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Ecosystem dynamics of crop–pasture rotations in a fifty-year field experiment in southern South America: Century model and field results

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Abstract

The Century model was used to simulate soil C and N cycling and crop production dynamics in an ongoing field experiment in Uruguay (started in 1963). The model was calibrated using observed data from three treatments (crop or crop–pasture rotations) and validated with a fourth treatment. The model correctly predicted the impact of different treatments on microbial biomass, N mineralization, soil respiration, and crop yields. The model and observed data show that soil respiration, N mineralization, soil C, and crop yields increase with increasing plant-derived C inputs caused by increasing the frequency of pastures in the rotations. This is one of the first papers that show the strong positive correlation of observed soil C with plant C soil inputs to field-observed microbial biomass, soil respiration, and N mineralization. The results also showed that reducing tillage and transitioning to a no-till system increased soil C and reduced soil erosion. The main path of soil C losses was heterotrophic microbial respiration, which accounted for 66% of the total C lost in a continuous crop rotation and no fertilizers, 71% in a continuous crop rotation with fertilizers, and 86% in a crop–pasture rotation with fertilizers. Model results from a degraded cropping system showed that adding grass–clover (*Trifolium* spp.) pastures greatly increased plant production and soil C, whereas reducing the frequency of grass–clover pastures in high-fertility cropping systems from 50% of the time to 25% reduces crop yields and soil C. Including cover crops substantially increases crop production and maintains soil C in high-fertility and degraded cropping systems.

1 | INTRODUCTION

Long-term agricultural experiments have been used extensively to evaluate the impact of crop rotations, organic and inorganic N fertilizer inputs, and tillage practices on crop production, nutrient cycling, and soil C dynamics (Paustian, Parton, & Persson, 1992; Smith et al., 1997). During the 1950s, inorganic N fertilizer became available to farmers at a reasonable price and started to be used by farmers to replace the N removed in harvested crops. Prior to the 1950s, farmers used crop rotations that included N-fixing perennial pastures and manure to replace the N removed by the crops.

Abbreviations: CS, cropping system; INIA, Instituto Nacional de Investigación Agropecuaria; PMN, potentially mineralizable nitrogen; RPG, Rio de la Plata grasslands; SOC, soil organic carbon.

Numerous long-term experiments were started around the world in the 1950s and 1960s to evaluate the consequence of replacing organic N inputs from manure and N-fixing pastures with inorganic N inputs on soil C and crop production (Rasmussen & Parton 1994; Paustian et al., 1992). Many experiments have compared the ecosystem impact of using perennial grass and N-fixing systems (Davis et al., 2012; Duval et al., 2013; Hudiburg, Davis, Parton & DeLucia, 2015; Paustian et al., 1992) with adding inorganic N. These experiments typically show similar crop yields with organic and inorganic N inputs, higher soil N mineralization rates, and larger amounts of N stabilized in the soil with organic N additions, and higher N loss rates for inorganic N additions. Chalhoub et al., 2013 and Palmer et al. (2017) recently showed that a major impact of increases in soil C is the resulting increase in soil N mineralization rates (plant production also increases because of higher available N). Although less documented in the literature, the long-term beneficial effects of rotations of annual crops with pastures include the improvement of soil structure, soil water holding capacity, and, in general, improved soil physical properties, which also contribute to increased crop productivity (Ernst, Dogliotti, Cadenazzi, & Kemanian, 2018).

The results from these long-term agricultural experiments have been used extensively to test the ability of crop growth and ecosystem models to simulate plant production, soil C dynamics, and nutrient cycling (Smith et al., 1997). The Century (Parton, Ojima, Cole, & Schimel, 1994), DayCent (Del Grosso et al., 2001; Parton, Hartman, Ojima, & Schimel, 1998), RothC (Jenkinson, Harkness, Vance, Adams, & Harrison, 1992), and other crop growth and ecosystem models have used the observed data from these experiments to test their ability to simulate the impact of different agricultural practices on crop production, soil C, and nutrient cycling. The Century model has also been used to determine the impact of soil erosion in agricultural systems in the United States (Harden et al., 1999; Manies, Harden, Kramer, & Parton, 2001).

