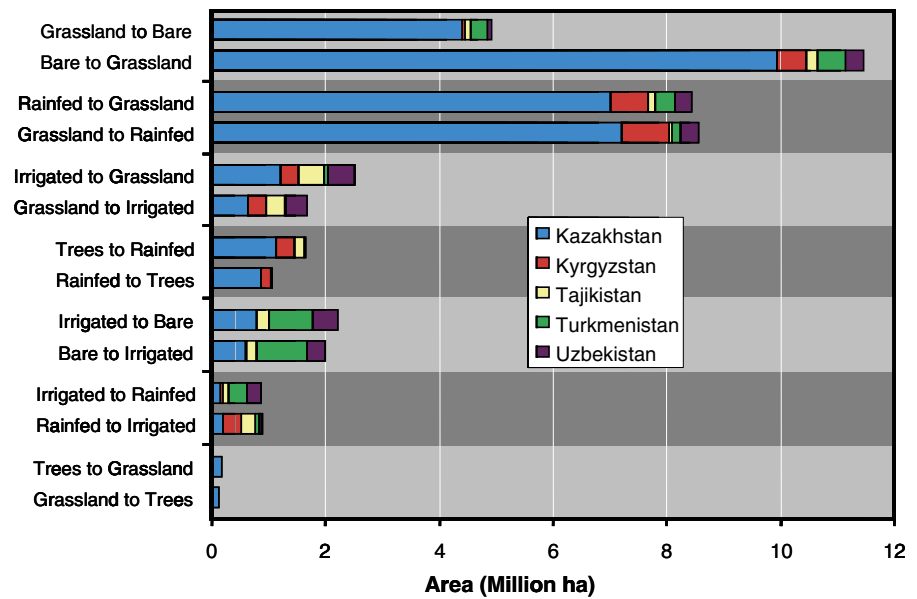
SOC increased in some areas along the Amu Darya and Sur Darya rivers, where desert areas were converted to intensive irrigated agriculture. This was also true for most of the irrigated lands of Turkmenistan.

For whole Central Asia we estimate that the conversion of native land into agricultural land and the degradation of rangelands on average ( $\pm 20\%$  uncertainty)



**Fig. 7** Land cover/land use of central Asia in 1993 (Celis et al. 2007a)

**Fig. 8** Land cover/land use change from 1982 to 2000 in Central Asia according to major LCLU classes (based on data from Celis et al. 2007b); Bare = bare land (~degraded/desert area), Trees = forest and/or tree crops

