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Can conservation agriculture increase soil carbon sequestration? A modelling approach

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ABSTRACT

Conservation agriculture (CA) involves complex and interactive processes that ultimately determine soil carbon (C) storage, making it difficult to identify clear patterns. To solve these problems, we used the ARMOSA process-based crop model to simulate the contribution of different CA components (minimum soil disturbance, permanent soil cover with crop residues and/or cover crops, and diversification of plant species) to soil organic carbon stock (SOC) sequestration at 0–30 cm soil depth and to compare it with SOC evolution under conventional agricultural practices. We simulated SOC changes in three sites located in Central Asia (Almalybak, Kazakhstan), Northern Europe (Jokioinen, Finland) and Southern Europe (Lombriasco, Italy), which have contrasting soils, organic carbon contents, climates, crops and management intensity. Simulations were carried out for the current (1998–2017) and future climatic scenarios (period 2020–2040, scenario Representative Concentration Pathway RCP 6.0).

Five cropping systems were simulated: conventional systems under ploughing with monoculture and residues removed (Conv – R) or residues retained (Conv + R); no-tillage (NT); CA and CA with a cover crop, Italian ryegrass (CA + CC). In Conv – R, Conv + R and NT, the simulated monocultures were spring barley in Almalybak and Jokioinen, and maize in Lombriasco. In all sites, conventional systems led to SOC decline of 170–1000 kg ha^{-1} yr^{-1}, whereas NT can slightly increase the SOC. CA and CA + CC have the potential for a C sequestration rate of 0.4% yr^{-1} or higher in Almalybak and Jokioinen, and thus, the objective of the "4 per 1000" initiative can be achieved. Cover crops (in CA + CC) have a potential for a C sequestration rate of 0.36–0.5% yr^{-1} in Southern Finland and in Southern Kazakhstan under the current climate conditions, and their role will grow in importance in the future. Even if in Lombriasco it was not possible to meet the "4 per 1000", there was a SOC increase under CA and CA + CC. In conclusion, the simultaneous adoption of all the three CA principles becomes more and more relevant in order to accomplish soil C sequestration as an urgent action to combat climate change and to ensure food security.

1. Introduction

Land Use and Land-Use Change (LULUC) is estimated to emit 1.3 ± 0.5 peta-grams of carbon per year, representing 8% of annual emissions (Le Quéré et al., 2015; Potma Gonçalves et al., 2018). The conversion from natural ecosystems to managed agroecosystems creates a reduction in the soil organic carbon stock (SOC) by 30% to 50% over 50 years in temperate climates, and 75% in 10 to 25 years in the tropics (Lal, 2016). Nevertheless, global estimation of SOC and sequestration potentials showed that under best management practices, 4 per thousand or even higher sequestration rates can be accomplished (Corsi et al., 2012; Minasny et al., 2017). An annual growth rate of 0.4% in the soil C stocks, or 4‰ per year, in the first 30–40 cm of soil, would significantly reduce the CO_2 concentration in the atmosphere related to human activities (https://www.4p1000.org/).

The adoption of conservation agriculture (CA) is promoted by FAO as a response to sustainable land management, environmental protection and climate change adaptation and mitigation (Pisante et al.,

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2012; 2015). According to the FAO definition, 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 (FAO, 2017). Conservation agriculture implies the application of the three principles at the same time: however, in practice and in past research, the three principles were applied and studied separately. Moreover, in legislation and in offering subsidies to improve the environment by farmers, CA is considered a synonym of no-till and reduced tillage, thus, it is often unclear whether the full three-part CA was actually applied. Frequently, statistical data refer to "no-till" without any other specification.

In Central Asia, a faster development of CA has taken place in the past 10 years in Kazakhstan, which is among the top 10 countries in the world with the largest crop area under CA systems (Kassam et al., 2019). The areas under no-till increased from virtually nothing in 2000 to 2 million ha in 2014 (Karabayev et al., 2014), and to 2.5 million ha in 2016 (Kassam et al., 2019). The utilization of CA-based technologies has become an official state policy for agriculture in Kazakhstan. In fact, since 2008, the government of Kazakhstan has been subsidizing farmers who adopt CA-based technologies.

Italy is one of the European countries where the adoption of no-tillage and minimum tillage has been growing recently (Kassam et al., 2019). In Italy, 15 out of 21 Rural development programmes 2014–2020 grant support to farmers for adopting practices such as no-tillage, with a Utilized Agricultural Area (UAA) target of approximately 192,000 ha (Marandola et al., 2019). Cultivation of cover crops over the autumn to spring period is also promoted, but it is usually a non-compulsory additional practice to obtain CA funds. Currently, the agricultural holdings which declare themselves to have at least a part of the arable land under no-tillage represent 6% of the total UAA surveyed in Italy (ISTAT Agriculture Census, 2011). Beyond the no-tillage practice, further information about the CA practices they implement is not available.

Finland is the most northern country adopting no-tillage with the highest application rate of 10% (200,000 ha) in Europe (González-Sánchez et al., 2017). The "4 per 1000" initiative, launched at the COP21 climate conference in Paris, has triggered several European projects on soil carbon. In Finland, over 100 farms have engaged in increasing soil carbon sequestration, as part of the "Carbon Action Platform" (https://carbonaction.org). The aim is to identify carbon-accumulating farming methods suitable for each farmer, to apply them in practice and to measure changes in SOC over the course of five years.

Conservation agriculture provides many benefits, such as enhanced biodiversity and natural biological processes above and below the soil surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production. Moreover, increases in SOC could increase crop yield (Zhao et al., 2017) and reduce yield variability since the SOC accumulation not only sequestrates atmospheric CO_2, but also increases soil fertility and soil water holding capacity (Franzluebbers, 2002). Healthy soils are key to developing sustainable crop production systems that are resilient to the effects of climate change.

Conservation agriculture also reduces fuel consumption through the reduction or the elimination of soil tillage (Stajnko et al., 2009; Guardia et al., 2016; Houshyar and Grundmann, 2017). As demonstrated by Alluvione et al. (2011), the reduction of tillage itself reduces the consumption of fossil fuel by 11.2% of the total energy input of the cropping system in the case of minimum tillage, thus increasing energy use efficiency of the system. In the case of no-tillage, the reduction is even higher. However, the quantification of this advantage is mostly determined by the farm organizations.

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 CA sequesters soil C (Palm et al., 2014). In a review of Chinese studies, Du et al. (2017) suggested that no-tillage only stratified SOC; a near-surface increase in SOC was offset by a concomitant decrease in the subsurface. The authors concluded that no-tillage farming may have some value as a climate change mitigation strategy in some situations, but its impact varies greatly between sites (i.e., showing positive and negative C gains), and the magnitude of the impact should not be overestimated. Powlson et al. (2016) reviewed the effects of separate CA components as well as their combinations on the rates of SOC increase, which ranged between 0.16 and 1.01 t ha $^{-1}$ yr $^{-1}$ in tropical agro-ecosystems. The source of variation was, however, not identified, but the authors concluded that in many cases CA practices would deliver only a small degree of climate change mitigation through soil C sequestration.

These doubts stem from the fact that previous literature on SOC has often discussed the 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 determine the amount of C inputs and, thus, the ability of CA to store more C than conventional tillage. Intensification of cropping systems with high above and belowground biomass (i.e., deep-rooted plant species) input may enhance CA systems for storing soil C relative to conventional tillage (Luo et al., 2010). The authors stressed that the complicated patterns of soil C change under different cropping systems highlight the fact that cropping systems must be considered when assessing soil C dynamics under various management practices.

Moreover, CA practices such as no-tillage may not store more soil C than conventional tillage if they leave limited amounts of residues. High-residue producing crops may sequester more C than crops with low residue input. Intensification of cropping systems, such as increased numbers of crops per year, double cropping, and the addition of cover crops can result in increased soil C storage under NT (West and Post, 2002). Meta-analysis of 122 studies to examine crop rotation effects on total soil C demonstrated that adding one or more crops in rotation to a monoculture increased total soil C by 3.6%, but when rotations included a cover crop, total C increased by 8.5% during 18 years, on average (McDaniel et al., 2014).