Increased concern about greenhouse gas emissions and global warming in the last few decades have prompted numerous studies on the role of agricultural production systems as net CO_2 sources or sinks. The relationships between soil C net mineralization, soil C sequestration, and atmospheric CO_2 concentration have been the subject of numerous studies that explore soil C balances in agricultural production systems and land use changes (Houghton & Goodale, 2004). Lal (2018) identifies three basic strategies that can augment C sequestration: (a) increasing the input of biomass C, (b) decreasing the losses of soil C by erosion and decomposition, and (c) increasing mean residence time by stabilizing sequestered soil C. The increased pressure for feeding a world population that grows exponentially has caused the conversion of natural ecosystems (grasslands, forests) into croplands with large net losses of soil C. Assessing the impact of agricultural production systems on soil C changes requires data from long-term experiments and simulation models that can evaluate the soil C balances expected with different agronomic practices and cropping systems.

Core Ideas

- Century model adequately simulated C and N dynamics in a +50-yr field experiment.
- Century simulated observed impacts of crop and pasture sequences on components of the C and N cycle.
- Continuous crop sequences resulted in negative soil C balances.
- Inclusion of pastures cover crops and no-till resulted in positive or neutral soil C balances.
- Use of cover crops and pastures increases grain crop plant production.

An experiment was established in 1963 in Estanzuela, western Uruguay to evaluate the impact of tillage, inorganic fertilizer, and crop rotations on crop and pasture production, soil C and N, soil fertility, and nutrient cycling. This experiment continues today and is the longest-running experiment of its kind in Latin America. The Century model (Parton, Schimel, Cole, & Ojima, 1987) was used to simulate the ecosystem dynamics for the different agricultural practices, and model results were compared with observed annual estimates of soil C and N content, soil N mineralization rates, soil microbial biomass, and soil respiration rates for the different treatments. A major factor considered in this experiment is the impact of soil erosion on ecosystem dynamics, since soil erosion rates differ across treatments. The impact of reduced soil erosion rates due to use of reduced tillage (late 1990s to 2009) and of no-till during the last 7 yr has also been evaluated as part of the experiment. The observed plant production data from annual cropping with and without fertilizer, and cropping with 4 yr of annual crops followed by 4 yr of pastures, were used to calibrate the model parameters, whereas the data from the annual cropping followed by 1 yr of pasture were used to validate model results. The Century model is also used to simulate the long-term potential impact and the sustainability of different crop–pasture rotations in Uruguay. The model runs will demonstrate how increasing the frequency of pasture years in the crop rotations will increase soil C and N, N mineralization, and crop yields and will reduce soil erosion rates for degraded Uruguay agricultural land. These scenarios are relevant in Uruguay, where farmers have recently increased the area dedicated to annual crops (especially soybeans) in response to increased crop prices observed in the last 10 yr. The calibration and testing of the Century model

FIGURE 1 Region of southern South America that includes the Rio de la Plata grasslands (RPG) where large areas of grasslands have been converted to crops in the last 60 yr. The red symbol shows the location of the field experiment

in this experiment is also relevant to study the ongoing and expected changes in ecosystem dynamics in the Rio de la Plata grasslands (RPG) where land uses have been changing dramatically in the last few decades. The RPG cover an area of >70 million ha and include southern Brazil, all of Uruguay, and parts of central Argentina (Figure 1). Recent investigations by Baeza and Paruelo (2020) have found a large increase in the area under agricultural intensification (summer crops, winter crops, and double crops), and >5 million ha of new crops have been added to the RPG in the first 15 yr of the current century.

2 | MATERIALS AND METHODS

2.1 | Experimental site

Treatments were selected from a long-term experiment established in 1963 in La Estanzuela Experimental Station (Instituto Nacional de Investigación Agropecuaria [INIA], the Uruguayan National Agricultural Research Institute) located in southwestern Uruguay (34˚20′ S, 57˚41′ W; 82 masl). Annual precipitation in the area is approximately 1,000 mm, almost evenly distributed throughout the year, but with substantial interannual and interseasonal variability. Maximum monthly mean temperature varies from 15 ˚C in the winter to 28 ˚C in the summer, and minimum monthly mean temperature varies from 6 ˚C in the winter to 17 ˚C in the summer. Climatic conditions in the region allow for double cropping and typical production systems consist of four crops in 3 yr. Before the establishment of the long-term experiment in 1963, the soil had been cropped for more than 40 yr (mostly wheat [*Triticum aestivum* L.]–fallow). Dominant soil at the site is a Typic Argiudoll with a slope of about 2.5–3%. Soil chemical and physical properties at the trial establishment and after 51 yr of experimentation are presented in Table 1.

