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Changes in Soil Organic Carbon and Nitrogen Stocks in Long-Term Experiments in Southern Brazil Simulated with Century 4.5

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ABSTRACT: The Century model has successfully simulated soil organic matter dynamics in many agroecosystems. However, initial applications in southern Brazil produced mixed results. The objective of this study was to calibrate and validate Century 4.5 to simulate soil carbon (C) and nitrogen (N) dynamics under diverse soil management practices in subtropical Brazil. Soil C and N data from two long-term experiments established on a degraded Acrisol in the early 1980s were used. Treatments were conventional or no-tillage; grass or grass/legume cropping systems; and corn with or without mineral N fertilizer. The calibration process iteratively modified model parameters to match simulated values of C additions and Soil Organic Carbon (SOC) and Soil Organic Nitrogen (SON) stocks to field data measured throughout the 25 years of the experiments. Improved fit between measured and observed data was obtained after key parameter changes. Soil C and N stocks were simulated accurately after these modifications were implemented. Other experimental treatments were used to validate the model. Century successfully simulated increases in C and N stocks under no-tillage cropping systems including legumes. However, the model overestimated Soil Organic Matter (SOM) decomposition in treatments with low N availability, like oat/corn without N fertilizer. Overall, Century version 4.5 showed adequate performance in simulating C and N trajectories of contrasting cropping systems commonly found in southern Brazil. The few discrepancies between measured and modeled SOC stocks do not preclude using Century in regional-scale applications to assess impacts of agricultural practices on soil C and N in southern Brazil.

Keywords: cover crop, carbon storage in soil, soil tillage, soil organic matter.

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INTRODUCTION

Soils can be sources or sinks of CO_2 and other greenhouse gases (GHG) depending on land use and management and agricultural practices (Lal, 2004). Intensive soil tillage and low addition of crop residues decrease Soil Organic Matter (SOM) stocks and increase GHG emissions, ultimately leading to general soil degradation (Zanatta et al., 2007). Conversely, no-tillage (NT), combined with large crop residues left on soil, has been shown to be an effective agricultural practice for C sequestration and mitigation of GHG emissions (West and Post, 2002; Carvalho et al., 2009). However, in addition to management practices, SOM dynamics are markedly dependent on site-specific factors such as soil type, climate, and antecedent (original) stocks (Zinn et al., 2005a; Dieckow et al., 2009).

Environmental performance of cropping and tillage systems is a crucial research topic, best addressed by long-term experiments and field monitoring. In this context, mathematical modeling is an accessory tool to simulate and predict long-term changes in Soil Organic Carbon (SOC) stocks (Paustian et al., 1992; IPCC, 2006).

There is currently great interest in models that explicitly simulate temporal SOC changes. However, as C and N cycles are closely associated, it is implicit that soil N dynamics also need to be modeled adequately (Shaffer and Ma, 2001). Indeed, several studies suggest that uncertainties in soil C sequestration estimates are largely derived from insufficient understanding of soil N availability, because SOC accumulation could be limited by N in many instances (Hungate et al., 2003; Liu et al., 2005).

The Century model (Parton et al., 1987) was initially developed to simulate SOM dynamics in North American prairies. One of the most used and reviewed soil C models, Century has performed well in model comparison studies (Smith et al., 1997). Recent versions of the model have added the capability of simulating a wide array of agricultural practices (Falloon and Smith, 2002) tested in diverse ecosystems such as semi-arid savannas in Sudan (Ardö and Olson, 2003), tropical forests in the Amazon (Cerri et al., 2004), and the Atlantic Forest of Eastern Brazil (Leite et al., 2004).

Early applications of Century (version 4.0) to simulate changes in SOC stocks of soils in the major grain-producing areas of southern Brazil under conservation and no-tillage management were conducted in an Acrisol (UISS, 2007) by Fernandes (2002) and Bortolon et al. (2009), and in Ferralsols (UISS, 2007) by Tornquist et al. (2009a,b), Bortolon et al. (2011) and Lopes et al. (2013), respectively, *Argissolos* and *Latossolos* in the Brazilian Soil Classification System (Santos et al., 2013). In this region of Brazil, there is also an application of Century in soils with *Eucalyptus* sp. (Wink et al., 2015). Although these studies Brazil were generally satisfactory, many suggestions for improving performance of the model in subtropical and tropical regions have been presented.

The hypotheses of this work is that the Century 4.5 model requires changes in values of their parameters to properly simulate the dynamics of SOM under different crop and tillage systems in an Acrisol in southern Brazil. These systems affects soil C and N stocks, and their impact on the SOM can be evaluated through studies with the model Century 4.5.

The objective of this study was to calibrate and validate the updated version of the Century model (4.5) to simulate changes in C and N stocks using selected treatments from 25-year-old experiments that are representative of cropping and tillage systems currently practiced in southern Brazil.

MATERIALS AND METHODS

This study is based on long-term experiments at the agronomic experimental station of the Universidade Federal do Rio Grande do Sul (AES) in the state of Rio Grande do Sul in southern Brazil (30° 06’ 37.65” S; 51° 40’ 37.17” W, altitude 60 m, mean slope 6 %). The climate is subtropical (Köppen type Cfa), with mean annual rainfall of 1,440 mm and monthly mean air temperature ranging from 13.9 °C in June to 24.8 °C in January (Bergamaschi et al., 2003). Soil in the experimental plot is Acrisol according to the World Reference Base for Soil Resources (UISS, 2007) or *Argissolo Vermelho Distrófico* in the Brazilian Soil Classification System (Santos et al., 2013). Mineralogy of the clay fraction in the surface layer (0.00-0.20 m) is dominated by kaolinite (720 g kg^{-1}) and Fe oxides (109 g kg^{-1}).

This study used data from two concurrent long-term experiments (which are ongoing): the "cropping systems experiment" (Exp1) and the "tillage experiment" (Exp2), established in 1983 and 1985, respectively. The original vegetation in this area was subtropical grasslands, representative of the eastern most portion of the South American Pampas biome, which had been lightly grazed by beef cattle for several decades. The field where the research plots are located was first plowed in 1970, and rapeseed and sunflower were continuously cropped under conventional management until the experiments were established. Exp1 was established in a two-factor block design with 10 cropping systems under no-tillage with corn grown as a summer cash crop with two N rates (0 and 120 kg ha^{-1} until 1993 and 0 and 180 kg ha^{-1} from 1994 onwards). Exp2 is a three-factor block design with three tillage systems (conventional, minimum, and no-tillage) in the summer (continuous corn [*Zea mays* L.] crop, Sept.-March) and no-tillage in the winter (cover crops: black oats [*Avena strigosa* Schreb.] and common vetch [*Vicia sativa* L.]), and two N rates (0 and 120 kg ha^{-1} until 1993 and 0 and 180 kg ha^{-1} from 1994 onward) applied to the summer corn crop (Zanatta et al., 2007). Both experiments were initially conducted under rainfed conditions; more recently, a sprinkler irrigation system has been used when severe drought conditions occur. Winter cover crops were sown in the fall (April/May), desiccated with herbicide, and managed with a crop roller in the spring (September/October). Subsequently, corn was planted either with no-tillage or conventional tillage management (one disc plow and two disc harrow passes).

Selected treatments from the above experiments were chosen for this modeling study to include diverse management aspects, such as tillage and N fertilization, as well as multiple crops (Table 1).

In Exp1, above-ground biomass production for the winter season cover crops was measured for several years, whereas corn biomass was estimated from grain yield (Lovato et al., 2004). In Exp2, crop biomass data were obtained from Zanatta et al. (2007). Below-ground biomass in both experiments was estimated as 30 % of the above-ground biomass, and C in grain and residue was estimated as 40 % of dry weight (Bayer et al., 2000).