Cover crops, legume or non-legume, are not productive crops as such, but are useful to protect the 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 C in agricultural soils (Govaerts et al., 2009; Mazzoncini et al., 2011; Poeplau and Don, 2015; Muhammad et al., 2019). Moreover, cover crops can increase C concentration and stocks, potentially offsetting residue removal-induced losses to SOC and harm to other soil properties (Ruis and Blanco-Canqui, 2017).

Thus, CA involves complex and interactive processes that ultimately determine soil C storage making it difficult to identify clear patterns, particularly when the results originate from a large number of independent studies. To solve these problems, a model approach can be useful to assess the contribution of each principle of CA in soil C sequestration. We used the ARMOSA model to simulate different CA components and their interactions, and to understand their contributions to SOC increase in comparison to the results under conventional agricultural practices. We simulated SOC changes in three sites, located in Central

Asia (Almalybak, Kazakhstan), Northern Europe (Jokioinen, Finland) and Southern Europe (Lombriasco, Italy) for the current climate conditions and for a future climate scenario. The three sites are very contrasting for soil texture and organic C contents, climates, crops used and management intensity. To assess the feasibility of options, allowing for C sequestration in soils in future years, simulations under a short-term future climate scenario were carried out.

2. Methods

2.1. ARMOSA model overview

An effective way to quantify the long-term effect of CA practices on soil C sequestration is modelling, which allows us to consider various processes at the same time and to represent many what-if scenarios. The ARMOSA process-based crop model (Perego et al., 2013) was applied in this study (Fig. 1). This model integrates four main modules simulating evapotranspiration (ET), crop growth and development, water dynamics, and carbon and nitrogen cycling, respectively. The reference evapotranspiration (ET_0) can be estimated using the Penman – Monteith or the Priestley-Taylor equation. Crop evapotranspiration (ET_c) is estimated using the FAO 56 approach (Allen et al., 1998) and actual evapotranspiration (ET_a) is calculated using a water stress factor (kws, Sinclair et al., 1987), which influences the crop-related processes such as carbohydrate production and photosynthetate partitioning. The crop module implements the WOFOST (de Wit et al., 2019) approach with two improvements: the canopy is divided into 5 layers with different light interception and the development is described with the BBCH scale (Biologische Bundesanstalt, Bundessortenamt and Chemische Industrie), which allows a detailed representation of the phenology and the thermal time required to reach the stages.

The soil properties (i.e., sand – %, silt – %, clay – %, bulk density – t m^{-3} (BD), C content – g kg^{-1} and nitrogen in stable, litter, and manure fractions – kg ha^{-1}, van Genuchten – Mualem equation parameters) are required for each pedological horizon. The soil horizons are further split into 5 cm-layers for the daily estimation of the soil-related variables, which are available in the output files.

The water dynamic is simulated with the Richards' equation resolution used in the SWAP model (van Dam et al., 2008). Carbon and nitrogen related processes are implemented following the approach of the SOILN model (Johnsson et al., 1987) with the difference that each input of C and nitrogen is considered independently, with each one having its own decomposition rate and fate. The input could be of three types, to which correspond three types of organic C pools: C-stable, C-litter and C-manure.

Besides daily weather data and soil parameters (texture, BD, organic C, with the option to insert the observed values of the water retention curve parameters), the model setting requires information related to the cropping system (i.e. crop sequences, sowing and harvesting dates, residues management), irrigation (water amount, timing, option of automatic irrigation as a function of water depletion threshold), nitrogen fertilization (mineral or organic, amount, timing, application depth, carbon over nitrogen ratio, ammonia nitrogen over total nitrogen), and tillage (Fig. 1).

The tillage module depicts the effects of tillage operations on soil variables, namely BD and organic C pools. Tillage operations are simulated as function of till depth, timing, degree of soil layers mixing and perturbation, as proposed in the WEPP model (Laflen et al., 1997). The mixing of two consecutive soil layers (e.g. the first two in the topsoil, involved in the tillage operation) determines pools mixing and the recalculation of pools (e.g. mass or volumetric variables, such as C-litter and soil water content).

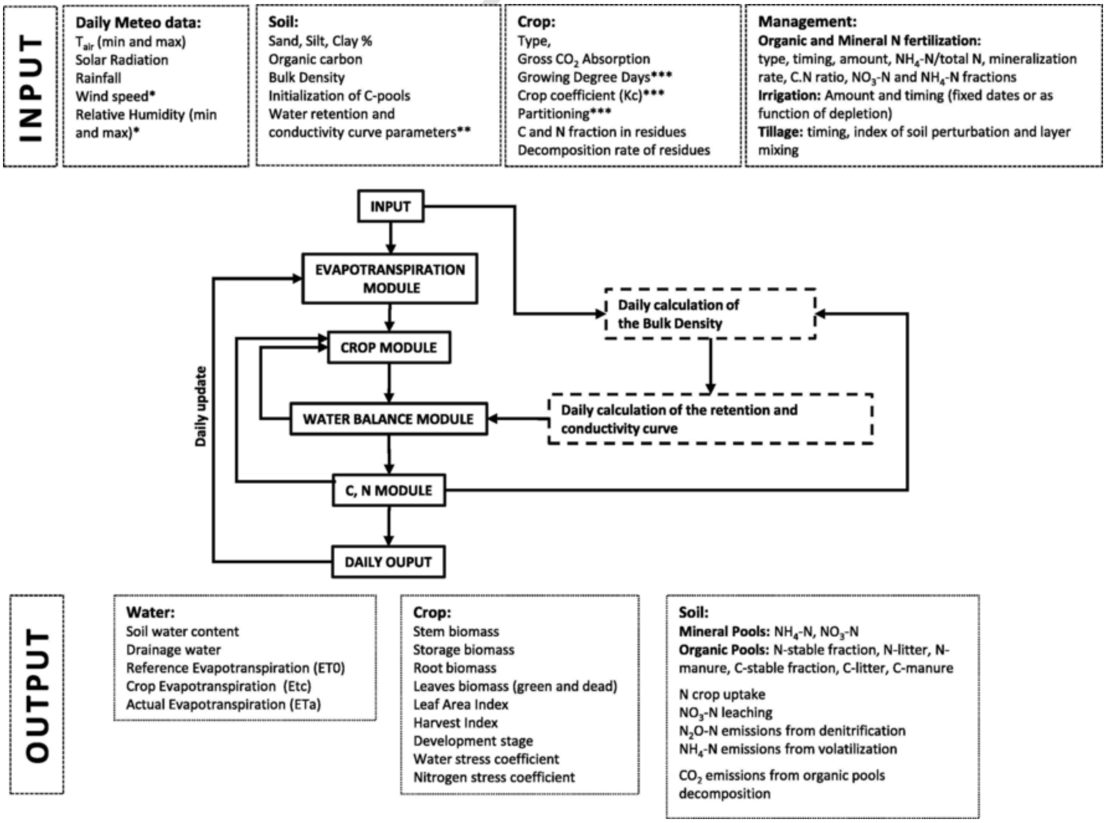

Fig. 1. Structural overview of the ARMOSA simulation model, and list of input and output parameters. *required in the Penman Monteith equation for ET0, alternatively to Priestley Taylor ** option for using observed data *** development stage specific.