TABLE 1 Soil chemical characteristics at the establishment of the long-term experiment (1963) and in 2015 (0–20 cm)

Year	CS[a]	pH (H_2O)	Total C	Total N	P Bray-I	K	Clay	Sand	Silt
			g m^{-2}			cmol kg^{-1}	g kg^{-1}		
1963	(All)	5.9	5,825	1.9	7.1	0.91	351	88	561
2015	CS-1	6.3	2,687	1.2	1.1	0.56	–	–	–
2015	CS-2	5.7	4,416	1.7	14.6	0.37	–	–	–
2015	CS-5	5.5	5,958	2.1	10.1	0.48	–	–	–

[a] CS, cropping system treatment.

2.2 | Field experiment

The long-term experiment includes seven treatments with different crop sequences, and agronomic input use. The four treatments (cropping systems, CS) selected for our research were:

- CS1: a sequence that includes annual crops only (wheat or barley [*Hordeum vulgare* L.] in the winter and sunflower [*Helianthus anuus* L.] or sorghum [*Sorghum bicolor* (L.) Moench] in the summer) with no fertilizer application.
- CS2: the same crop sequence as CS1 but with N and P fertilizer application.
- CS5: a system that includes 4 yr of annual crops (in the same sequence as CS and CS2) followed by 4 yr of a perennial pasture consisting of a mixture of white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), birdsfoot trefoil (*Lotus corniculatus* L.), tall fescue (*Festuca arundinacea* Schreb.), and ryegrass (*Lolium mutliflorum* Lam.).
- CS4: in 1963–1983, the system included the same crop sequence as in CS1 and CS2 followed by 1 yr of pasture (red clover). After 1983, the system increased the proportion of time under pastures. Sixty-seven percent of time, the soil is covered with the same pasture as the one described in CS5. The remaining 33% of the time the treatment includes the same sequence of annual crops as described above for all cropping systems.

Treatments are arranged in a randomized complete block design with three replications on 25-m by 200-m (0.5-ha) plots. Crop sequences are not synchronized in the three replications and, therefore, the year effect is partially considered by the experimental design. Given the large plot size, the equipment used for tillage, agrochemical application, and harvest is similar to that used by commercial farmers in the region. Conventional tillage was used in the first 20 yr of the experiment, and then in the 1980s, moldboard and disk plows were gradually replaced by the chisel plow. By the mid-1990s, moldboard and disk plow use was eliminated. In 2009, all mechanical tillage operations were eliminated in favor of no-till. A detailed description of the experiment was presented in Baethgen, Díaz, and Bozzano (1980) and in Morón and Díaz (2003). In CS2, CS4, and CS5, annual crops are fertilized with N and P, and pastures are fertilized with P following INIA recommendations based on soil testing.

2.3 | Century model description

We parameterized the Century model to simulate the field trial at La Estanzuela Experimental station in Uruguay. The Century model (Parton et al., 1994) includes plant production, soil C dynamics, nutrient cycling submodels, and water and temperature submodels. The Century model simulates plant production for forest, grassland, savanna, and agricultural cropping systems. The plant production model simulates potential plant production as a function of monthly solar radiation, soil temperature, and the ratio of rainfall to potential evapotranspiration. Carbon allocation to the different plant parts changes as a function of water and nutrient stress (greater fine root production for stressed plants). Potential plant production is reduced if there are insufficient mineral nutrients (primarily N) available for plant growth. The plant production model can simulate the mean values of plant production and crop yields for different treatments but is not as accurate at predicting yearly changes in crop yields because of the monthly time step (daily precipitation is needed to make more accurate predictions of yearly changes in crop yields). The soil C model simulates the flow of C for the soil surface of mineral soils using five soil organic matter pools (structural and metabolic litter, active organic matter, slow and passive soil organic matter). The nutrient cycling submodel simulates mineralization of N, P, and K from decomposing dead plant material and the soil organic matter pools, leaching of organic and inorganic N, P, and K, and uptake of N, P, and K by live plants. Nutrient cycling and soil C dynamics are simulated for the 0-to-20-cm soil depth, which includes the typical plow depth with the highest soil C and N level in the soil profile. The soil water and temperature submodels simulate soil water and temperature dynamics, with the impact of soil temperature and water controlling many of the C and nutrient flows in the model. The Century model uses a monthly time step, and has been tested using extensive observed datasets from grasslands, forests, savannas, and cropping systems around the world (Parton & Rasmussen 1994; Paustian et al., 1992; Smith et al., 1997).