Soil C and N content and bulk density data for calculating C and N stocks were obtained from several studies (Weber, 2010). Carbon was initially determined by the Walkley-Black (WB) wet combustion method (Nelson and Sommers, 1996); dry combustion (with a Shimadzu TOC-V CSH analyzer) was used after 2002. As organic C recovery can differ significantly according to these methods, a correction factor of 0.9422 obtained for this experiment was applied to WB measurements (Dieckow et al., 2007). Total N was obtained by a micro-Kjeldahl method with modifications (Tedesco et al., 1995). Carbon and N stocks - obtained at a fixed-depth (0.00-0.20 m) layer - were adjusted to an equivalent mass as proposed by Ellert and Bettany (1995).

Century 4.5 requires a minimum data set: a) climate (precipitation, monthly maximum and minimum temperature, wet and dry N deposition); b) plant production (primary productivity, yield, N and lignin content); and c) soil properties (particle size distribution, initial C and N content, water). Although it is possible to directly input SOC and SON data in Century, model developers recommend an equilibrium (''spin up'') simulation of thousands of years to initialize model state variables before the simulation of interest (the experimental period) is conducted. Climatic data (monthly means for precipitation, minimum and maximum temperature) were obtained from the meteorological station at

Table 1. Selected treatments from AES long-term experiments used in Century 4.5 simulations

Treatment	Crop		Tillage	Applied N
	Winter	Summer		
				kg ha^{-1} yr^{-1}
		Calibration		
Exp1				
NT O/C 180N	Black oat	Corn	No-tillage	180
NT O+V/C 0N	Black oat+vetch	Corn	No-tillage	0
NT O+V/C 180N	Black oat+vetch	Corn	No-tillage	180
Exp2				
CT O/C 180N	Black oat	Corn	Conventional	180
		Validation		
Exp1				
NT O/C 0N	Black oat	Corn	No-tillage	0
NT O+V/C+Cp 0N	Black oat+vetch	Corn+cowpea (*Vigna unguiculata*)	No-tillage	0
NT O+V/C+Cp 180N	Black oat+vetch	Corn+cowpea	No-tillage	180
NT C+L 0N	Lablab (*Lablab purpureus*)	Corn+lablab	No-tillage	0
NT C+P 0N	Pigeon pea (*Cajanus cajan*)	Corn+pigeon pea	No-tillage	0
Exp2				
NT O/C 0N	Black oat	Corn	No-tillage	0
NT O/C 180N	Black oat	Corn	No-tillage	180
NT O+V/C+Cp 0N	Black oat+vetch	Corn+cowpea	No-tillage	0
NT O+V/C+Cp 180N	Black oat+vetch	Corn+cowpea	No-tillage	180
CT O/C 0N	Black oat	Corn	Conventional	0
CT O+V/C+Cp 0N	Black oat+vetch	Corn+cowpea	Conventional	0
CT O+V/C+Cp 180N	Black oat+vetch	Corn+cowpea	Conventional	180

AES and site-specific soil data from Fernandes (2002): soil particle size distribution (sand 509 g kg^{-1}, silt 262 g kg^{-1}, clay 229 g kg^{-1}) and pH(H_2O) 5.1. Crop parameters, especially the PRDX parameter (potential primary production parameter), were modified iteratively until simulated C additions by plants matched observed biomass measurements from the experiments. Because Century can not explicitly simulate intercropping or plant mixtures, such as oat-vetch commonly used as cover crops in southern Brazil, a compromise solution was adopted by setting up a fictitious plant that represented both crops in terms of total biomass and residue production, as well as symbiotic N additions.

A 4,000-year equilibrium model spin-up was conducted using default tropical grassland parameters adjusted to local grasslands. Symbiotic N fixation was set to account for legumes that occur in the Pampas grasslands (e.g. *Desmodium* sp.), as reported by Escosteguy (1990). Prior to the establishment of the experiments (1983 or 1985), a "base" simulation period was introduced to represent the breaking of sod and cultivation of rapeseed and sunflower from 1970 to 1983. These crop parameters were adjusted to simulate mean annual C addition of 2.1 Mg ha^{-1} yr^{-1} C (sunflower) and 1.7 Mg ha^{-1} yr^{-1} C (rapeseed). Large soil C losses observed in this period were represented by increased cultivation parameters that affect decomposition rates, reported in table 2.

The Century 4.0 calibration procedure followed the model developed and further detailed in other studies (Paustian et al., 1992; Richards et al., 2007; Álvaro-Fuentes et al., 2009). Parameters from the management and fixed sets (CULT.100 and FIX.100 files) were iteratively adjusted by inspecting output until SOC and SON output stocks matched measured stocks

Table 2. Modified Century 4.5 "fixed" and management parameters (FIX.100 and CULT.100 file) adjusted to southern Brazilian conditions

Parameter	Original	Modified
FIX.100 (Same in all Blocks)		
DEC4[(1)]	0.0045	0.0057
VARAT2(1,1)[(2)]	18	25
VARAT3(1,1)[(3)]	8	15.6
VLOSSG[(4)]	1	0.01
CULT.100 (Base Block)		
Summer: CLTEFF[(5)]	1.6	1.6
CLTEFF[(5)]	1.6	1.8
Winter: CLTEFF[(5)]	1.6	1.6
CULT.100 (Experimental Block)		
CLTEFF[(5)] - Conventional tillage	1.6	2.0
CLTEFF[(5)] - No-tillage	1.0	1.1
Additional tillage effect[(6)]	-	4.0

(1) Maximum decomposition rate of soil organic matter with slow turnover. (2) Maximum C/N ratio for material entering slow pool. (3) Maximum C/N ratio for material entering passive pool. (4) Factor, as a function of soil texture based on clay content, with multiplicative effect on N fraction volatilized per month of gross mineralization. (5) Cultivation factor for active, slow, and passive pool and for soil structural material decomposition; functions as a multiplier for increased decomposition in the month of cultivation. (6) Cultivation factor for active, slow, and passive pool and for soil structural material decomposition; functions as a multiplier for increased decomposition one month after cultivation.

(Table 2). Calibration of conventional tillage was conducted with the experimental treatment CT O/C 180N; treatments NT O/C 180N, NT O+V/C 0N, and NT O+V/C 180N were used to calibrate the model for no-tillage (Table 2). As proposed by Bortolon et al. (2009), an "additional effect of cultivation" was included in the conventional tillage block in the month following tillage to extend the effect of soil disturbance on SOM decomposition into the next month.

Test runs with default parameters and the initialization procedure described above resulted in an overestimation of SOC and SON stocks, as well as an unrealistically low soil C/N ratio. To resolve this issue, key "fixed" parameters were altered (Table 2): DEC4 (decomposition rate of the passive pool), VARAT2 (maximum C/N ratio for material entering slow C pool) and VARAT3 (maximum C/N ratio for material entering passive C pool), and VLOSSG (fraction per month of gross mineralization which is volatilized).

Validation of Century 4.5 relied on simulated and observed soil C and N stocks from an independent dataset comprising treatments from both long-term experiments that were not in the calibration phase (Table 1).

Statistical assessment of the validation runs used root mean square error (RMSE) and coefficient of correlation (r) performed in the MS Excel worksheet "ModEval" developed for model performance evaluation by Smith et al. (1996).

RESULTS AND DISCUSSION

Simulation and calibration

Biomass production of grasslands at AES-UFRGS was observed by Escosteguy (1990), who reported 2.79 Mg ha^{-1} yr^{-1} C. Spin-up Century simulation showed 8.66 Mg ha^{-1} above-ground biomass C in grasslands in the research area prior to agriculture. This large grassland biomass production was a result of increasing the production parameter (PRDX) to 0.53 g cm^{-2}, which was necessary to match measured and simulated soil C stock. Although the biomass estimate was large, it was accepted because it was only required to establish the initial soil conditions before the experimental period of interest was simulated. Nevertheless, the mismatch between simulated and measured above-ground biomass could be explained by aspects of the C cycle in grasslands that are not considered in the model: enhanced accumulation of soil C in grasslands due to greater root density, and associated higher production of organic compounds in comparison to annual crops.