The BD measured (or estimated) in each soil horizon is required for the initialization. After this, the model estimates the daily BD change as a function of the C content. In addition, BD is simulated to decrease due to tillage; however, this decrease is temporary because BD increases back to the consolidated value due to the time-lapse and rainfall. During the period from the tillage operation until the consolidated BD value is reached, the mineralization rate of the organic C pools increases due to the higher macroporosity, as reported in the literature (Reicosky, 1997; Ball et al., 1999; Rádics et al., 2014; Kabiri et al., 2016). The value of this temporary increase in the mineralization rate is correlated with the degree of soil disturbance caused by the tillage operation: it is maximum when soil disturbance is maximum. Hydrological parameters of the water retention curve are then calculated daily according to the estimated daily values of BD and C content. This recalculation seems to be, according to our knowledge, peculiar to this model, increasing its credibility (Bellocchi et al., 2015).

The model outputs are above ground biomass, grain yield, gross primary production nitrogen crop recovery, soil water content, water percolation, nitrate leaching, ammonia volatilization, carbon dioxide as result of soil respiration, nitrous oxide emissions, and SOC in the three pools (Fig. 1). The model was calibrated and validated with datasets of yield, aboveground biomass, nitrate leaching, and carbon dioxide emissions from 15 sites throughout Europe (Groenendijk et al., 2014; Pirttioja et al., 2015; Sándor et al., 2017).

2.2. Model calibration and validation

The model was calibrated and validated for the prediction of the SOC using the sets of data collected during 8 years in Almalybak (Almaty region, Southern Kazakhstan), for 14 years in Jokioinen (Southern Finland) and for 21 years in Lombriasco (Northern Italy). The description of the sites and management options appear in Table 1.

Cropping systems were spring barley (*Hordeum vulgare*) in the first two sites, and irrigated maize-based (*Zea mays*) in Lombriasco. Tillage treatments involve conventional ploughing and no-tillage or reduced tillage. In all sites, crop yields were measured annually for each tillage treatment. Initial C content was high in Jokioinen, while it was poor in the other two sites, but higher in Almalybak than in Lombriasco.

In Lombriasco, there was no regular rotation, since maize (irrigated) was the principal crop, present in 10 out of 21 years, soybean (irrigated) and oilseed rape in 3 out of 21 years; pea, spring barley, sunflower and Italian ryegrass in 1 out of 21 years. In several years there was more than one crop per year. Some more details about the experiment are reported in Alluvione et al. (2011).

In Almalybak, BD and organic C contents were measured annually at 0–30 cm soil depth. In Jokioinen, BD and organic C contents were measured within the range of 0–10, 10–20 and 20–30 cm soil depths in 2003–2004 and in 2017, while within the range of 0–10, 10–20 cm soil depths in 2009 and in 2013. In Lombriasco, BD and organic C contents were measured with 3–5 years interval at 0–30 cm depth.

Organic C content was assessed using the Tjurin method (Anonymous, 1992) in Almalybak and with elemental analyzers in Jokioinen and Lombriasco (respectively, LECO CN-2000 and ThermoQuest NA1500® Carlo Erba, Milano, Italy). The two methods showed a very high correlation between them ($r = 0.995$) (Barančíková and Makovníková, 2016).

The SOC (t ha^{-1}) was estimated in the 0.3 m topsoil by using the formula reported by Batjes (1996):

$$SOC = C \times \text{topsoil depth} \times BD \times (1 - RF) \times 10,000\, m^2$$

where C is the organic carbon content (%), topsoil depth is 0.3 m, BD is the topsoil bulk density (t m^{-3}), and RF is the rock fragment content (%). BD was measured on a known volume soil sample, which was collected with a cylindrical metal sampler pressed into the soil. The sample was oven-dried at 105 °C and then weighed; the value of BD was calculated as the ratio of oven-dried mass over the soil sample volume (g cm^{-3}). As rock fragments were absent in all sites, RF was set to zero in all simulation scenarios.

The models were calibrated on the ploughing-based treatments and validated on the no-till treatments in Almalybak and Jokioinen, and in the reduced tillage treatment in Lombriasco. The model performance evaluation was carried out using well-known indices, which were selected according to Sanna et al. (2015). The selected indices were:

1. Bias and %Bias (Addiscott and Whitmore, 1987), optimal value 0, range $+\infty$ to $-\infty$; Bias% $<$ 10% could be considered very favorable (Moriasi et al., 2007).
2. Root Mean Square Error (RMSE) and %RMSE ($\frac{RMSE}{Observed\_Mean} * 100$) (Fox et al., 1981), optimal value 0, range $+\infty$ to $-\infty$. A %RMSE value lower than 10% is considered to be favorable (Bellocchi et al., 2002).

Table 1
Description of sites and experiments used for model validation and calibration.

Parameter	Almalybak (Kazakhstan)		Jokioinen (Finland)		Lombriasco (Italy)	
Coordinates	43°13′N, 76°41′E		60°48′N, 23°29′E		44°51′N, 7°38′E	
Climate (Köppen climate classification)	Hot summer continental (*Dfa*)		Boreal (*Dfc*)		Humid subtropical (*Cfa*)	
Annual precipitation (mm)	574		597		772	
Average temperature (°C)	8.4		4.1		12.9	
Soil type	silt loam		clay		sandy loam	
Sand (%)	12		19		66	
Silt (%)	67		19		24	
Clay (%)	21		62		10	
Duration of experiments	2002–2009 (8 yr)		2004–2017(14 yr)		1996–2016 (21 yr)	
Crop	Spring barley		Spring barley		Maize-based	
Residues	Retained		Retained		Mostly retained	
N fertilization (kg ha^{-1})	34		100		200[a]	
Tillage treatments	Ploughing at 20–22 cm	No-tillage	Ploughing at 20–22 cm	No-tillage	Ploughing at 30 cm	Vertical tillage at 15 cm/No-tillage
Bulk density	1.31	1.31	1.31	1.26	1.51	1.7
Initial C (%) in 0–30 cm	1.38	1.68	2.35	2.58	1.01	1.01
Initial SOC (t ha^{-1}) in 0–30 cm	54.4	65.5	91.2	95.6	45.9	51.3
Average yield ± SD (kg ha^{-1})	1660 ± 660	1400 ± 600	3970 ± 1000	3220 ± 1450	11579 ± 1815[b]	12515 ± 1811[b]

[a] Refer to maize.

[b] Refer to maize-grain.

3. Nash Sutcliffe Efficiency index (EF; Nash and Sutcliffe, 1970), optimal value 1, range $+1$ to $-\infty$. The value of $EF > 0.5$ must be considered satisfactory (Moriasi et al., 2007).
4. the Pearson correlation coefficient, optimal value 1, range $+1$ to -1.
5. the slope of the regression of observed data to the estimated ones, optimal value 1, range $+\infty$ to $-\infty$.
6. Index of Prediction Quality (IPQ) to assess the overall ability of the model to simulate variables of interest according to Strullu et al. (2020). IPQ is defined as:

$$IPQ = 0.25 * EF + 0.25 * R^2 + 0.5 * (1 - \%RMSE)$$

For the evaluation of the index we have used the original scale of evaluation proposed by the authors: $1 \geq IPQ > 0.85$: excellent; $0.85 \geq IPQ > 0.70$: very good; $0.7 \geq IPQ > 0.55$: good; $0.55 \geq IPQ > 0.40$: acceptable; $IPQ < 0.40$: poor.

Following the approach used by Acutis and Confalonieri (2006), calibration was carried out using a multi start point, bounded (for parameter ranges) version of the downhill simplex method (Nelder and Mead, 1965), in which the objective function was the minimization of the sum of RMSE + Bias.

As the calibration parameter, we used the mineralization rate of stable carbon and the nitrification coefficient. The choice of limiting to a minimum the number of calibrated parameters is coherent with what is often suggested in modelling studies (e.g., Confalonieri et al., 2016).

Initialization of the model organic matter pools was done by attributing 90% of organic matter at the start of the experiment to stable C pool and 10% to the litter pool and simulating the conventional (real) system for 20 years. At the end of this period, there is a new ratio of stable/litter pools that was applied to the initial total organic C content to run the calibration of the model.