2.4 | Model calibration and validation

The observed crop yield and soil C data from CS1, CS2, and CS5 treatments were used to parameterize crop growth parameters for wheat, barley, sunflower, and sorghum. Observed crop yield and soil C data from CS4 were used to test of the ability of the model to simulate crop yield and soil C. The impact of genetic changes in the crop production during the 50-yr period was represented in the model by altering the maximum growth rate of the crops and the harvest index of the crops. Observed monthly average daily minimum and maximum air temperature; monthly total precipitation from 1963 to 2015; soil sand, silt, and clay content; bulk density; and soil pH were used as inputs to the model. The model was set up to simulate the actual time series of crops sown, timing of the fertilizer events, timing and number of crop cultivation events, and harvest dates since 1963 for the different treatments. This is performed in the Century model using a schedule file that includes the observed dates when events occur. The model runs were initialized using actual historical patterns of land use with (a) grazed grasslands for several thousand years with stochastic weather based on observed data (1915–2015) to reach an equilibrium value of soil organic C (SOC) prior to 1930, (b) an annual wheat–fallow system from 1930 to 1963, and (c) the observed detailed land use for each treatment (one model run for one field replication of each treatment) from 1963 to 2015. The Century-simulated initial SOC content for the first year of the experimental manipulations closely approximated the initial measured SOC content at the site (Table 1). Century version 4.0 was used for this paper, and files used to make the model can be obtained from the Century website (https://www.nrel.colostate.edu/projects/century/).

2.5 | Century model simulations of scenarios

One of the most valuable uses of calibrated simulation models is to assess the expected impacts on cropping systems of possible future scenarios such as variations in production technologies, climate, and shifting land uses. This paper explores changes in the soil C, N mineralization, and crop yields when changing the proportion of time under pasture and annual crops. These scenarios are relevant for Uruguay agriculture where farmers have recently increased the area dedicated to annual crops (especially soybeans) in response to increased grain prices in the mid-2000s. Scenarios are also relevant for the Rio de la Plata Grasslands (RPG), that cover >70 million ha in southern Brazil, Uruguay, and central Argentina, where land uses have been changing dramatically, with increases in agricultural intensification and the addition of >5 million ha of new crops (Baeza & Paruelo, 2020; Figure 1). Questions evaluated in this paper are;

1. Is it sustainable to produce annual crops with no inclusion of pastures in the rotation?
2. What is a reasonable proportion of crops and pastures in a rotation if we want to maximize the crop production and avoid net soil C losses?
3. Starting with a degraded soil, is it possible to significantly restore soil C content by including pastures in rotation with crops?
4. In regions where livestock production is not feasible, and therefore the inclusion of multiyear pastures is not practical, can the soil C content be maintained using cover crops ("green manure"; Fageria, 2007; Pinto, Fernández Long, & Piñeiro, 2017) in rotation with grain crops?

We evaluated these questions by establishing scenarios and running the model for 85 yr (2016–2100) using two starting points: CS2, where only annual crops (no pastures) had been included in the 53 yr of the field experiment, and CS5, where rotations included the same number of years with crops and with pastures. Using those two starting points, we tested five scenarios (all under no-till): (a) continuing the current practice of CS2 of 100% of the time with annual crops fertilized with N and P (CCont); (b) using a sequence with 3 yr of pastures followed by 9 yr of annual crops (C9P3; 25% of the time with pastures, 75% with crops); (c) using a sequence with 3 yr of pastures followed by 6 yr of annual crops (C6P3; 33% pastures, 67% crops); (d) using a sequence of 3 yr of pastures and 3 yr of crops (C3P3; 50% pastures, 50% crops; i.e., continuing the current practice of CS5); and (e) using a sequence of five annual crops alternating with two cover crops (CC) in 4 yr.