At the end of this grassland simulation, SOC stocks stabilized at 43.38 Mg ha^{-1} C, comprising 1.52 Mg ha^{-1} C in the active pool, 23.57 Mg ha^{-1} C in the slow pool, and 18.29 Mg ha^{-1} C in the passive pool (Table 3). Conversely, SON stabilized at 3.48 Mg ha^{-1} C: the passive N pool was larger than the slow N pool. The relative proportions of SOC and SON pools under grasslands are similar to those reported earlier by Fernandes (2002) and Bortolon et al. (2009), working with Century 4.0.

From 1970 to 1982, simulated C in residues were 1.73 Mg ha^{-1} yr^{-1} C for sunflower and 2.10 Mg ha^{-1} yr^{-1} C for rapeseed, consistent with reported above-ground biomass production and yields for these crops throughout the region at that time. Soil C data indicated a loss of approximately 10 Mg ha^{-1} C (23 % of the total C stored in the 0.00-0.20 m layer under grasslands) and 0.32 Mg ha^{-1} N in this period, which was attributed to diminished biomass C inputs and frequent intensive tillage operations. Century was able to capture these soil management effects after changes in cultivation parameters (Table 3).

In the experimental period (from 1983 onwards) crop parameters in the selected treatments were also altered to match observed crop C inputs (Table 4). These modifications improved coincidence between simulated and observed SOC stocks (Figure 1): simulations showed significant correlation (r=0.89; $p \leq 0.05$) and low RMSE (3.16 %) within the 95 % confidence limits (Figure 2a).

Table 3. Observed and simulated soil organic C, total soil N, Century pools, and soil C/N at the end of the equilibrium and base period simulated by Century 4.5 and measured in the experimental plots

Variable	Grasslands (end of equilibrium, 1970)		Start of experiments (end of base, 1983)	
	Observed	Simulated	Observed	Simulated
C above-ground addition (Mg ha^{-1} yr^{-1})	-	8.66	-	3.83
Total SOC (Mg ha^{-1})	43.37	43.38 (100)[(1)]	33.40	33.82 (100)
Active C (Mg ha^{-1})	-	1.52 (3.5)	-	0.98 (2.9)
Slow C (Mg ha^{-1})	-	23.57 (54.3)	-	15.61 (46.2)
Passive C (Mg ha^{-1})	-	18.29 (42.2)	-	17.22 (50.9)
Total soil N (Mg ha^{-1})	3.47	3.48 (100)	3.09	3.16 (100)
Active N (Mg ha^{-1})	-	0.25 (7.2)	-	0.21 (6.7)
Slow N (Mg ha^{-1})	-	1.09 (31.3)	-	0.91 (28.0)
Passive N (Mg ha^{-1})	-	2.14 (61.5)	-	2.03 (64.4)
Soil C/N	12.50	12.46	10.81	10.70
Active C/N	-	6.13	-	4.64
Slow C/N	-	21.54	-	17.08
Passive C/N	-	8.55	-	8.47

[(1)] Numbers in parenthesis are percentages of total SOC and N.

Table 4. Observed and simulated annual average C addition by Century model 4.5 during calibration

Treatment	Nitrogen	Average C addition	
		Simulated	Observed
	kg ha^{-1}	Mg ha^{-1} yr^{-1}	
NT O/C	180	7.2	7.4
NT O+V/C	0	7.2	6.4
NT O+V/C	180	7.7	7.6
CT O/C	180	7.1	6.3

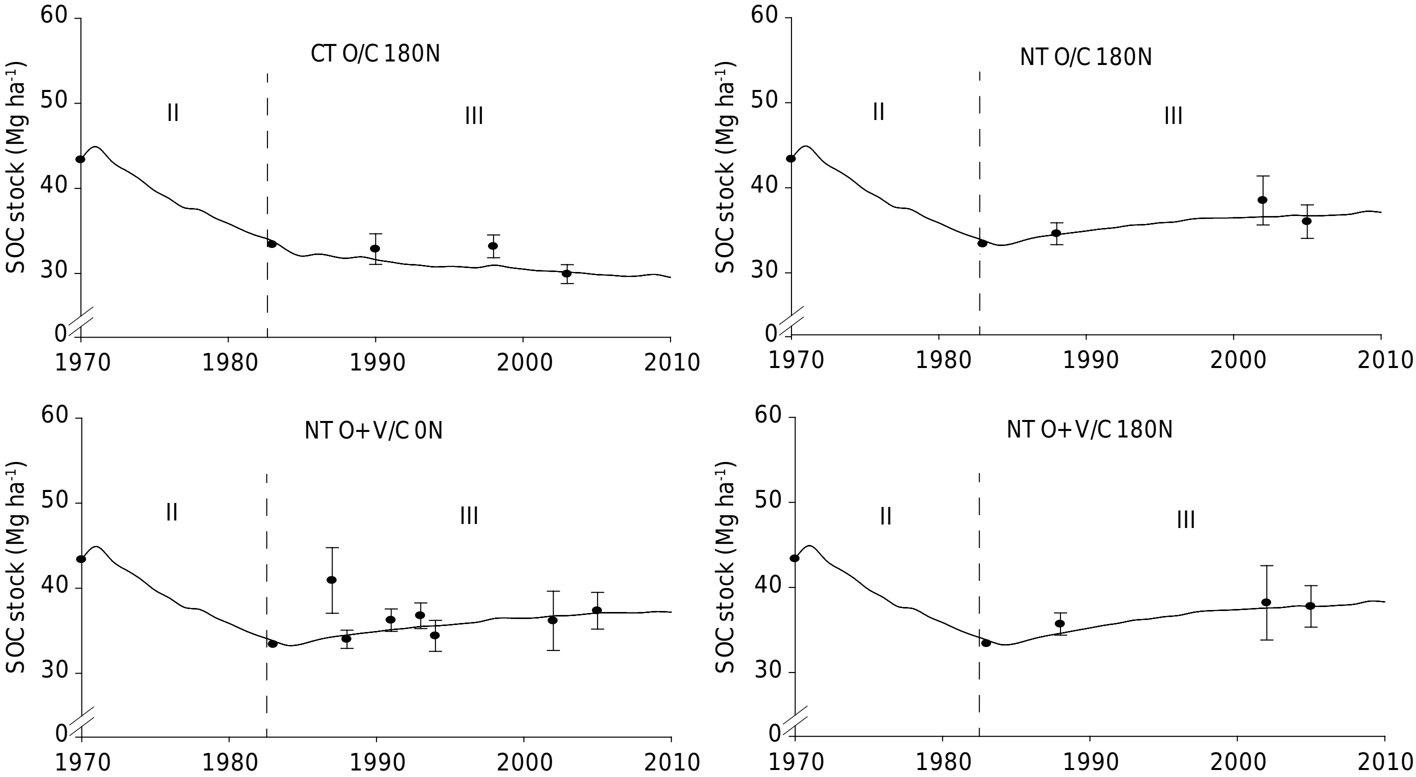

Figure 1. Simulated SOC dynamics in the topsoil layer (0.00-0.20 m) in the base (II) and experimental (III) blocks in an Acrisol under contrasting tillage and cropping systems in southern Brazilian conditions. CT: conventional tillage; NT: no-tillage; O/C: oat/corn; O+V/C: oat+vetch/corn; 0N: 0 kg ha^{-1} yr^{-1} N; 180N: 180 kg ha^{-1} yr^{-1} N. Line represents simulated SOC stocks and dots, measured SOC stocks. Error bars represent standard deviations.