2.3. Simulation setup

We used a set of daily data of maximum and minimum temperature, precipitation (Fig. 2) and global solar radiation for the whole period obtained from the local meteorological stations present in all three experimental sites. We performed a comparative assessment of SOC changes in 0–30 cm soil layer over 20 years in three sites under conventional cropping systems with residues removed (Conv – R) or retained (Conv + R), no-tillage (NT) and two CA systems with no cover crops (CA) or with cover crops (CA + CC) (Table 2). In Conv – R, Conv + R and NT, simulated monocultures were spring barley in Almalybak and Jokioinen, and maize in Lombriasco. In CA and CA + CC, crop rotations were winter wheat (*Triticum aestivum*) – winter wheat – spring barley – chickpea (*Cicer arietinum*) in Almalybak, spring barley – oilseed rape (*Brassica napus*) – oats (*Avena sativa*) – spring wheat in Jokioinen and maize – winter wheat – soybean (*Glycine* max) in Lombriasco. In CA + CC, Italian ryegrass (*Lolium multiflorum*) was sown either in spring together with spring cereals (in Almalybak and Jokioinen) or after wheat harvest, and then it was terminated before soybean sowing (Lombriasco).

2.4. Future climate scenarios

For Jokioinen and Lombriasco, the future climate change scenarios were obtained from the JRC- Agri4Cast "Daily weather data for crop modelling over Europe derived from climate change scenarios" available at https://agri4cast-jrc-ec-europa-eu.pros.lib.unimi.it:2050/DataPortal/Index.aspx?o = d (Duveiller et al., 2017). The resource consists of future daily weather data for Europe on a 25x25 km grid designed for crop modelling for the A1B SRES scenario. The dataset consisted in 30 synthetic years of weather variables to characterize the time horizon of 2030, which were generated using ECHAM5 GCM coupled with the HIRHAM5 RCM (Christensen et al., 2007). The weather generator ClimGen (Stöckle et al., 2001) was then used to obtain daily weather data. Global radiation was estimated using the Bristow-Campbell model (Bristow and Campbell, 1984), according to Duveiller et al. (2017).

For Kazakhstan, the future scenario was obtained from the resource available at the climatic knowledge portal of the Word Bank (https://climateknowledgeportal.worldbank.org/country/kazakhstan/climate-data-projections) and from 35 available global circulation models (GCMs) used by the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report. Data are presented at a 1°x1° global grid spacing, produced through bi-linear interpolation (Harris et al., 2014). We have used the Representative Concentration Pathway (RCP) 6.0 scenario, that is the most similar to the A1B SRES used for Europe, in particular for time horizon close to the actual time as evident in https://www.globalchange.gov/browse/multimedia/emissions-concentrations-and-temperature-projections where a comparison between the 2 scenarios is shown in graphical form. The resource offers the monthly difference in comparison with the actual scenario of temperature and precipitation. After the summation of the differences to the actual data, as in Duveiller et al. (2017) the climatic generator ClimGen was used to obtain daily future data of temperature and rain and the Bristow-Campbell model was used to estimate the radiation. CO_2 concentration for future scenarios was set at a fixed value of 430 ppm, according to the forecast of RCP 6.0 (http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action = htmlpage&page = compare).

In Almalybak, the future climate shows a relevant increase in the average annual temperature of 1.6 °C (+17%) due to the temperature increases in the coldest and in the hottest months of the year, while there was little change in precipitation in comparison with the actual climate (Fig. 2 a, b).

In Jokioinen, the future climate shows an increase in the average annual temperature of 0.6 °C (+11%) compared to the current average annual temperature, however, in December and January, the temperature in the future scenario is lower than in the actual conditions by more than 1 °C, while there is an increase greater than 2 °C in March and in July (Fig. 2c). Annual precipitation appears strongly reduced (-120 mm y^{-1}, −20%). The rainfall reduction is roughly uniform during the year, apart from in February, where an increase of precipitation from 20 to 37.4 mm is forecast (Fig. 2d).

In Lombriasco, the future climate demonstrates a 1.1 °C (+8.6%) increase of the average temperature, mainly due to temperatures in December, January, February and July (Fig. 2e). The rainfall is forecast to decrease by 140 mm y^{-1} (−17.5%), with a general decrease from June to December, while there is a remarkable increase (+83 mm, +164%) in February (Fig. 2f).

3. Result

3.1. Evaluation of model performance

The modelled trends of SOC together with the measured values appear in Fig. 3. Table 3 reports the indices used for the model evaluation, and Supplemental Material shows the measured against modelled data scatterplots. The values of the different indices are very similar in calibration and in validation, indicating in general reliability of the model (Perrin et al., 2001). %RMSE < 10% is met both for calibration and validation in all sites. In general, the model shows lower performance in Almalybak, due to low EF (close to zero both in calibration and validation) and correlation coefficient (0.43 and 0.32 in calibration and validation, respectively).

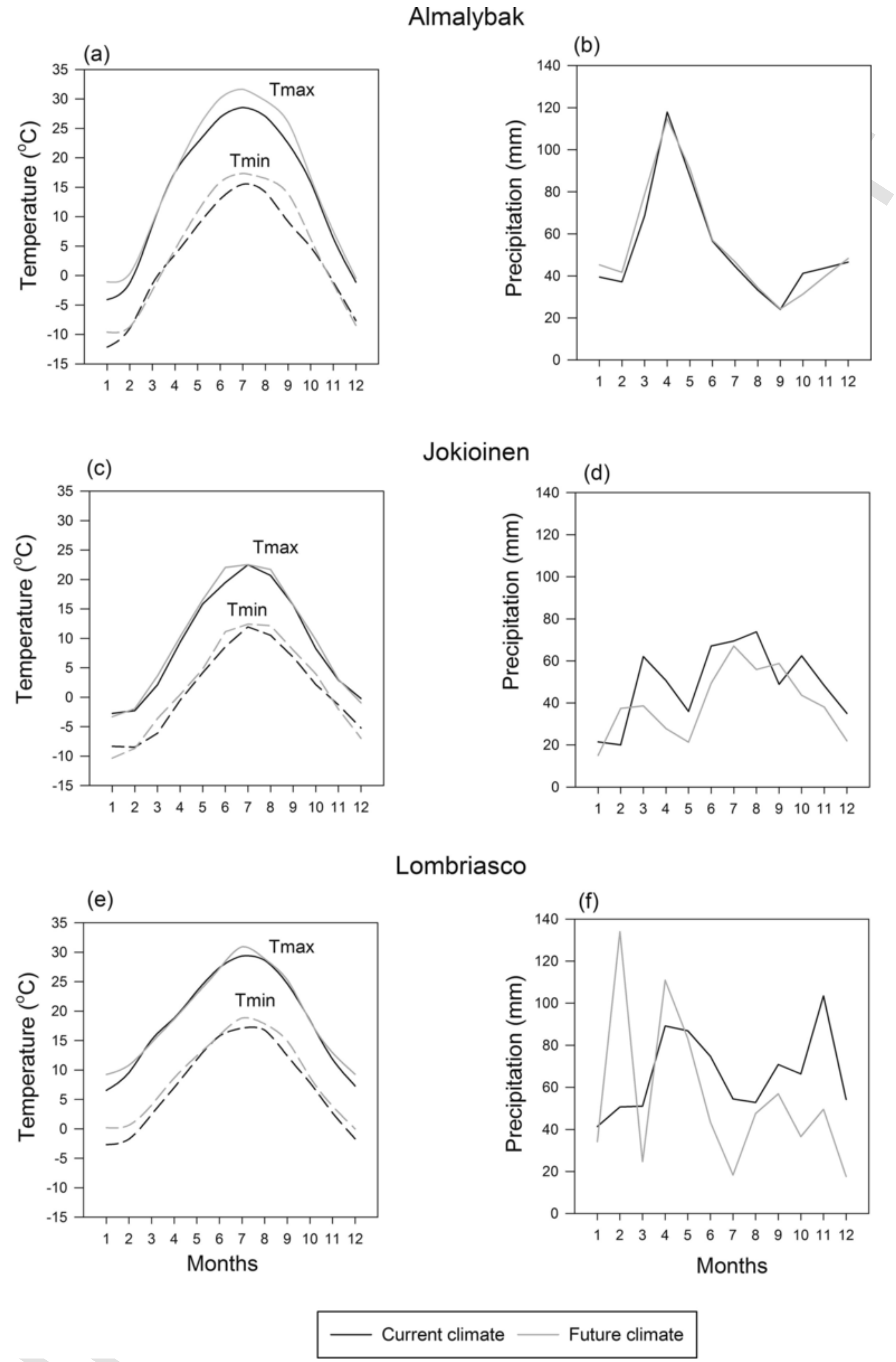

Fig. 2. Monthly maximum (Tmax) and minimum (Tmin) temperature and precipitation for the current climate conditions and future climate scenarios in (a, b) Almalybak, Kazakhstan, (c, d) Jokioinen, Finland and (e, f) Lombriasco, Italy.