2.6 | Soil analyses

2.6.1 | Soil organic C and total N

Soil samples were annually taken from 0-to-20-cm depth in every plot and analyzed to total SOC content. In 1963–2012, SOC was measured using $K_2Cr_2O_7$ and heat, as described by Tinsley (1950). Since 2012, SOC was measured using dry combustion (900 ˚C) on a LECO analyzer (Wright & Bailey, 2001). The values obtained with LECO were corrected to be comparable with Tinsley values using a factor of 0.81 obtained with a regression analysis with previous samples. Total soil N content was determined with sulfuric acid digestion, distillation with micro Kjeldahl, and titration, as described by Bremner (1965).

2.6.2 | Soil C mineralization in the field

Carbon mineralization rates under field conditions were determined daily for 14 d during two periods: one in spring and one in winter 1992 (Morón & Baethgen, 1994), based on the methodology described by Anderson (1982). Two areas measuring 1.5 m × 22.4 m were marked in two replications of each cropping system, and the plants in those areas were hand removed a few weeks before the experiment started. Ten mineralization determinations were performed daily in each plot for the four cropping systems. Metallic cylinders (0.25-m diameter and 0.28-m height) were placed in the soil (0.03 m deep). One glass beaker containing 1 M NaOH was placed inside each cylinder to trap the CO_2 evolving from the soil. Each day, the excess NaOH in the beakers was titrated with HCl to determine CO_2, and the beakers were replaced with new NaOH solution. The same procedure was used to determine the CO_2 present in the air by placing NaOH beakers inside closed cylinders, which were not in contact with the soil. Soil temperature was monitored daily with geothermographs placed at 0.05-m depth. Soil moisture content was determined gravimetrically.

2.6.3 | C and N content in the soil microbial biomass

Soil samples from the top 20 cm obtained from each of the cropping systems at five different dates (two in the winter, two in the spring, and one in the summer) were used to analyze C and N content in the soil microbial biomass (Garcia & Morón, 1992). Methods for soil incubations were based on Jenkinson and Powlson (1976). Carbon determinations used the method described by Cerri, Galdos, Carvalho, Feigl, and Cerri (2013). Nitrogen determinations were based on Brookes, Landman, Pruden, and Jenkinson (1985).

2.6.4 | Nitrogen mineralization potential

Potentially mineralizable N (PMN) was determined anaerobically (Morón & Sawchik, 2002), by waterlogged incubation at 40 ˚C for 7 d in wet-sieved soil samples, following the methodology recommended by Bundy and Meisinger (1994). An equivalent of 5 g of oven-dry soil was placed in a 25-ml glass tube with 12.5 ml of distilled water, then sealed and incubated at 38 ˚C for 7 d. At the end of the incubation period, the solution was transferred to 125-ml plastic flasks, and 12.5 ml of 4 M KCl was added. The supernatant was then filtered (Whatman 1 filter paper) and NH_4–N was determined using colorimetric analysis with sodium salicylate according to Mulvaney (1996). Nonincubated soil was used to determine initial NH_4–N content. The PMN was calculated as the difference between the NH_4–N at the end of the incubation and the initial NH_4–N value. These PMN measurements were made for winter 1999 (Morón & Sawchik, 2002), and for one annual value for each fall season of 2010–2015.

2.7 | Soil erosion losses

Soil erosion losses from each cropping system were estimated using results from runoff plots established in the experiment (García Préchac & Baethgen, 1982), and reviewed with runs of the U.S. Soil Erosion Loss Equation (RUSLE) in the 1990s (García Préchac, 1992) and in 2010 (Pérez Bidegain, García Préchac, Hill, & Clérici, 2010). This information provided the estimated mean annual soil and SOC losses for each cropping system in different periods of the experiment, as affected by crop rotations and by soil tillage practices (conventional, reduced, and no till). The observed values of soil erosion losses were used as inputs to the Century model for the different treatments.

Soil tillage practices changed throughout the lifespan of the experiment: during the 1960s and 1970s the typical practices included the use of moldboard plow (one or two passes), disk harrow (two or more passes), and tooth harrows. The objective of those tillage systems was to obtain a seedbed that was fine to improve the contact of the soil with the seeds. Given that the pasture seeds are typically smaller than the seeds of annual crops, tillage operations were even more intensive when preparing the soil for sowing pastures. Given this, and the relatively high frequency of rainfall events of 50–100 mm in one day in Uruguay, the erosion losses were substantial in the early stages of the experiment (García Préchac, 1992). In the 1980s, given the observed soil erosion losses, the moldboard plow was gradually eliminated and substituted with chisel plows. The disk harrows were also eliminated, and the total number of tillage operations was reduced. Consequently, during the 1980s and 1990s, soil erosion losses in the experiment were considerably reduced. In 2009, all conventional tillage operations were eliminated and crops and pastures in all treatments were sown using no-till.