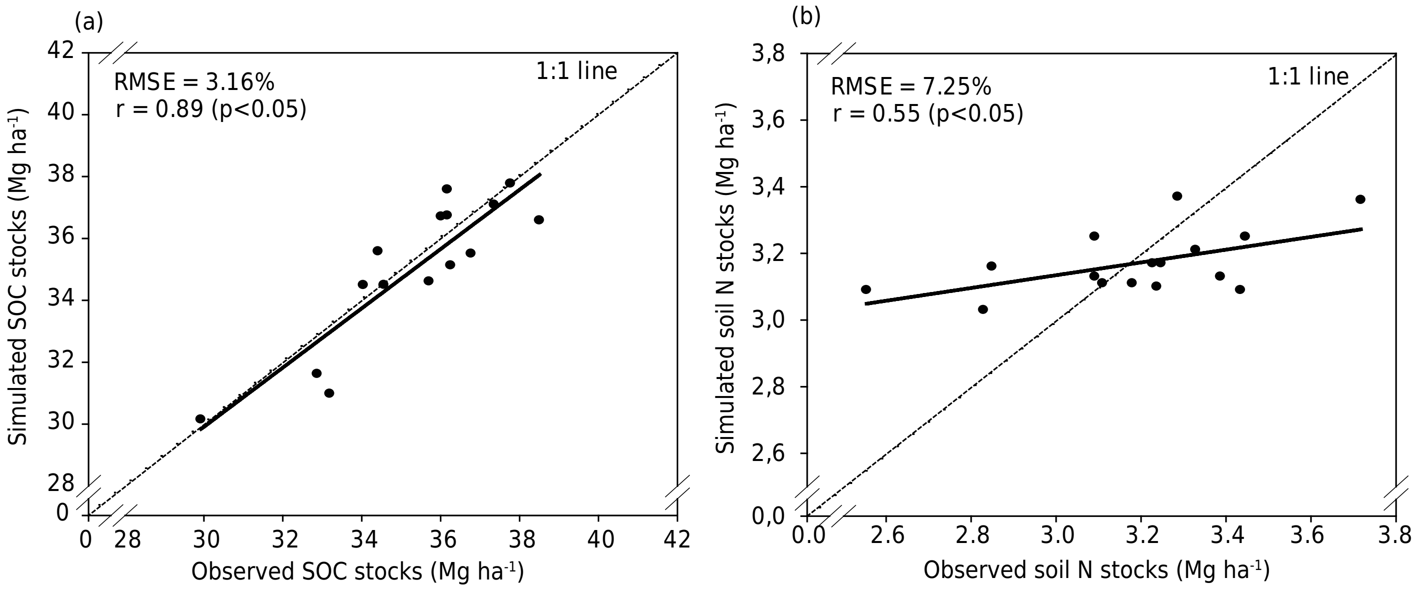

Figure 2. Observed and Century-simulated SOC stocks (a), and soil N stocks (b) in an Acrisol in the experimental block of different tillage and crop systems under southern Brazilian conditions during calibration.

During the 1983-2005 period, simulated soil C stocks decreased by 3.92 Mg ha^{-1} under CT, and increased 3.38 Mg ha^{-1}, on average, under NT treatments (Table 5). These simulated losses and gains of soil C are highly correlated with observed values (Figure 1). The changes were noted mostly in the slow soil C, whereas the passive soil C pool was only slightly affected by soil tillage and crop management practices throughout the period (Table 5).

Table 5. Simulated total soil organic carbon (SOC), nitrogen stocks, C/N ratio, and Century 4.5 pools at the end of the experimental period (2005)

Treatment	Total SOC		Active C	Slow C	Passive C
	Mg ha^{-1}				
CT O/C 180N	29.9		0.94 (3.1)[(1)]	13.33 (44.6)	15.60 (52.3)
NT O/C 180N	36.7		0.90 (2.5)	18.97 (51.7)	16.83 (45.9)
NT O+V/C 0N	37.1		1.02 (2.7)	19.17 (51.7)	16.90 (45.6)
NT O+V/C 180N	37.8		0.96 (2.5)	19.95 (52.8)	16.87 (44.7)
	Total soil N		Active N	Slow N	Passive N
	Mg ha^{-1}				
CT O/C 180N	3.00		0.23 (7.7)	0.88 (29.3)	1.89 (63.0)
NT O/C 180N	3.25		0.26 (8.1)	0.96 (29.7)	2.03 (62.3)
NT O+V/C 0N	3.17		0.21 (6.6)	0.96 (30.1)	2.00 (63.3)
NT O+V/C 180N	3.37		0.28 (8.3)	1.06 (31.4)	2.03 (60.3)
	C/N ratio SOM		C/N ratio pools		
	Simulated	Observed	Active C	Slow C	Passive C
Initial C/N[(2)]	10.70	10.81	4.64	17.08	8.47
CT O/C 180N	9.95[(3)]	10.56[(3)]	4.08	15.15	8.25
NT O/C 180N	11.30	11.66	3.46	19.76	8.29
NT O+V/C 0N	11.70	11.50	4.85	19.97	8.45
NT O+V/C 180N	11.20	11.52	3.43	18.82	8.31

[(1)] Numbers in parenthesis are percentages of total SOC and N. [(2)] At start of experiment in 1983. [(3)] In 2003.

An earlier application of Century (version 4), with AES experiment data using the default N parameters to simulate soils under grasslands, consistently overestimated soil N stocks (Fernandes, 2002). Later, following suggestions of Century developers, Bortolon et al. (2009) included changes in the VARAT2(1.1) and VARAT3(1.1) fixed parameters. The same modifications where adopted in our study (Table 2), as they were adequate for simulating soil N stocks (Figures 2 and 3).

If key components of the N cycle (SON stocks and soil mineral N) are overestimated, the Century model will simulate higher plant biomass production, which will be reflected in unrealistic SOC stock trajectories. Therefore, it is essential to calibrate the N cycle submodel in a SOM dynamic model. However, most published studies on SOM modeling focus almost exclusively on C, with little reference to soil N dynamics (Alvaro-Fuentes et al., 2009; Galdos et al., 2009; Shrestha et al., 2009).

The calibration procedure improved model performance with regard to SOC (Figure 2). However, these modifications affected SON dynamics to a lesser extent. This observation could be explained in part by an inherent Century limitation in representing biological fixation of N, N losses due to volatilization of NH_3, leaching, and denitrification, which have not been addressed in the otherwise enhanced version 4.5. Additionally, the large variability of SON measured in some treatments contributed to these poorer matches.

In these simulations, all treatments started the experimental period with equal soil N stocks (3.16 Mg ha^{-1}), of which 0.21 Mg ha^{-1} was in the active pool, 0.91 Mg ha^{-1} in the slow pool, and 2.03 Mg ha^{-1} in the passive pool. Simulated SON stocks decreased under the CT and increased under the NT treatments during the experimental period. N losses occurred in both the slow and passive pools, but N increased after adoption of no-tillage, mostly in the slow pool. The relative soil N partition in the Century pools did not vary significantly in the experimental period, remaining close to the initial values (7-8 % active, 29-30 % slow, and 60-63 % passive pool) (Table 5).