Table 2
Simulated cropping systems in three sites.

Cropping systems	Tillage	Residues	Cover crop	Crops		
				Almalybak (Kazakhstan)	Jokioinen (Finland)	Lombriasco (Italy)
Conventional (Conv – R)	Ploughing at 25 cm (30 cm for maize)	Removed	No	Spring barley	Spring barley	Maize
Conventional (Conv + R)	Ploughing at 25 cm (30 cm for maize)	Retained	No	Spring barley	Spring barley	Maize
No-tillage (NT)	No-tillage	Retained	No	Spring barley	Spring barley	Maize
Conservation agriculture (CA)	No-tillage	Retained	No	Winter wheat-winter wheat-spring barley-chickpea	Spring barley-oilseed rape-oats-spring wheat	Maize-winter wheat-soybean
Conservation agriculture (CA + CC)	No-tillage	Retained	Italian ryegrass	Winter wheat-winter wheat-spring barley-chickpea	Spring barley- oilseed rape-oats-spring wheat	Maize-winter wheat-soybean

3.2. Simulation of SOC and residue biomass production

3.2.1. Conventional cropping systems

Under the current climate conditions the simulations of SOC changes showed that during 20 years of Conv – R practicing, SOC declined in all sites, but to a larger extent in Jokioinen (about 1000 kg ha^{-1} yr^{-1}, 1.17% yr^{-1}) and Almalybak (560 kg ha^{-1} yr^{-1}, 1% yr^{-1}), than in Lombriasco (310 kg ha^{-1} yr^{-1}, 0.6% yr^{-1}) (Fig. 4). In Almalybak, even with residues incorporation to the soil, Conv + R lost almost as much SOC as Conv – R (Fig. 4a, b). In contrast, in Jokioinen and Lombriasco, Conv + R reduced SOC about 2–3 times less compared to Conv – R (Fig. 4c-f). One of the reasons is the large difference in residue biomass between the sites (Fig. 5). Barley residues biomass was 1.8 times more in Jokioinen (about 3500 kg ha^{-1} yr^{-1} of dry matter - DM) than in Almalybak (about 2000 kg ha^{-1} yr^{-1} DM), while in Lombriasco, maize residue production was over 8000 kg ha^{-1} yr^{-1} DM.

Conv – R and Conv + R systems lost SOC somewhat to a larger extent under the future climate scenario, than under the current climate conditions in Almalybak (Fig. 4a, b) and Lombriasco (Fig. 4e, f). However, the SOC drop was substantial, up to 800 kg ha^{-1} yr^{-1} (0.87% yr^{-1}), under Conv + R in Jokioinen (Fig. 4c, d), but it was not related to changes in residue production, which remained almost unchanged (Fig. 5b) under the future climate scenario. According to simulation, only in Almalybak, barley residues may decrease to 1500 kg ha^{-1} yr^{-1} DM under the future climate scenario (Fig. 5a).

3.2.2. No-tillage and conservation agriculture

Under the current climate scenario, NT prevented SOC decline, keeping it on a slightly positive level, ranging from 25 to 90 kg ha^{-1} yr^{-1}, depending on site (Fig. 4). However, under the future climate scenario, NT depleted SOC storage at the rate of 160 and 88 kg ha^{-1} yr^{-1} in Jokioinen and Almalybak, respectively, but not in Lombriasco (Fig. 4). Compared to Conv + R, no substantial changes in residue biomass could be expected in NT under the current and future climates (Fig. 5).

In Almalybak, CA allowed for the annual C sequestration of 300 kg ha^{-1} and for achieving the objective of the “4 per 1000” initiative under the current climate scenario (Fig. 4 a, b). It is clear that the rotation of spring barley-oilseed rape-oats-spring wheat under CA produced a higher residue biomass compared to barley monoculture under NT (Fig. 5 a). Particularly, CA + CC was beneficial, since cover crops produced an annual residue biomass of 960 kg ha^{-1} yr^{-1} DM and provided additional annual SOC increase of 320 kg ha^{-1}, resulting in a total rate of C sequestration of 620 kg ha^{-1} or 0.95% yr^{-1} (Fig. 4 a, b). Under the future climate scenario, the model predicted somewhat less C sequestration under CA and CA + CC, probably, due to the reduction of residue biomass (Fig. 5a). However, the objective of the “4 per 1000” initiative can be still achievable (Fig. 4b).

In contrast, the pattern between the current and future climates was noticeably different in Jokioinen. CA increased SOC to 315 kg ha^{-1} yr^{-1} (0.35% yr^{-1}) under the current climate conditions, but led to a decline under the future climate scenario (Fig. 4 c, d), that, probably, stems from insufficient biomass production (Fig. 5 b). Under the current climate scenarios, the growing of cover crops in CA + CC supplied the additional biomass of 1300 kg ha^{-1} yr^{-1} DM, allowing high rates of C sequestration of 650 kg ha^{-1} yr^{-1} (0.71% yr^{-1}). Under the future climate scenario, despite the high residue biomass production, the rate dropped, and barely achieved 0.4% yr^{-1}.

Under both climate scenarios in Lombriasco, CA and CA + CC prevented SOC decline and kept it on the slightly positive level, however, the objective of “4 per 1000” initiative could not be accomplished (Fig. 4e, f). It is clearly visible a shift from the highly productive maize in NT to a lower producing maize rotation with winter wheat and soybean in CA and CA + CC (Fig. 5c).

4. Discussion

In this study, we used a model approach to assess the contribution of CA to soil C sequestration in the 0–30 cm soil layer, under the current climate conditions and future climate scenarios in three sites, located in Southern Kazakhstan (Almalybak), Southern Finland (Jokioinen) and Northern Italy (Lombriasco), which have contrasting climates, soils, managements and crops.

With the aim to simulate the concurrent effects of the three CA principles on C dynamics in contrasting soil and climate conditions, it is required to represent the complexity of the agro-ecosystems and in particular the crop- and soil-related processes. The ARMOSA model was chosen due to its ability to simulate in detail the changes in soil properties (organic C, hydrological parameters, BD), the cropping systems features (crop sequences, sowing and harvesting dates, residues management, decomposition rate of different crops’ residues), and the complexity of management practices (time of tillage, tillage depth, layer mixing, N fertilization, irrigation) in both conventional systems and CA. Since ARMOSA was calibrated and validated in a wide range of climate and soil conditions throughout Europe (Groenendijk et al., 2014; Pirttioja et al., 2015; Sándor et al., 2017), it is reasonable to consider the model results reliable under future climatic scenarios (Angulo et al., 2013).