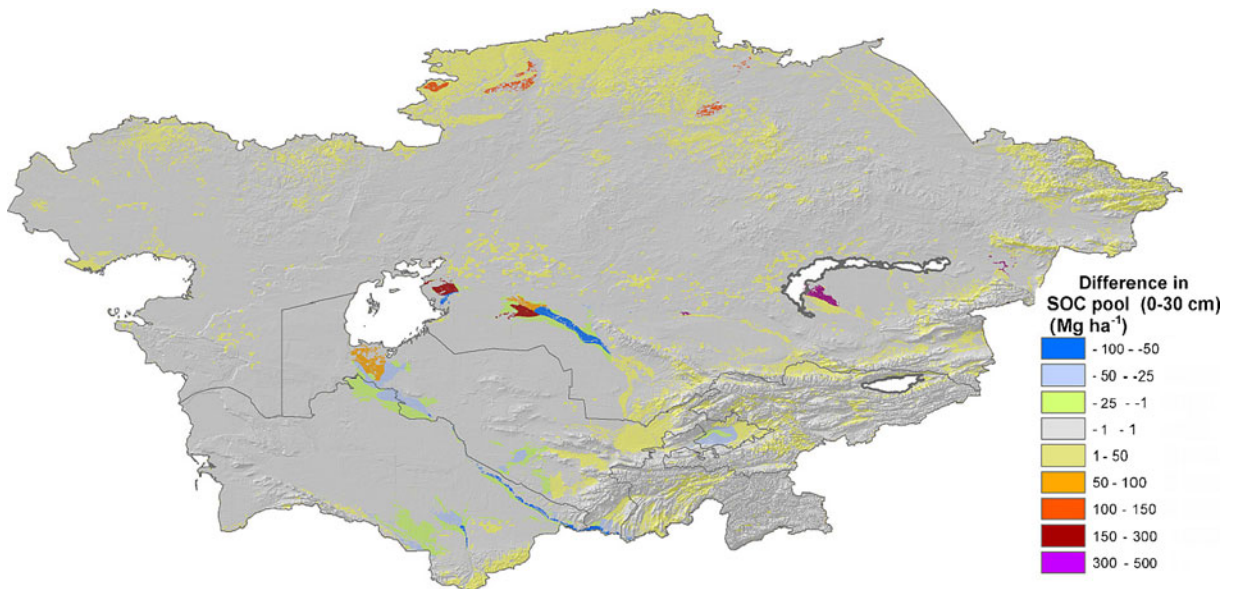


is responsible for a reduction of SOC contents (0–30 cm depth) of roughly  $828 \pm 166$  Tg C, or 4.1% of the total SOC stocks of Central Asia (Table 4).

To this reduction, degradation of rangeland observed on 4.9 Mha ('grassland to bare' in Fig. 8) with on average 50 Tg contributes 6.0%. Here, it should be noted that on the other hand grazing had been abandoned on 11.5 Mha ('bare to grassland' in Fig. 8). Assuming that such areas sequestered  $0.1 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  as stated by Schuman et al.

(2002), each year 1.15 Tg C would be sequestered. For the 18 year LCLU time-period (1982 to 2000) this would amount to 20.7 Tg, or close to half (42%) of the above-mentioned SOC losses caused by degradation of rangelands.

Irrigation of land in the very arid regions of Turkmenistan resulted in a gain of SOC that did offset losses of SOC stemming from rangeland degradation and rainfed agriculture (Table 4). In total thus, land use in Turkmenistan constituted a carbon



**Fig. 9** Losses of soil organic carbon due to land use (positive values denote losses of carbon, negative values denote gains)

**Table 4** Native soil organic carbon (SOC) stocks and losses in response to land use in Central Asia by country

Country	Native soil organic carbon $\pm 20\%$		Losses of SOC by			Total losses	
	(Tg)		Rainfed agriculture	Irrigated agriculture	Rangeland degradation	(%)	
Kazakhstan	15,639	$\pm 3,128$	416	299	46	761	4.9
Kyrgyzstan	1,377	$\pm 275$	33	11	1.0	45	3.3
Tajikistan	907	$\pm 181$	17	7	1.1	25	2.7
Turkmenistan	957	$\pm 191$	15	-69	1.2	-53	-5.6
Uzbekistan	1,292	$\pm 258$	5	45	0.3	51	3.9
Total	20,172	$\pm 4,034$	486	292	50	828	4.1
% of total			58.7	35.3	6.0		

sink of 53 Tg. Contrarily, as literature data (Fig. 6) revealed that irrigation did lead to losses of SOC in soils predominating in the northern and eastern part of Central Asia under moderately arid conditions, irrigated agriculture on the whole in Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan contributed to SOC losses. Not surprisingly, given the extensive areas under rainfed agriculture in the north of Kazakhstan, this type of land use was responsible for 50% (416 Tg) of Central Asia's total losses of SOC.

Thus, it can be concluded that most of the contribution to the release of CO<sub>2</sub> from land-use change in Central Asia resulted from past conversion of native rangelands into rainfed or irrigated agricultural land. Rangeland degradation in Central Asia, contributed only a small fraction with Kazakhstan (in relative terms) being the major contributor.

SOC losses re-sequestered—a sequestration potential of global importance?

Assuming against all existing obstacles that improved agronomic management could be put in place at large scale and instantaneously, and assuming that there-with SOC levels in all of Central Asia's cropland and degraded rangeland can be brought back to native levels in the next 50 years, on average 16.6 Tg C could be sequestered each year.