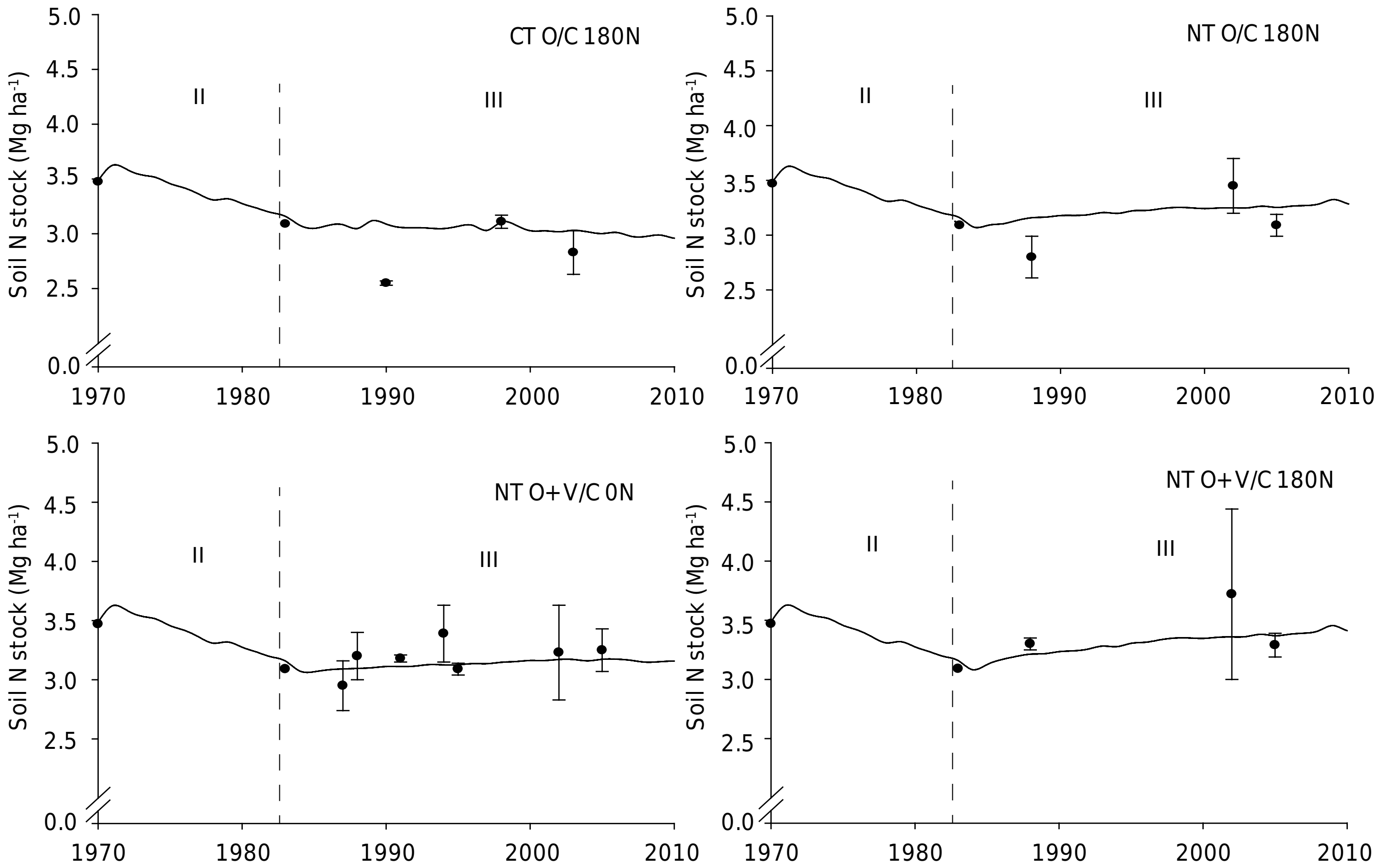

Figure 3. Simulated SON dynamics in the topsoil layer (0.00-0.20 m) in the base (II) and experimental (III) blocks in an Acrisol under contrasting tillage and cropping systems under southern Brazilian conditions. CT: conventional tillage; NT: no-tillage; O/C: oat/corn; O+V/C: oat+vetch/corn; 0N: 0 kg ha^{-1} yr^{-1} N; 180N: 180 kg ha^{-1} yr^{-1} N. Line represents simulated SON stocks and dots, measured SON stocks. Error bars represent standard deviations.

Because C losses were greater than N losses in the slow pool, a decrease in the C/N ratio of this pool was observed in the conventional tillage treatment in 2005 (Table 5). Adoption of no-tillage led to proportionally larger C increases than N increases in the slow pool, resulting in an increase in the C/N ratio in this pool. There was minimal variation in the passive pool, as this pool is less responsive to changes in management systems. The combined effect of pool changes produced a decrease in the C/N ratio of SOM in CT and its increase in NT systems (Table 5).

Validation

Simulated C additions through crop residues were significantly correlated with observed data, including cover crop mixtures (Figure 4). The variability of C additions in the experiments is mainly due to cropping systems and N management. Lower additions occurred in systems with oat/corn without N fertilizer (4.9 Mg ha^{-1} yr^{-1} with the observed data, and 4.3 Mg ha^{-1} yr^{-1} with the simulated data). Adding N fertilizer to these systems increased biomass production to 6.4 Mg ha^{-1} yr^{-1} C, and this management effect was captured by the model (7.1 Mg ha^{-1} yr^{-1}). Across experimental treatments, legumes introduced as a cover crop increased C additions to 7.5 Mg ha^{-1} yr^{-1}, with a maximum of 12 Mg ha^{-1} yr^{-1} in treatments where pigeon pea was part of the cropping system. The introduction of legumes in grass-based cropping systems has been reported to increase the availability of N for non-N fixing crops and to increase yields (Da Ros and Aita, 1996; Amado et al., 2006; Weber and Mielniczuk, 2009). Moreover, summer legumes such as cowpea, pigeon pea, and lablab can further increase biomass production, in comparison to systems with only a winter legume (vetch).

The validation runs of Century 4.5 showed output consistent with the observed SOC dynamics (Figure 5a). Overall accuracy of the simulations showed RMSE (7.34 %) within the confidence interval (95 %) of the observed data. Soil C trajectories of selected validation treatments of Exp1 and Exp2 simulated for 18 years were consistent with observed data (Figures 6 and 7). Soil C stocks in conventional tillage systems were generally smaller than in no-till systems. The lower SOC stocks in CT derive from the higher rates of decomposition of SOM in these systems (Lovato et al., 2004; Zinn et al., 2005b).

Conventional tillage promoted a decrease in C stocks in the grass-based cropping system without N fertilizer (CT O/C 0N) because of low C additions in this edaphoclimatic context.

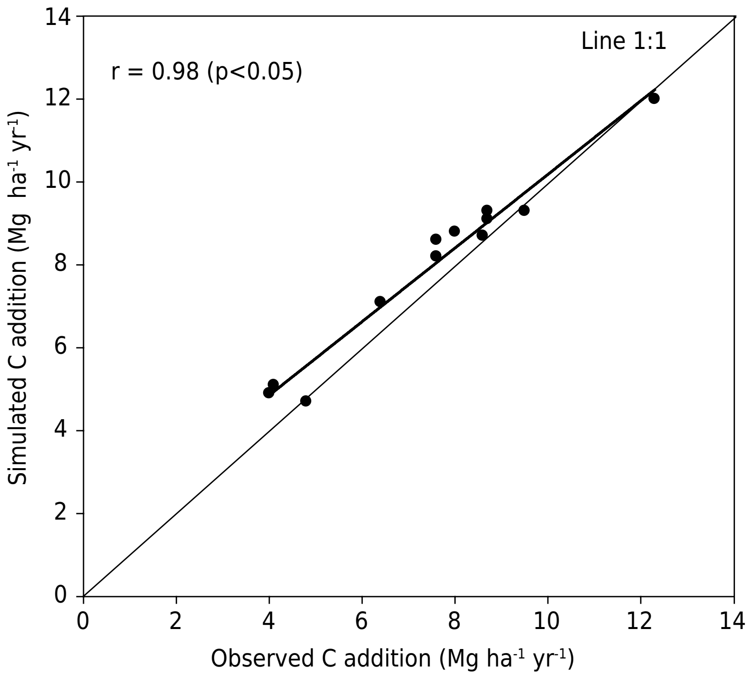

Figure 4. Observed and Century simulated C addition in an Acrisol in the experimental block of different tillage and crop systems under southern Brazilian conditions.