First, we validated the model on the long-term experiments carried out in the same sites, with satisfactory results. Five cropping systems were simulated for each site: two conventional systems (with residues removed or retained), no-tillage, and two conservation agriculture systems (without or with cover crops). Bias% is to be considered favorable in all cases. The values of EF must be considered satisfactory in calibration and validation for Jokioinen and Lombriasco, but not for Almalybak, due to EF values below or close to zero. The values of IPQ were acceptable both in calibration and validation for Almalybak, and very

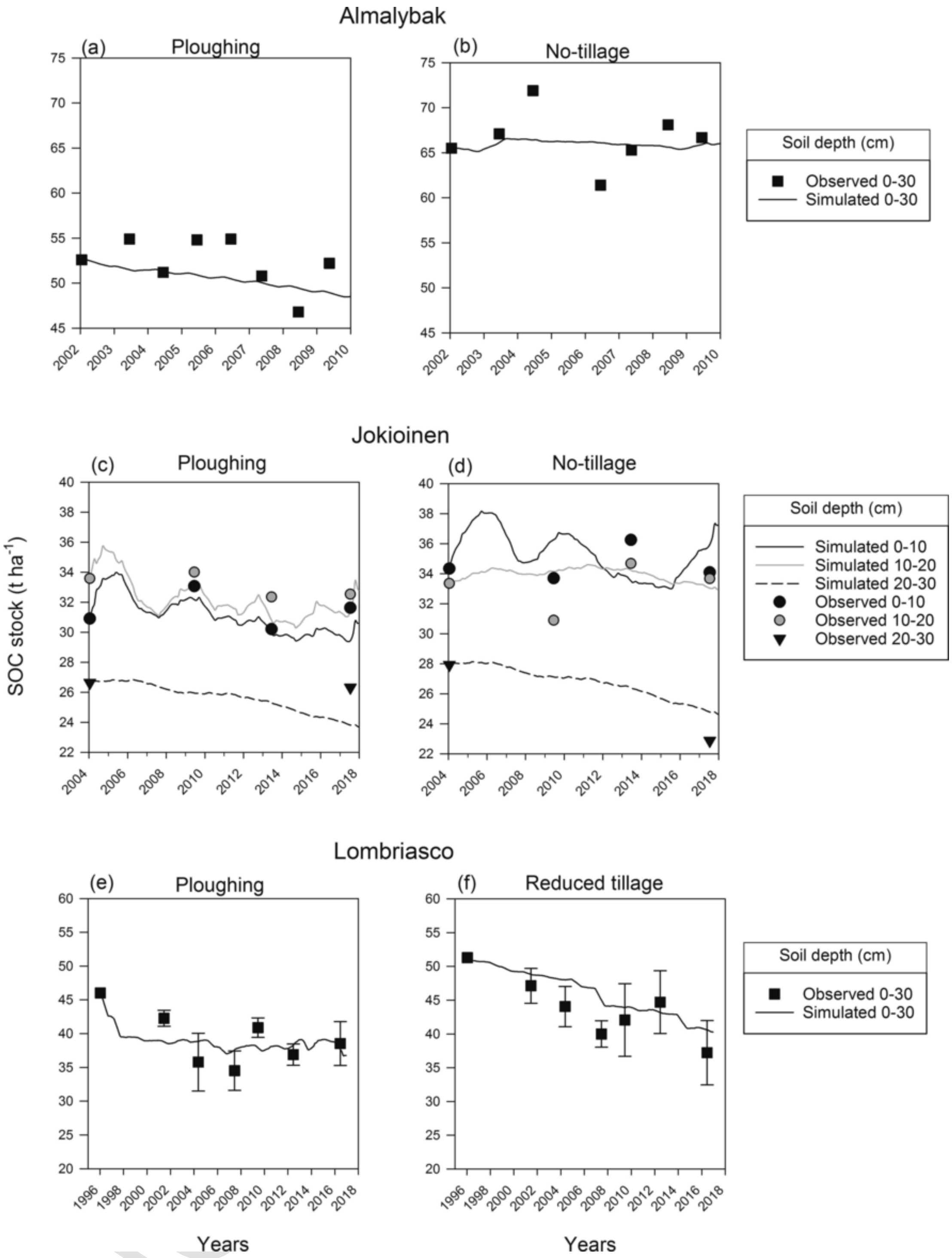

Fig. 3. Simulated and observed SOC stocks for different treatments: ploughing, no-tillage or reduced tillage in (a, b) Almalybak, Kazakhstan, (c, d) Jokioinen, Finland and (e, f) Lombriasco, Italy. Bars in (e, f) indicate SD. Note: Difference in initial SOC stock in (a, b) may be due to the different history of experimental plots.

good or excellent for other sites. This was probably, due to the shorter length of the series (8 years) in Almalybak that did not allow us to capture clear trends of soil C evolution, therefore, the sampling errors could play a relevant role in reducing of the EF and correlation values.

4.1. Conventional cropping systems

The model results demonstrated that, in all sites, conventional cropping systems, involving ploughing with residues removal and continuous monoculture (Conv – R) during 20 years, caused SOC decline, however, with the larger magnitude in Jokioinen (about 1000 kg ha^{-1} yr^{-1}, 1.17% yr^{-1}) and Almalybak (560 kg ha^{-1} yr^{-1}, 1% yr^{-1}) than in Lombriasco (310 kg ha^{-1} yr^{-1}, 0.6% yr^{-1}). In Northeast China, conventional tillage with continuous maize and residues removal during over 10 years depleted SOC storage at rate of 520 kg ha^{-1} yr^{-1} relative to the start of the experiment (Zhang et al., 2018).

In Almalybak, barley residues retention under conventional tillage (Conv + R) provided no benefits in terms of SOC loss prevention, due

Table 3
Statistical indicators of model performance for SOC changes under ploughing and no-tillage/reduced tillage in three sites.

	Almalybak (Kazakhstan)		Jokioinen (Finland)		Lombriasco (Italy)	
Indices	Ploughing	No-tillage	Ploughing	No-tillage	Ploughing	Reduced tillage
RMSE[a] (kg ha^{-1})	2834	2740	1557	2149	2471	2954
RMSE (%)	5.6	4.2	5.0	7.0	6.3	6.4
Bias (kg ha^{-1})	−1607	−595	−1385	825	−6	2056
Bias (%)	−3.1	−0,9	−4.0	2.6	0.0	4.7
EF[b]	−0.20	0.01	0.75	0.66	0.56	0.53
Correlation coefficient	0.43	0.32	0.98	0.88	0.75	0.87
Slope	1.01	1.23	0.83	1.01	1.04	1.09
IPQ[c]	0.47	0.51	0.90	0.82	0.75	0.79
N	8	7	7	7	7	7

[a]RMSQ, Root Mean Square Error; [b]EF, Nash Sutcliffe Efficiency index; [c]IPQ, Index of Prediction Quality.

to their low production caused by insufficient N fertilization. In Lombriasco, due to a very high maize residue biomass, SOC decline was only 170 kg ha^{-1} yr^{-1} under Conv + R. In USA, a similar cropping system with maize monoculture depleted SOC by 250 kg ha^{-1} yr^{-1} (Dalzell et al., 2013).

In Jokioinen, barley residue biomass production was 1500 kg ha^{-1} yr^{-1} DM, larger than that in Almalybak, and, thus, Conv + R showed much less SOC decline (340 kg ha^{-1} yr^{-1}, 0.38% yr $^{-1}$) respect to Conv – R. Study in Finland, based on the national inventory data from 1974 to 2009, demonstrated that the arable mineral soils annually lose 220 kg C ha^{-1} (0.4% yr^{-1}) at 0–15 cm soil depth (Heikkinen et al., 2013). The authors suggested that the reason for C decline was the change in management practices in the last decades from perennial croplands toward increasing cultivation of annual crops. Another important factor stressed by Heikkinen et al. (2013) is climate warming, which most probably increases the decomposition of soil organic matter in the humid boreal zone, but it also enhances the growth of the biomass and, as a consequence, carbon returns to the soil. The overall effect depends on whether the enhanced growth is large enough to counteract the increased decomposition. The model results of this study suggest the predominance of SOC decomposition in a future climate scenario under Conv + R, since the residue biomass decreased slightly respect to actual climate, while SOC is depleted at rate of 800 kg ha^{-1} yr^{-1} (−0.87% yr^{-1}).