On the one hand, 16.6 Tg C represent the sizeable amount of 15.5% of the 2004 annual anthropogenic C-emissions of Central Asia. On the other hand, Central Asia is only a minor emitter of CO<sub>2</sub>, as has been outlined at the beginning. In comparison to worldwide emissions from fossil fuel burning in 2004, a sequestration potential of 16.6 Tg C repre-

sents merely 0.22%. As it is, the mitigation effect on rising atmospheric CO<sub>2</sub> levels and climate change of such ambitious sequestration plans, if put into practice, were hardly notable.

Nevertheless, given the chance to sell carbon sinks on the international carbon market, our figures should raise the attention of national politicians in the region. Once such carbon sinks are eligible for so-called Clean Development Mechanism projects within the framework of the Kyoto protocol (which they are not yet), sequestering 17.5 Tg C per year, at a price of €16.50 per ton C (status April 2010) are currently worth approximately 273 Million Euro.

## Discussion

The influence of different tillage and residue (or manure) management practices on SOC elsewhere in the world has been well described in literature, and no attempt is made here to summarize them. Unfortunately, a review of Russian literature, on the dynamics of carbon in soils of Central Asia in response to different land use practices in the different agro-ecosystems has not yet been done; or at least is not available in English. The book on terrestrial carbon sequestration in Central Asia (Lal et al. 2007) probably provides the most comprehensive insight so far in this respect, though also here information is sometimes incomplete.

There seems to be consent that turning native land into rainfed or irrigated agricultural land under conventional management practice entails a notable decrease of SOC within a relatively short period of time (Sanginov and Akramov 2007; Suleimenov and

Thomas 2007); evidence which we have accommodated by the decision rules on SOC losses outlined in “Material and methods”.

SOC losses reported by Suleimenov and Thomas (2007) range from 0.52–0.81 Mg ha<sup>-1</sup> yr<sup>-1</sup> (dark, regular and southern Chernozems) in the north of Kazakhstan to 0.29–0.46 Mg ha<sup>-1</sup> yr<sup>-1</sup> (rainfed Sierozems and light Kastanozems) in the south. Sanginov and Akramov (2007) presented SOC losses of 12.8 Mg ha<sup>-1</sup> (0–50 cm soil depth) observed over a 15 year period of a typical Sierozem in Tajikistan, i.e. on average 0.85 Mg ha<sup>-1</sup> yr<sup>-1</sup>.

The assumed high reduction of the SOC content of Histisols in response to land use by 80% is in line with reports on SOC losses of soils rich in organic matter for southern Ural/Volga area by Medvedev et al. (2003). An 80% reduction would bring down SOC contents of Histisols to native levels of Eutric Gleysols.

Assuming that lost organic carbon from degraded wetland could be re-sequestered in period of only 50 years certainly is a quite optimistic assumption. Thus, in that regard our (re-) sequestration estimates might over-predict achievable goals. However, wetlands are not major emitters of SOC in our budget, and figures would only change slightly if wetlands were excluded.

The assumption that native rangelands are at equilibrium and thus neither act as carbon source nor sink seems valid for the Kazakh steppe. Based on CO<sub>2</sub>-flux measurements carried out in 2001 Wylie et al. (2006) revealed that native (*Tselina*) rangelands of Kazakhstan act as carbon sinks during the vegetation period. From April to October they sequestered on average 0.79 Mg C ha<sup>-1</sup>. Off-season C-fluxes were not measured, but modeling C-dynamics disclosed that roughly the same amount of carbon is released through decomposition of OM in the autumn, winter and early spring season (Saliendra, personal communication), hence offsetting previous gains.

We assumed that destructive overgrazing of rangelands would lead to a reduction of the native SOC contents by 35%, similar to what has been reported by Han et al. (2008) for Inner Mongolia, China. Anecdotal reports about the impact of grazing in northern Kazakhstan (Anonymous 1999) confirm this assumption. A loss of SOC by (over)grazing was also reported by Bauer et al. (1987; USA), McIntosh et al. (1997; New Zealand), Hiernaux et al. (1999; Niger), Cui et al. (2005; Inner Mongolia) and Snyman and du

Preez (2005; South Africa). However, it should be noted that in some other publications the opposite, i.e. an increase of SOC in response to grazing, has been observed (Derner et al. 1997; Reeder and Schuman 2002; Schuman et al. 2002). Derner and Schuman (2007) tackle the issue in a review article, whereby addressing grazing of rangelands at various intensities; not exclusively deteriorative overgrazing as we did. They emphasize that there is considerable uncertainty and rather limited information as far as semi-arid environments (250–500 mm annual precipitation) are concerned. Cui et al. (2005) argue similarly: “Up to now, there is still a discrepancy regarding the response of soil C storage to grazing pressure” (*ditto* page 590).