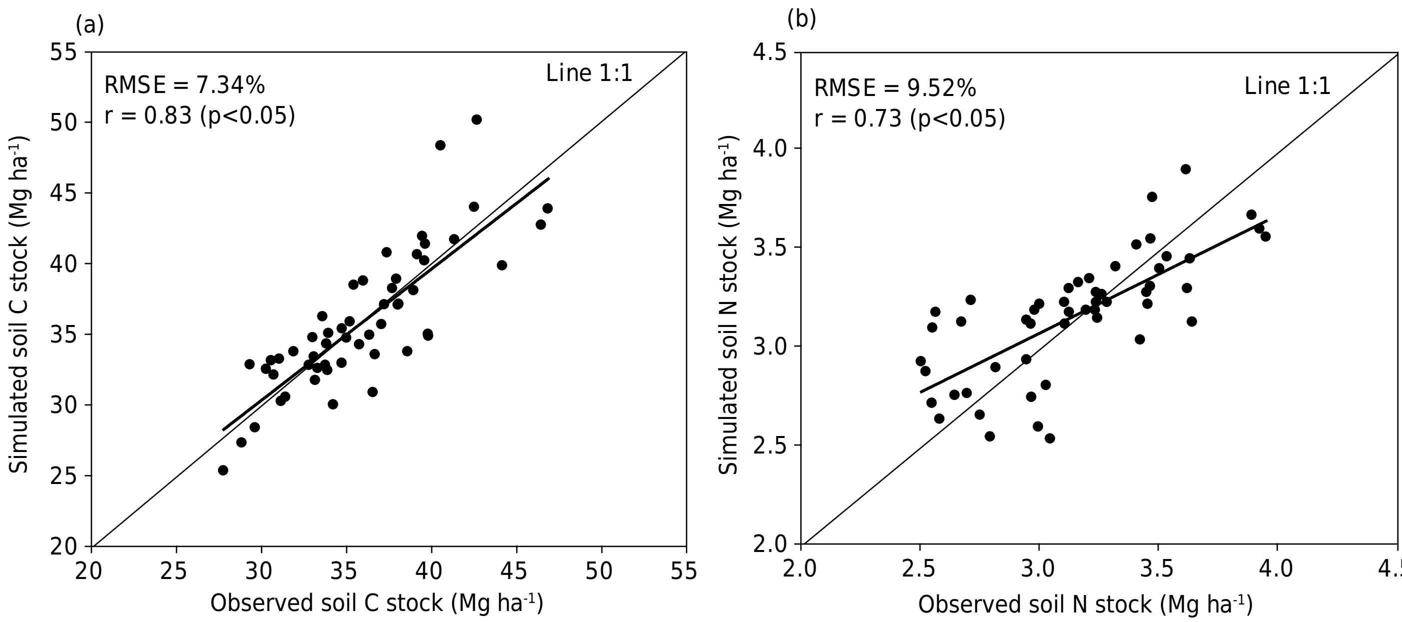

Figure 5. Observed and Century simulated C stocks (a), and soil N stocks (b) in an Acrisol in the experimental block of different tillage and crop systems under southern Brazilian conditions during validation.

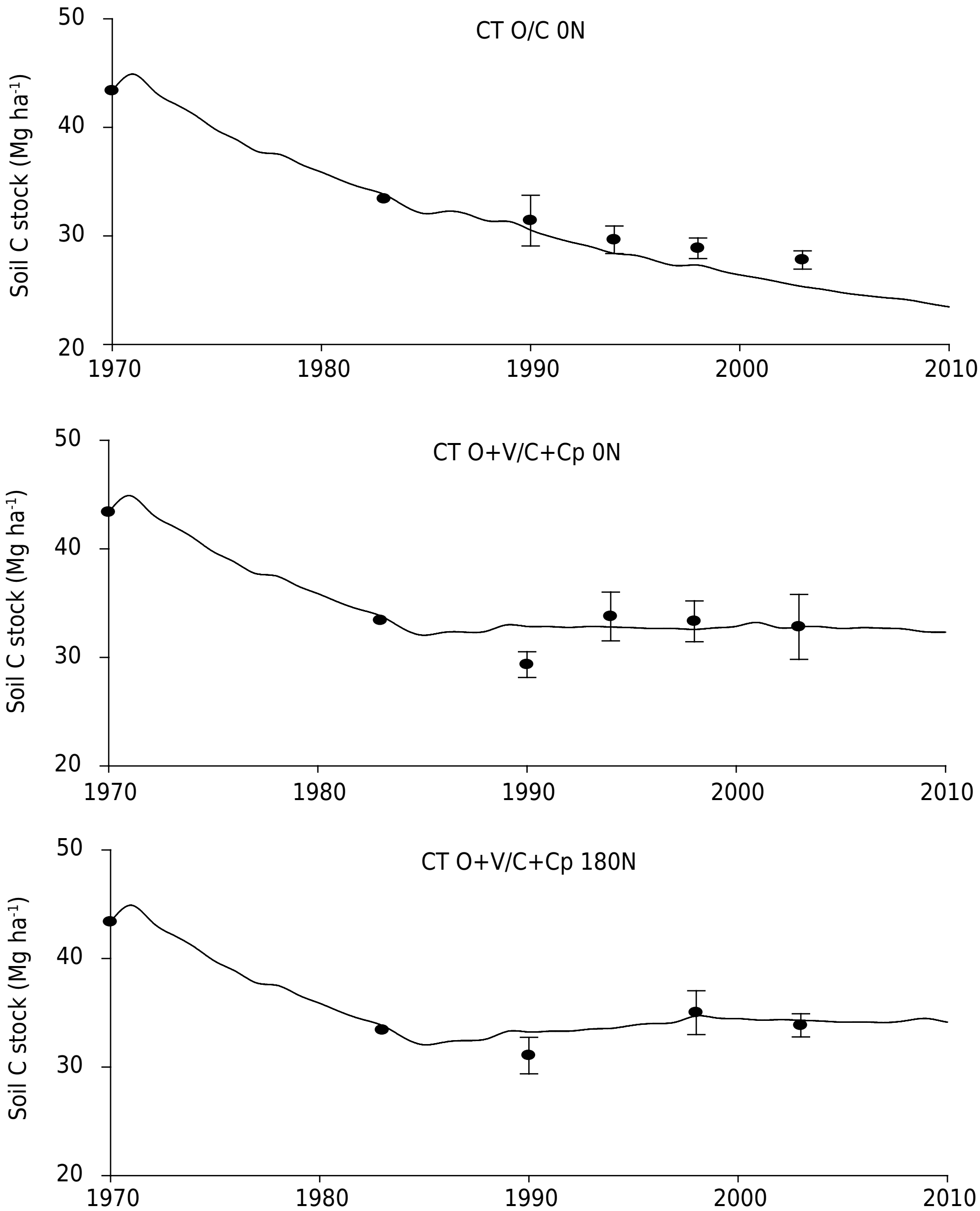

Figure 6. Simulated SOC dynamics in the topsoil layer (0.00-0.20 m) in the base and experimental blocks in an Acrisol under different conventional tillage systems under southern Brazilian conditions during validation. Line represents simulated SOC stocks and dots, measured SOC stocks. Error bars represent standard deviations.

Conversely, in cropping systems such as Oat + Vetch (O+V)/Corn +Cowpea (C+Cp) (with legumes, but without N fertilizer), an increase in biomass production and C additions to soils stabilizes C. It appears that a slight increase in C stocks occurs when N fertilizer (as urea) is applied in comparison with the same cropping system without N fertilizer.