4.2. No-tillage and conservation agriculture

The models indicated the site-specific rates of SOC changes under NT, CA and CA + CC, as well as the responses of cropping systems to the future climate scenario. In Almalybak and Jokioinen, NT with barley monoculture, producing as much residue biomass as Conv + R, allowed a slight increase in SOC during 20 years, but the future climate scenario forecast a small decline. Global meta-analysis of over 300 studies demonstrated a 4.6 t ha^{-1} (0.78–8.43 95% Confidence Interval) C stock increase in the upper soil (0–30 cm) under NT compared to conventional tillage over ≥10 years (Haddaway et al., 2017). In contrast, previous long-term experiments, conducted in Finland on the monocultures of spring cereals, showed no difference in SOC (in 0–20 cm soil layer) between NT and conventional tillage after 10 years (Sheehy et al., 2015). Since the initial SOC values were not reported by the authors, it is unclear whether both treatments simultaneously kept SOC on the same level or there were declining trends during 10 years.

Our model results clearly demonstrated that, in Southern Kazakhstan and in Southern Finland, cropping systems have a potential to achieve the “4 per 1000” initiative only under CA practices, involving crop rotations (and cover crops). In USA (Nebraska), on similar climate (*Dfa*) and soil type (silty clay loam) as in Almalybak, an annual SOC increase of 0.52% (12.5% during 24 years) at the 0–20 cm soil depth was demonstrated for tillage treatments with soybean–grain sorghum and corn–soybean rotations (Kibet et al., 2016). In particular, attention should be paid to cover crops, which are not yet widely spread in practical farming in Kazakhstan, whereas in Finland, cover crops are used in about 123,000 ha, which represents about 10% of the national agricultural area with grain and other crops (Yli-Viikari, 2019). Cover crops seem to have a significant role in C sequestration by providing an additional residue biomass to soil, particularly lacking C, due to continuous low nitrogen fertilization as in Kazakhstan. According to our model, in Southern Kazakhstan and Southern Finland, CA + CC would allow a higher annual sequestration rate of 620–650 kg C ha^{-1} yr^{-1} (0.71–0.95% yr^{-1}) in 0–30 cm soil layer than CA (300–315 kg C ha^{-1} yr^{-1}, 0.35–0.45% yr^{-1}).

Likewise, in a long-term experiment in northern France, the rate of change in SOC stocks in the 0–30 cm soil layer was 630 kg ha^{-1} yr^{-1} in CA systems with cover crops (Autret et al., 2016). Many studies and previous projects (Poeplau and Don, 2015; Perego et al., 2019) have demonstrated that SOC storage can be increased in cover crops-based farming systems by 300–600 kg ha^{-1} yr^{-1}, especially if at the same time intensity of tillage is reduced and diversification of crop rotations is enhanced. Cover crops may be particularly beneficial for no-till rotations with limited or no annual biomass input or in systems where crop residues are removed for off-farm uses (Blanco-Canqui et al., 2011).

In addition to SOC increasing, incorporation of cover crops enhanced no-till performance by improving near-surface soil physical and hydraulic properties (Blanco-Canqui et al., 2011). In their experiment, soil water content was greater under cover crops than in plots without cover crops by an average of 35% at the 0–20-cm depth. Soil temperature during the day was also consistently lower under cover crops than in plots without cover crops, on the average, in early spring by 4 °C at the 5-cm depth, 2 °C at 15 cm, and 1 °C lower at 30 cm. These properties of cover crops will become relevant to mitigate the future climate change in Southern Kazakhstan, where an average annual temperature increase is predicted to be 1.6 °C for the next 20 years, as well as in Southern Finland, where there is a prediction for the annual temperature increase of 0.6 °C (but greater than 2 °C in March and in July), and a strong reduction in the annual precipitation (−120 mm yr^{-1}, −20%).

In Northern Italy, the models predicted negligible, but positive annual SOC changes under NT, CA and CA + CC for both current and future climates. In general, these cropping systems prevented SOC decline, but failed to accomplish the objective of the “4 per 1000” initiative. Unlike the results from our models, a higher rate of SOC increase (600–700 kg ha^{-1} yr^{-1}) in 0–30 cm soil depth was recorded under NT with residue retained and crop rotations in the long-term experiments conducted in Central Italy (Mazzoncini et al., 2011) and in Southern Italy (Badagliacca et al., 2018). These contrasting results most likely stem from, in addition to climates, the differences in the soils’ silt-clay fraction, which is only 34% in Lombriasco, while it is > 50% in the other two Italian experiments. High fractions of silt-clay content are known to be more resistant to mineralization and, thus, they protect