3 | RESULTS

3.1 | Calibration and testing

Figure 2 compares observed and simulated crop yields for wheat, sorghum, and sunflower for the different treatments (10-yr averages for each decade, to account for asynchronous crop rotations), whereas Figure 3 compares mean simulated and observed crop yield of wheat, sorghum, and sunflower for the different treatments. The Century model effectively ($r = .85$, $P < .01$) simulated crop yields with sorghum having

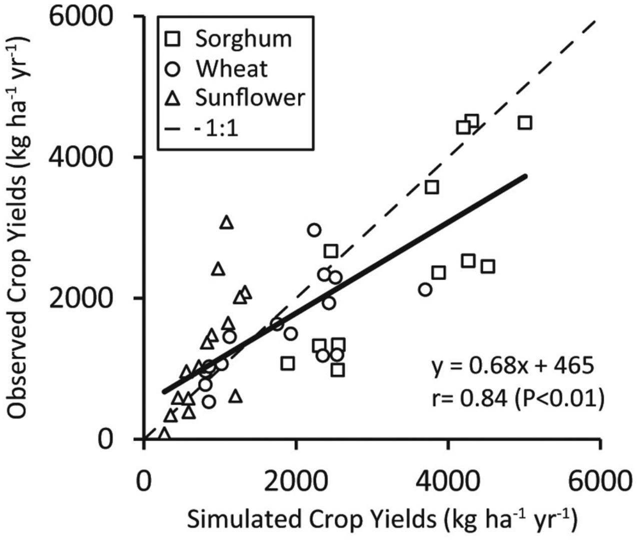

FIGURE 2 Comparison of observed and simulated 10-yr average grain yields for sorghum, wheat, and sunflowers for CS1, CS2, and CS5 model runs from 1965 to 2015

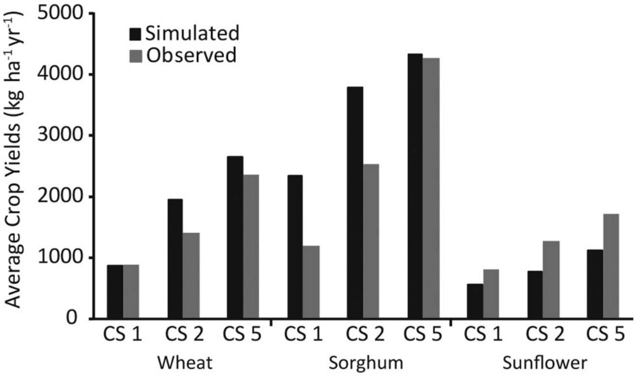

FIGURE 3 Comparison of simulated and observed mean (1965–2015) crop yield for sorghum (SG), wheat (W), and sunflower (SF) for CS1, CS2, and CS5 treatments

the highest yields followed by wheat and sunflowers. Both the model and observed data (Figure 3) show that crop yields are lowest for the CS1 treatments, higher for the CS2 treatments, and highest for the CS5 and CS4 treatments. It is unclear why the model tended to overestimate mean sorghum total biomass in CS2 and CS1 (Figure 3). These results show that adding inorganic fertilizer to the CS1 treatment greatly increases crop yields (78% increase), whereas adding grass–clover pastures to the fertilized crop rotation system (CS2) enhances crop production (58% increase for CS5 compared to CS2, Figure 3). Higher crop yields for the grass–clover rotations is a result of increased plant C soil inputs (grass–clover root inputs) and increased N inputs from clover plant N fixation. Increased observed crop yields in the systems with grass–clover rotations are also likely due to improved soil structure and higher water holding capacity (Ernst et al., 2018). Although the model does not take into account the effect of soil physical properties, it correctly simulated observed crop yields and pasture biomass production as a function of time for the CS5 treatment except for the overestimate of grass production from 1985 to 1995 (Figure 4). The ability of the model to simulate observed crop yields and biomass production is important, since this indicates that the model correctly simulates differences in C inputs of the different treatments.

