Author(s): Elena Valkama, Gulya Kunypiyayeva, Rauan Zhapayev, Muratbek Karabayev, Erbol Zhusupbekov & Marco Acutis

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Modeling of soil organic carbon and carbon balance under conservation agriculture in Kazakhstan

Elena Valkama[42], Gulya Kunypiyayeva[43], Rauan Zhapayev, Muratbek Karabayev, Erbol Zhusupbekov[44], Marco Acutis[45]

Abstract

Traditional farming systems, involving intensive tillage, returning the low amounts of organic matter to field and frequently monoculture, lead to a decrease in soil organic carbon (SOC) and land degradation. In contrast, conservation agriculture (CA) has a large potential for carbon sequestration. However, the efficacy of no-till agriculture for increasing C in soils has been questioned in recent studies. These doubts stem from the facts that previous literature on soil C stocks has often discussed effects of tillage, rotations, and residue management separately. The objectives of this study are (1) to assess the potential of each CA component for soil C sequestration in Almaty state (Kazakhstan), proposing a methodology that could be extended to other conditions in Kazakhstan; and (2) to estimates CO_2 *balance and possibility to obtain carbon credits. Modeled results showed that no tillage with crop rotation and residue retained and/or cover crop increased SOC by about 300–1 000* kg^{-1} ha^{-1} yr^{-1} *in the ploughing layer. It seems that the contribution of each CA element into SOC stock decreased in the following order: cover crops > residues > rotation. In particular, attention should be paid to cover crops, which seem to have significant role in C sequestration, but are not yet widely spread in practical farming in Kazakhstan. Conservation agricultural practices involving, in addition to no-tillage, crop rotation, residues retained and/or cover crops allowed achieving the objective of 4 per 1 000 initiatives. The initiative claims that an annual growth rate of 0.4 percent in the soil carbon stocks, or 4‰ per year, would halt the increase in the* CO_2 *concentration in the atmosphere related to human activities. In addition, these CA practices had the negative total carbon balance indicating reduction of GHG emissions and indicating possibility to obtain carbon credits.*

Key words: no tillage, residues, cover crop, rotation, carbon market.

Introduction

Traditional farming systems, involving intensive tillage, returning the low amounts of organic matter to field and frequently monoculture, lead to a decrease in soil organic carbon (SOC) and land degradation. In contrast, conservation agriculture

(CA) has a large potential for carbon sequestration. According to FAO definition, conservation agriculture (CA) is a farming system that promotes maintenance of (1) minimum soil disturbance avoiding soil inversion (i.e. no tillage or minimum tillage), (2) a permanent soil cover with crop residues and/or cover crops, and (3) diversification of plant species through varied crop sequences and associations involving at least three different crops. In the Americas, CA occupies more than 50 percent of agricultural land. In Kazakhstan, the areas under no-till have been increasing from virtually nothing in 2000 to 2.5 million ha in 2016 that is, however, only about 1.1 percent of agricultural lands. Therefore, FAO consider Kazakhstan to be “high” in terms of the potential area for the further spread of CA.

However, the efficacy of no-till agriculture for increasing C in soils has been questioned in recent studies. This is a serious issue after many publications and reports during the last two decades have recommended no-till as a practice to mitigate greenhouse gas emissions through soil C sequestration (Ogle *et al.*, 2012). Only about half the 100+ studies comparing soil carbon sequestration with no-till and conventional tillage indicated increased sequestration with no till; this is despite continued claims that conservation agriculture sequesters soil carbon (Palm *et al.*, 2014). Some studies suggested that no-tillage only stratified SOC; a near-surface increase in SOC was offset by a concomitant decrease in the subsurface (Du *et al.*, 2017). Moreover, results at global scale are different according to different climatic conditions.

These doubts stem from the facts that previous literature on soil C stocks has often discussed effects of tillage, rotations, and residue management separately. According to Palm *et al.* (2014) it is important to recognize that these CA components interact. For example, the types of crops, intensity of cropping, and duration of the cropping systems, cover crops determine the amount of C inputs and thus the ability of CA to store more C than conventional tillage.

Cover crops, legume or non-legume, are not productive crops, useful to protect soil avoiding bare soil periods. To date, cover crops have been in the scientific focus mainly for their capacity to improve soil quality and thereby to foster crop production. Inclusion of cover crops in cropping systems is a promising option to sequester carbon in agricultural soils. Many studies and previous projects (Poeplau and Don, 2015; Perego *et al.*, 2019) have demonstrated that soil organic carbon storage can be increased in cover crops based farming systems by 0.3–0.6 t ha^{-1} yr^{-1}, especially if at the same time intensity of tillage is reduced and diversification of crop rotations is enhanced.

Since SOC change is a very slow process, long-term experiments (at least 10 years) are required to obtain reliable data and to assess the carbon sequestration of agricultural systems. There is a need to evaluate the performance of alternative cropping systems in different pedo-climatic conditions, and to assess their potential in terms of the SOC increase.