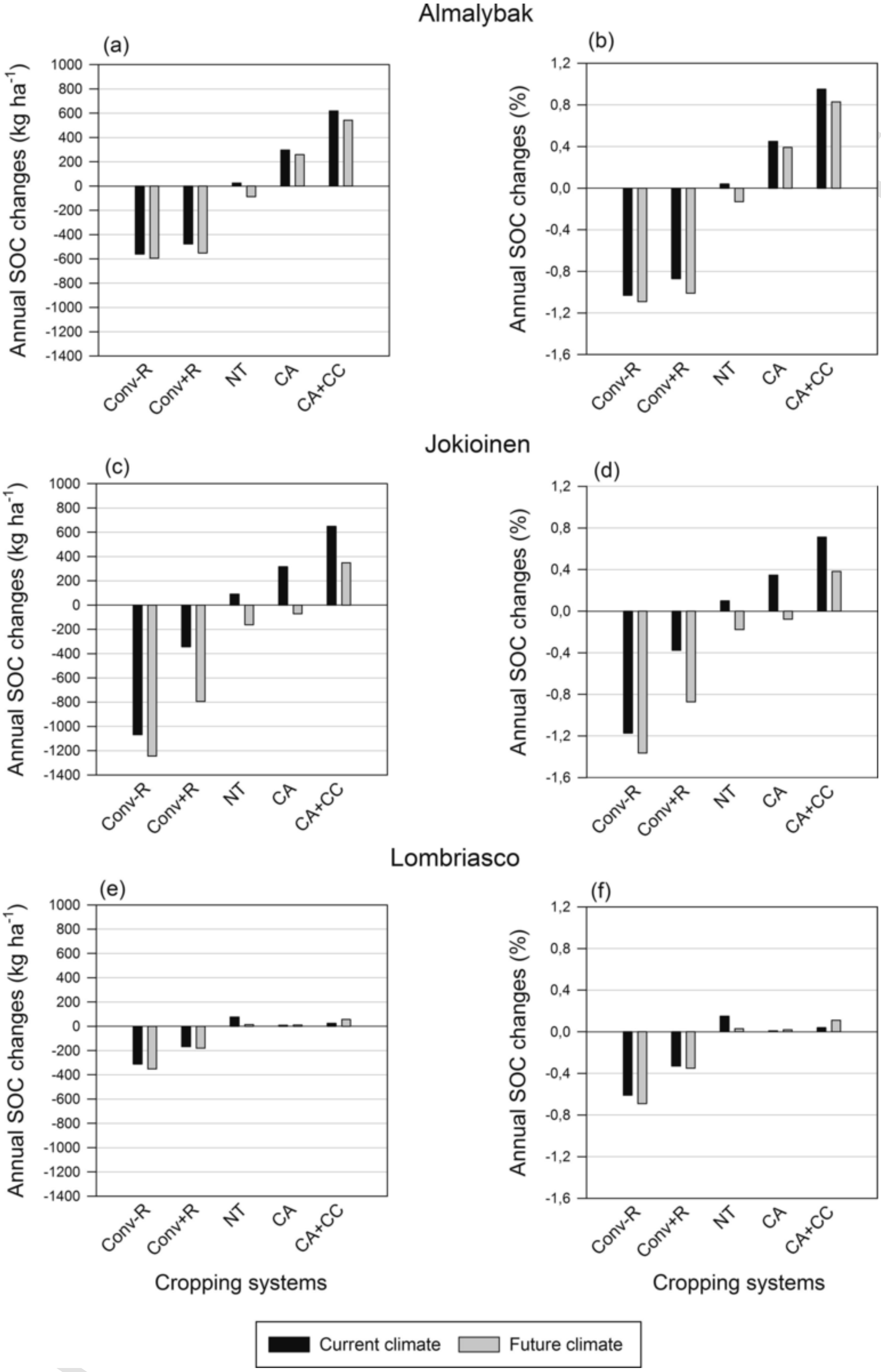

Fig. 4. Simulated annual SOC stocks changes at 0–30 cm soil depth for 20 years expressed as absolute values and percentage changes for different cropping systems under the current climate conditions and future climate scenarios in (a, b) Almalybak, Kazakhstan; (c, d) Jokioinen, Finland; (e, f) Lombriasco, Italy. Conv – R, conventional tillage with residue removed; Conv + R, conventional tillage with residue retained; NT, no-tillage; CA, conservation agriculture; CA + CC, conservation agriculture with cover crops. Entire description of cropping systems appears in Table 2.

SOM from decay. This agrees with the results of a recent study conducted on 20 farms in the Po valley, in which the CA practices (NT or minimum tillage) resulted in higher SOC than ploughing on four farms where soils were silty loam, sandy clay loam and clayey in texture (Perego et al., 2019). Therefore, site-specific models are needed for the estimation of C dynamics under the different managements of the field crops in actual and future climate conditions.

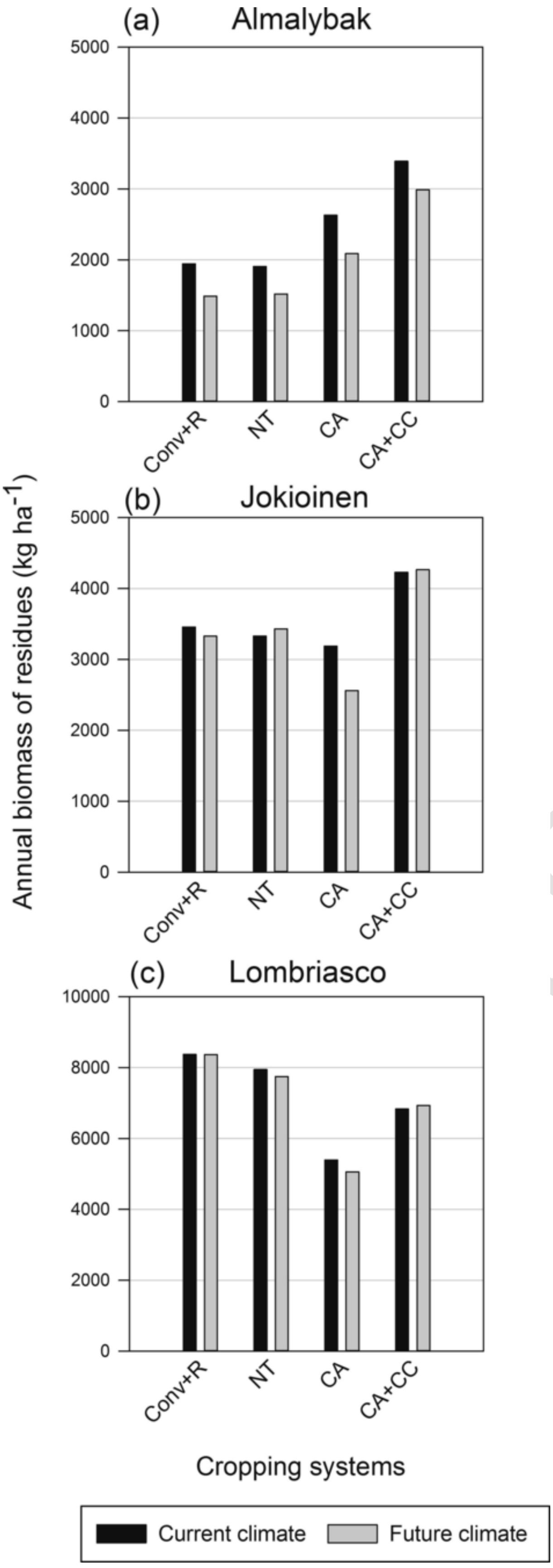

Fig. 5. Simulated annual biomass of residues (dry matter) for different cropping systems under current and future climate scenarios in (a) Almalybak, Kazakhstan; (b) Jokioinen, Finland; (c) Lombriasco, Italy. Conv + R, conventional tillage with residue retained; NT, no-tillage; CA, conservation agriculture; CA + CC, conservation agriculture with cover crops. Entire description of cropping systems appears in Table 2.

In addition to soil texture, the amount of residue biomass left on a field is an important factor for SOC sequestration under NT in Italy. Despite the high silt-clay fraction (>50%), only a small SOC increase (130 kg ha^{-1} yr^{-1}) was found in a Mediterranean climate for NT, when residues were continuously removed from the long-term experiment (Barbera et al., 2012). A meta-analysis of Chinese studies showed that long-term (>10 years) no-tillage with residue retention increased SOC and crop yields by about 10% and 20%, respectively, 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 (Zheng et al., 2014; Powlson et al., 2014). By using the CENTURY model, Ogle et al. (2012) suggested that where C inputs decline by more than 15%, then SOC would also decline with the adoption of no-tillage, and that where C inputs decrease by less than 15% (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 alone will not always serve to mitigate CO_2 emissions.

As reviewed by Abdalla et al. (2013), adoption of CA may lead to the larger N_2O emissions compared to conventional tillage due to increased rates of nitrification, and greater BD and soil water content, however, some studies showed either smaller or similar N_2O fluxes. Most studies have found either no significant effect or a decrease in CH_4 emissions following the adoption of CA. The authors concluded that both climate and soil type are important factors affecting GHG emissions, and thus, conservation tillage management practices should be developed within the context of specific soil types and climate (Abdalla et al., 2013).

5. Conclusion

This study indicates that CA has a potential to significantly reduce the CO_2 concentration in the atmosphere related to human activities, since a C sequestration rate of 0.4% yr^{-1} or higher can be achieved in two out of three sites. Particularly, in Southern Kazakhstan, CA has the largest potential for C sequestration, twice exceeding the objectives of the “4 per 1000” initiative under both current and future climates. The important factors, determining whether the objective will be reached under CA, seem to be a high percentage of clay-silt fraction in the soil, in addition to sufficient residue biomass. The potential role of cover crops (in CA + CC) should be emphasized, since they provided a supplemental C to soil and a potential for C sequestration rate of 0.36–0.5% yr^{-1} in Southern Finland and in Southern Kazakhstan under the current climate conditions, and their role will grow in importance in the future.

The increase of SOC in agriculture is a feasible option, but the way to achieve this is site- specific. Models can support decision-making in a specific context, allowing a priori assessment of the effectiveness of the various management options. Selecting the options in a farm for SOC sequestration should be considered from the perspective of their interactions, since the adoption of one promising management alone (e.g., cover crops or no-till, or straw incorporation alone) frequently is not enough. As the ARMOSA model forecasts for the future climate scenario, the SOC loss in conventional systems will be more pronounced compared to that under actual climate, and the SOC sequestration will be hardly achievable with NT alone. Therefore, the simultaneous adoption of all the three CA principles – minimum soil disturbance avoiding soil inversion, permanent soil cover and crop diversification – becomes more and more relevant in order to accomplish soil C sequestration as an urgent action to combat climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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