Derner and Schuman (2007) cite a range of studies in which restoration of rangelands (e.g. by fertilization, re-seeding or legume-interseeding) in part led to a considerable sequestration of SOC; underlining validity of our assumption that the SOC status of degraded rangelands could be improved. For instance, Schuman et al. (2002) stated that rangelands under adequate grazing management in dry temperate eco-zones of the USA might sequester roughly 0.1 Mg C ha<sup>-1</sup> yr<sup>-1</sup>.

Our assumed 35% SOC reduction ranges at the upper end of reported losses, but we nevertheless think estimates are realistic, as we assumed that these losses had been taken place only in areas where land use changed from ‘grassland’ to ‘bare’, i.e. entailing a loss of vegetation. Most of the above-mentioned published articles on rangelands, on the other hand, rather consider a more or less sustainable land use, i.e. rangelands without “serious ecological or management problems” where “soil C ...can be considered relatively stable” (Schuman et al. 2002 page 394). It therefore seems appropriate to relate belowground OC losses to aboveground vegetation losses.

Details on Central Asia of the LCLU assessment revealed that by far more bare land turned into grassland than vice-versa. This was most likely related to the fact that grazing pressure in village-remote areas significantly reduced during this time due to various reasons (see Iñiguez et al. 2004 for more details). Subsequently degraded areas (due to overgrazing) could successfully recuperate, thereby potentially offsetting approximately half of the contemporaneous losses of SOC from rangeland degradation.

Some publications render outstandingly high percentages losses of soil carbon in response to (over)use of agricultural land (Khusanov and Kosimov 2007).

However they are rarely based on comprehensive surveys, but rather on single measurements (if at all). The same is true for figures provided on land degradation or desertification; *the* major driver for soil carbon loss. For instance, Dregne and Chou (1992) state that 70% of the rangeland of Central Asia are *prone to* desertification; a sentence that later-on was sometimes confounded and cited in a sense that desertification had actually already taken place on 70% of the rangelands. The study of Dregne and Chou (1992) was assessed for its reliability by Kniivila (2004). The author concludes: “*For the various estimates, anecdotal accounts, research reports, travelers’ descriptions, personal opinions and local experience have provided most of the evidence. Results are thus very subjective.*” (Ditto, p. 9). In the same line, Robinson et al. (2003) argue that “*the extent of degradation of the pastures in our case study areas [in Kazakhstan] was probably lower than suggested in the literature*” and that “*field assessments suggest that the rangelands are in good condition.*” (Ditto, p. 413).

Improved agronomic management involving conservation agriculture practices, improved grazing management (reduced pressure on land), or a change in cropping intensity (omitting fallow) can increase the SOC content in soils as compared to soils that underwent some decades of conventional management (Suleimenov 2006). The magnitude of increase is very site and soil-specific, and differences might be found between rainfed and irrigated systems. There is evidence that applying such improved SOC-management measures, SOC contents can be brought up to native levels, or in some case even above these levels (e.g. when dessert soils are turned into irrigated soils). The question is rather if the socio-economic and institutional circumstances allow for the introduction and dissemination of such measures, and what the involved costs would be; an issue that is not tackled in this paper.

Controversy might arise on the issue whether rainfed and irrigation areas and areas under intensive (unsustainable) grazing are currently still net emitters of carbon or whether they have reached a low equilibrium stage. It is also not clear how quickly soils could recuperate naturally, if unsustainable cropping or intensive grazing is abandoned. It seems however likely that, as opposed to a rather fast decline of carbon in soils in response to land use, a natural

increase of organic matter in abandoned soils occurs at slower rate. Heavily degraded areas, or former wetlands, might not at all reach original SOC levels again, at least not in time periods that are of interest in the carbon-sequestration debate.