Moreover, CA cropping systems may be suitable for carbon markets, which is continuously growing. Governments and industry need to offset CO_2 emissions that they are generating. The carbon credit system (1 credit = 1t CO_2 reduced) allows the compensation of the release of greenhouse gases (GHG) by funding emission reduction projects. In agriculture, some initiatives related to carbon credits already exist from longtime, but at local scale. In 2007, the Alberta state (Canada) created an organization to allow farmers to sell carbon credits created in biogas production process from anaerobic digestion. In 2012, conservation agriculture was adopted for the carbon markets under defined protocols. In 2017, a new door in carbon markets was opened for agriculture, when Microsoft bought carbon credits from US rice farmers.

The objectives of this study are:

1. To assess the potential of each component of CA for soil C sequestration in one Kazakhstan site, proposing a methodology that could be extended to other conditions in Kazakhstan;
2. To estimates CO_2 balance and possibility to obtain carbon credits.

Material and methods

We performed a comparative assessment of SOC changes over 20 years under CA and traditional cropping systems in the Almaty site by using the dynamic simulation model ARMOSA that simulates the cropping systems at a daily time-step at field scale (Perego *et al.*, 2013). The model simulates agrometeorological variables, the water balance, the carbon and nitrogen balance, and the crop development and growth. As input for ARMOSA, we used a set of daily data of maximum and minimum temperature and rain from 2002 to 2011. The soil used for the simulation was silt loam texture and a 1.41 percent of organic carbon in the 0–30 cm surface layer. Barley was fertilized with 60 kg N ha^{-1} at sowing.

For model validation, we used soil and yield data from the long-term experiment (2002–2009) located in Almaty involving no-tillage and conventional tillage treatments for spring barley (*Hordeum vulgare*) monoculture. Barley yields were measured annually. Dry bulk density and SOC content were measured annually at 0–30 depths.

We simulated the following cropping systems (Table 18):

- Conventional 1: ploughing at 0.25 m, spring barley monoculture, and crop residues (straw) removed;
- Conventional 2: ploughing at 0.25 m, spring barley monoculture, residues retained;
- CT 1: no tillage, crop rotation: winter wheat (*Triticum aestivum*) – winter wheat – spring barley – chickpea (*Cicer arietinum*), residues removed and no cover crop;
- CT 2: no tillage, monoculture, residues retained and no cover crop;
- CA 1: no tillage, crop rotation, residues retained and no cover crop;
- CA 2: no tillage, crop rotation, residues removed and Italian ryegrass (*Lolium multiflorum*) as cover crop undersown in spring;
- CA 3: no tillage, crop rotation, residues retained and cover crop.

We evaluated carbon balance by using SALM method (Verra organization, 2013; Tennigkeit *et al*., 2013). The method takes into account the dynamics of carbon stored in soil and the direct emission of N_2O due to use of fertilizers (organic and mineral) and CO_2 emission due to chemical fertilizer production, the effect of the use of N-fixing species, the amount of fuel used in tillage and other field operation. The CH_4 emissions and the effect of burning biomass were not included since these

Table 18. Simulated annual SOC changes in 0–30 cm soil depth for the different cropping systems

Cropping system	Tillage	Crops*	Residues	Cover crop**	kg ha^{-1}	percent
Conventional 1	+	monoculture	-	-	-560	-1.03
Conventional 2	+	monoculture	+	-	-477	-0.87
CT 1	-	rotation	-	-	-392	-0.60
CT 2	-	monoculture	+	-	10	0.01
CA 1	-	rotation	+	-	296	0.45
CA 2	-	rotation	-	+	493	0.75
CA 3	-	rotation	+	+	992	1.52

*Monoculture: spring barley (H.*vulgare*); Rotation: winter wheat (*Triticum aestivum*) – winter wheat – spring barley (*Triticum aestivum*) – chickpea (*Cicer arietinum*)
**Cover crop: Italian ryegrass (*Lolium multiflorum*)
Bold values indicate the objective of 4 per 1000 initiative achieved.

sources of emissions were not applicable for the cropping systems studied in this paper. We used the IPCC emission factor of 0.011 (IPCC 2006) for the N_2O emission from fertilizers, and for its CO_2 equivalence we used the coefficient of 298 proposed by IPCC 2013. We estimated the carbon changes stored in soil by the ARMOSA model. The fuel consumption (kg ha-1) was estimated, as rough approximation, from the Gazzetta Ufficiale della Repubblica Italiana n.50 – 01-03-2016 and the factor of emission used of 3.15 t of CO_2 per ton of diesel was taken from the Swiss environment department (Bundesamt fur Umwelt, 2016).

Results

The model simulated well organic carbon dynamics (RMSE, 8.6 percent; bias, -4.3 percent; modeling efficiency EF, 0.81, N=40), as well as barley yields, indicating sound prediction for the amount of residues. Simulations of SOC changes showed that both conventional systems, with either residue removed or retained lost SOC during 20 years (Table 18).

The decrease of SOC in conventional systems stems from straw removal, which is not compensated by the carbon in the roots and from ploughing, creating SOC oxidation. Likewise, no tillage with crop rotation, but with residues removal and lack of cover crop (CT 1) resulted in decrease of SOC.