Century was also able to simulate the C dynamics adequately in NT systems. SOC stocks increased slightly in those systems, except for O/C without mineral N fertilization (Figure 7). The use of legumes in NT had a major effect on C stocks (Figure 7). This positive effect of the use of legumes on C stocks has been demonstrated in several studies in various parts of the world. Pigeonpea showed the greatest potential for recovery of SOC stocks, with an increase of 18.9 Mg ha^{-1} in C stocks (0.00-0.20 m) measured in the experimental area and 19.6 Mg ha^{-1} simulated over 22 years.

There was a significant ($p<0.05$) positive correlation of 0.73 between observed and simulated N stocks (Figure 5b); and RMSE (9.52 %) indicates small differences between observed and simulated data. However, as in the calibration step, the model did not perform as well as in SOC simulations. Possible explanations for this difference could be related to the complexities of the N cycle, with multiple sinks and sources and high sensitive to residue quality and microbe-mediated processes that are not explicitly in the Century model.

Cropping systems with oats and corn under CT without N fertilizer inputs or symbiotic fixation showed a trend of N stock loss (Figure 8). When legumes were grown, SON stocks remained stable or even showed a slight increase. No-tillage management with legume crops or N fertilizerled to an overall increase in SON (Figure 9). The observed increase in SON under NT reflects the positive balance of N inputs and outputs of the system.

The Century model successfully simulated SON trajectories, in part because N fixation could be simulated adequately (data not shown). The practice of N fertilization was crucial for maintaining and increasing N stocks, especially in grass-based cropping systems such as the O/C treatment. However, in other treatments, N fertilizer had limited additional effect on N accumulation.

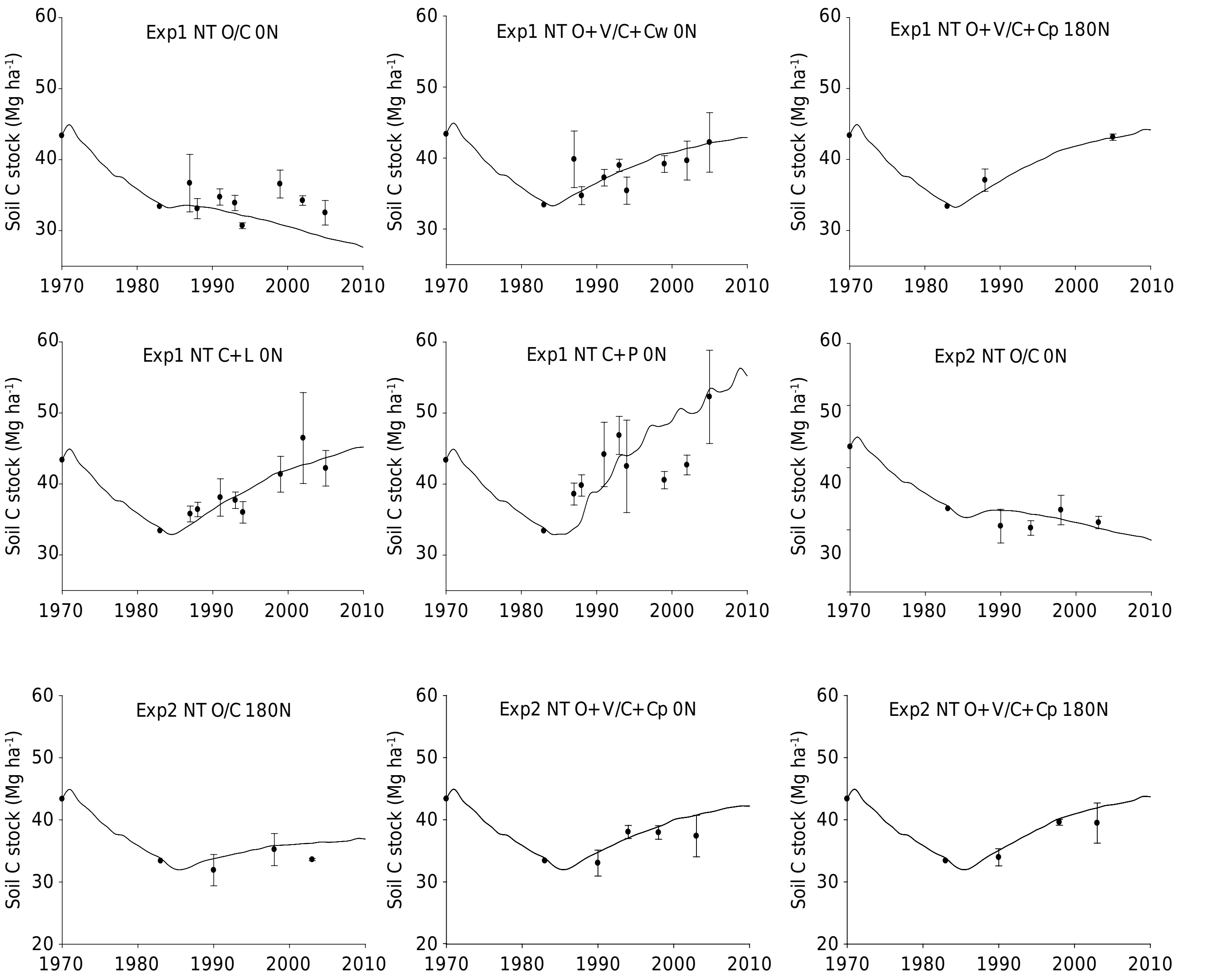

Figure 7. Simulated soil organic carbon (SOC) dynamics in the topsoil layer (0.00-0.20 m) in the base and experimental blocks in an Acrisol under different no-tillage systems under southern Brazilian conditions during model validation. Line represents simulated SOC stocks and dots, measured SOC stocks. Error bars represent standard deviations.