In summary, we believe that the figures that we present are fairly robust. Nevertheless, the results hinge to some extent on the quality and timeliness of land use/land cover and degradation studies undertaken in Central Asia, which are currently few. Thus, there is definitely a need for further studies.

The magnitude of potential SOC sequestration also has to be seen in the light of the fact that for the year 2003 the agricultural area of Central Asia covers the sizeable area of 283.0 Mha (FAOSTAT 2009), i.e. close to 6% of the world total. Surely, our Central Asian results cannot be up-scaled to the whole world. But, if 6% of the soils of the world’s total agricultural area have a sequestration potential equivalent to only 0.23% of the global fossil fuel emissions, how much (more) carbon must soils of other agro-ecosystems be able to sequester to eventually accomplish a notable impact?

In that regard the question might be raised why then other authors did draw a much more positive balance.

First of all, to our knowledge so far no study did put regional SOC sequestration potentials into the global picture of anthropogenic C emissions. Subsequently, regional figures are considerably overvalued. The study of Lal (2004) is such a case. Even though his final estimates—11.3 to 20.7 with a mean of  $16 \pm 6.6$  Tg C yr<sup>-1</sup>—are close to our annual SOC sequestration rates, Lal (2004) subsequently overrates the impact and states: “*Environmentally, soil C sequestration offsets 20 per cent of the CO<sub>2</sub> emission from fossil-fuel combustion, and decreases the rate of enrichment of atmospheric CO<sub>2</sub>. Thus, soil C sequestration is truly a win-win situation.*” (Lal 2004, page 569). As mentioned above, 16 Tg C sequestration per year does not put a notable dent into global C-emission, neither those caused by land use change (~2,000 Tg yr<sup>-1</sup> according to Houghton 2003), nor those caused by fossil fuel burning (7,497 Tg yr<sup>-1</sup>, Fig. 1).

Secondly, some publications elaborate on the fact that Central Asia is covered by vast areas of rangelands, and only a slight positive change, if taking place on all (!) rangelands, would make a difference (FAO 2004). Lal (2004) for example simply assumes

that Central Asia's total rangeland area, which he estimates to 248.7 Mha, could be turned into a carbon sink. Consequently, not surprisingly, in Lal's calculations 79% of the C sequestration potential of Central Asia would come from 'improved' rangelands. The study of Celis et al. (2007a) and that of Robinson et al. (2003) show that recent rangeland degradation in Central Asia does not affect the total area, but only a small share. Taking into account that non-degraded (pristine) rangeland soils are at equilibrium stage and their C content is stable (Schuman et al. 2002), there is limited scope for advancing their SOC-status. Rather the contrary, hotter temperatures and probably lower rainfall in the rangelands of Central Asia, as are predicted consequences of climate change, are more likely to trigger a depletion of C from soils, as has been visualized in Figs. 5 and 6.

Despite all cons presented, it should not be forgotten that investing in measure to improve soil organic carbon go hand in hand with an improvement of soil fertility, which triggers higher crop yields and thus ensures food security. There is also tremendous scope for investments in afforestation in some degraded mountain areas of Central Asia; an issue that was not tackled in this paper, but which is likely to provide a much higher carbon sink on a per-hectare basis than SOC sequestration.

## Conclusion

Preservation of agro-ecosystems in Central Asia is inevitable for maintaining a sustainable and productive agricultural resource basis. There is no doubt about the need to do the necessary to preserve these production systems. C-sequestration in soils might be a positive side-effect of such preservation efforts, but it would be disproportionate to use it as a main argument, because (a) based on our estimates sequestration quantities will be negligible as compared to anthropogenic CO<sub>2</sub> emissions worldwide, and (b) they are currently not eligible for a Clean Development Mechanism projects under the Kyoto protocol.

The central Asian example shows that, unfortunately, C sequestration in soil is not the solution to unconstrained fossil fuel CO<sub>2</sub> emissions. The strategy of soil C sequestration as a stand-alone measure is not a viable bridge to a future in which alternative energy source can substitute fossil fuel burning. It can only

be part of a set of mitigating measure, which for instance might include afforestation e.g. in some of the degraded mountain areas of Central Asia.

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