However, if residues were retained (CA 1), it allowed to improved C stock significantly. When acquisition of straw is needed for animal feeding or bioenergy production, carbon loss could be compensated by sowing of cover crop that supplies soil additional organic matter (CA 2). However, the largest effect was gained when both components – residues and cover crop – were presented in the cropping system as a source of additional C input (CA 3). Comparison between CT 2 and CA 1 shows the role of crop rotation in C sequestration that allowed increasing of SOC from 10 (in monoculture) to 296 (in rotation) kg $ha^{-1}yr^{-1}$.

Annual total CO_2 balance and estimated carbon credits are shown in Table 19. Conventional systems clearly caused positive CO_2 balance, indicating GHG emissions. Conservation tillage (CT 1 and CT 2) with a limited amount of additional organic matter resulted in positive carbon balance as well. Only CA practices involving, in addition to no-tillage, crop rotation, residues retained and/or cover crops had the negative total carbon balance, indicating reduction of GHG emissions. Moreover, all CT and CA cropping systems reduced total CO_2 balance compared to Conventional 1 (baseline), signifying possibility to obtain carbon credits equal to 24–130 € ha^{-1} y^{-1} (Table 19).

Discussion

Conservation agriculture involves complex and interactive processes that ultimately determine soil C storage making it difficult to identify clear patterns, particularly, when the results originated from a large number of independent studies. To solve these problems, we used a model approach to assess the contribution of each component of CA in soil C storage for Almaty site in Kazakhstan. It seems that the contribution decreased in the following order: cover crops > residues > rotation, according to the amount of organic matter remaining by the system. In particular, attention should be paid to cover crops, which seem to have significant role in C sequestration, but are not yet widely spread in practical farming in Kazakhstan.

Table 19. Annual CO_2 balance and the values of carbon credits for different cropping systems

Cropping system	**CO_2 balance (kg CO_2eq ha $^{-1}$)**						**Carbon credits (€ ha-1y^{-1})***
	Soil storage	**N fertilizer used**	**Chemical fertilizer production**	**N-fixing species**	**Fuel**	**Total CO_2 balance**	
Conventional 1	2 622	337	162	0	496	3 617	0
Conventional 2	2 300	337	162	0	496	3 295	7
CT 1	1 854	253	122	25	208	2 461	24
CT 2	523	337	162	0	233	1 255	50
CA 1	-666	253	122	24	221	-48	77
CA 2	-1 398	253	122	24	221	-779	92
CA 3	-3 218	253	122	25	233	-2 586	130

*1 credit = 1t CO_2 reduced = 21 € (price in December 2018).
Carbon credits are calculated respect to baseline (Conventional 1).

Moreover, no tillage may not store more soil C than conventional tillage if the amount of residues is limited. For example, a meta-analysis showed that no tillage with residue retention increased SOC by 3.9–10.2 percent compared to conventional tillage with residue removed (Zhao *et al.*, 2017). In contrast, reduced/no tillage alone without straw incorporation or mulching led to a negligible increase in SOC stock (Zheng *et al.*, 2014; Powlson *et al.*, 2014). High-residue producing crops may sequester more C than crops with low residue input. Intensification of cropping systems such as increased number of crops per year, double cropping, and addition of cover crops can result in increased soil C storage under no tillage (West and Post, 2002).

By using CENTURY model, Ogle *et al.* (2012) suggested where C inputs decline by more than 15 percent, then SOC stocks would also decline with adoption of no tillage, and that where C inputs decrease by less than 15 percent (or C inputs increase), then SOC stocks would be expected to increase. Consequently, a reduction in residue C inputs under no tillage, where they occur, does provide a mechanistic explanation for a lack of increase in SOC with no-till adoption, and therefore no-till will not always serve to mitigate greenhouse gas emissions.

The results of this paper showed that CA practices including residues retained and/or cover crops would allow achieving the objective of 4 per 1 000 initiative. The initiative claims that an annual growth rate of 0.4 percent in the soil carbon stocks, or 4‰ per year, would halt the increase in the CO_2 concentration in the atmosphere related to human activities. The total carbon balance considering all CO_2 emission sources was assessed to be negative only under CA practices including residues retained and/or cover crops (effective reduction of CO_2 in atmosphere). Estimation of carbon credits indicated that, compare to the conventional cropping systems, all CA systems, regardless additional C inputs (residues, cover crop), allowed for a reduction of CO_2 emissions, indicating possibility to obtain carbon credits.

Conservation agriculture has a large potential for C sequestration in Kazakhstan. Increase in SOC could increase crop yield and reduce yield variability since the SOC accumulation not only sequestrated atmospheric CO_2 but also increased soil fertility and soil water holding capacity (Franzluebbers, 2002). Therefore, future studies should be aimed to assess the performance of the cropping systems during field experiments in different climatic zones in Kazakhstan. Also there is a need to develop a concept of carbon credits from agriculture, since Europe recognizes voluntary carbon credits only from afforestation/reforestation projects. Development and implementation of agriculture-based carbon offset projects would ensure climate change mitigation and food security in Central Asia.

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