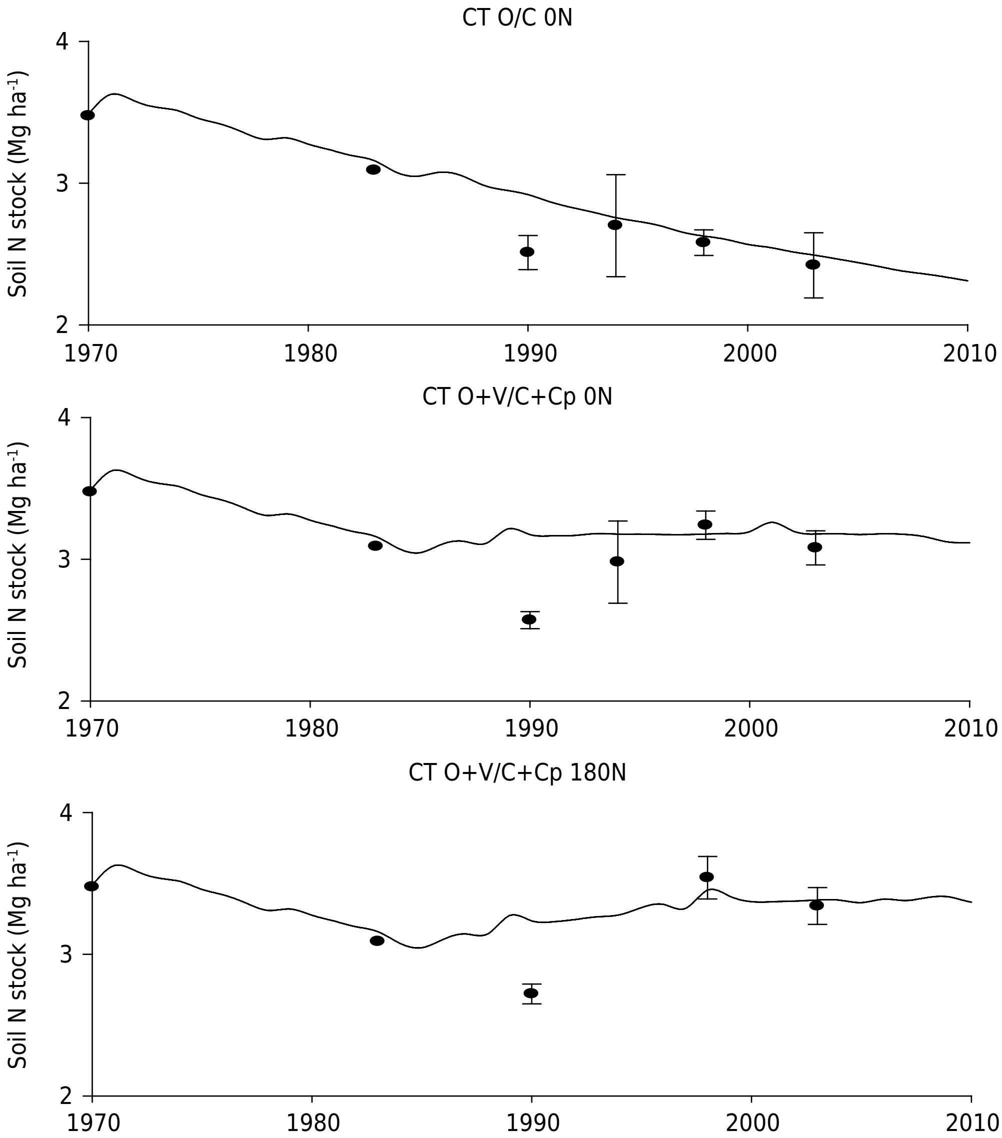

Figure 8. Simulated SON stock dynamics (0.00-0.20 m) in the base and experimental blocks in an Acrisol under different conventional tillage systems under southern Brazilian conditions during model validation. Line represents simulated SOC stocks and dots, measured SOC stocks. Error bars represent standard deviations.

As already noted with SOC stocks, Century underestimated SON stocks in the O/C without N fertilizer under the NT treatment. This treatment had the most marked loss of SOC (and SON). A key factor could be the higher than expected mean grain yield (3.5 Mg ha^{-1} C), whereas the data observed indicates an average yield of 2.5 Mg ha^{-1}. This elevated yield results in a higher than observed N export in grain. Plant uptake of N from soil layers deeper than the simulation layer considered by Century (0.00-0.20 m) could also have influenced C and N stocks. It has been estimated that corn plants take up 11 kg ha^{-1} yr^{-1} N on average from soil below the 0.20 m depth (Weber and Mielniczuk, 2009). The quality and quantity of residue added to soils affect competition and soil microbial activity, two aspects that are superficially treated by the model (Lugato et al., 2006). This interaction of quantity and quality of residue could alter the microbial community and hence the dynamics of C and N stocks (Fontaine et al., 2003). These factors are not represented by the model. Lugato et al. (2007) also observed this underestimation of soil C and N stocks in an N-limited environment. Parton and Rasmussen (1994) overcame this issue by adding a supplemental N supply to crops to attain a satisfactory calibration.

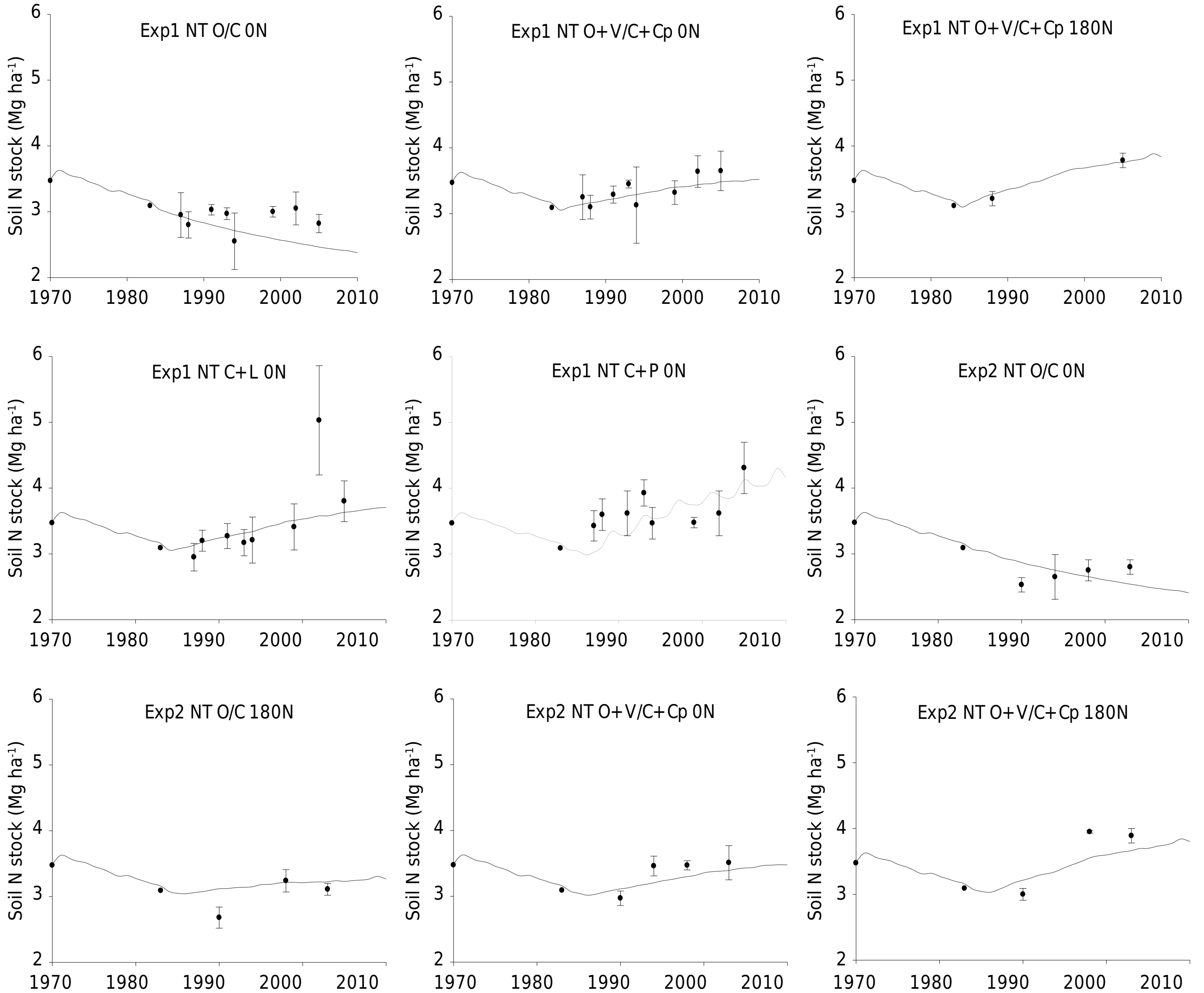

Figure 9. Simulated Soil N stock dynamics in the topsoil layer (0.00-0.20 m) in the base and experimental blocks in an Acrisol under different no-tillage systems under southern Brazilian conditions during model validation. Line represents simulated SOC stocks and dots, measured SOC stocks. Error bars represent standard deviations.

CONCLUSIONS

Soil organic C and N trajectories from contrasting cropping systems in a long-term experiment in southern Brazil were adequately simulated by using Century version 4.5.

The model overestimated SOM decomposition in systems with low N availability. This overestimation may be due to the complexity of the N cycle, not completely represented by the model, because microbial biomass is treated as a compartment of soil organic matter, not as an agent of decomposition.

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