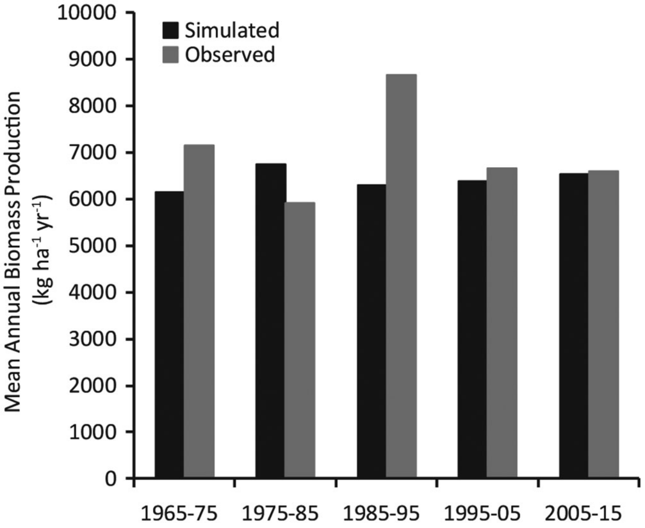

FIGURE 4 Comparison of observed and simulated grass–clover mean annual biomass production for the CS5 treatment

The Century model is not intended to simulate interannual variability of crop grain yields accurately; it basically estimates the reduction in a potential user-defined grain yield due to water and N limitations. The genetic improvement of the crops simulated in our study was partially considered. For example, we used “old” crop cultivars for the period 1960–1980 and “new” crop cultivars for simulations after 1980. Thus, our model runs were not set to simulate the gradual improvement of crops due to plant breeding. However, most of the genetic improvement of crop yields in the study period was achieved by adding resistance to crop diseases and to increasing the harvest index (i.e., the proportion of grain of the total biomass production). Therefore, the amount of total biomass in the cropping systems has probably not changed considerably, and that contributed to the adequate performance of the Century model to simulate grain yields. Comparison of the efficacy of crop yield simulations for CS4 (validation treatment) is similar to the calibrated simulations ($R^2 = .71$ vs. .68 for the calibration and validation treatments, respectively).

The Century model effectively simulated the changes in SOC in the three contrasting cropping systems (Figure 5a). Treatment CS1 showed continuous loss of SOC throughout the 53 yr of the experiment and ended with almost 40% less soil C than at the start of the experiment. On the other hand,

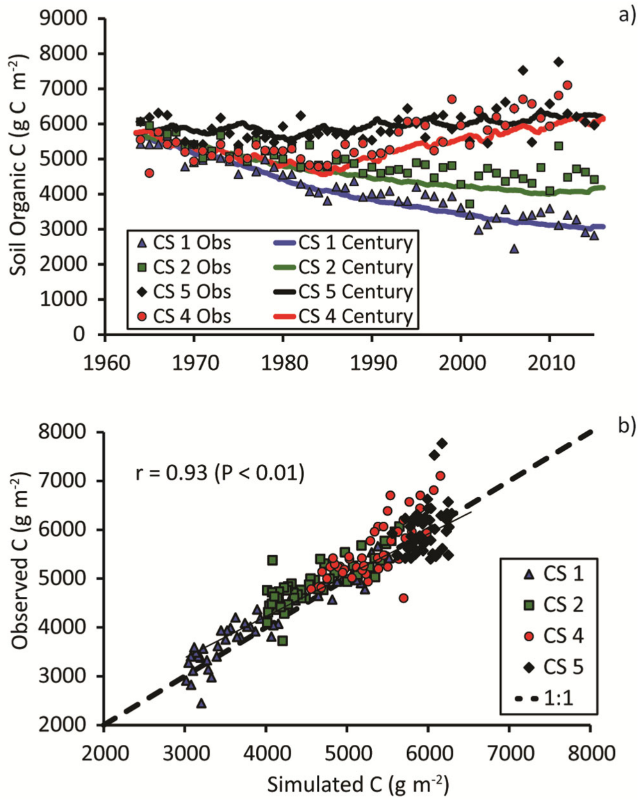

FIGURE 5 (a) Comparison of observed (points) and simulated (lines) time series of soil C levels from 1965 to 2015 for the CS1, CS2,CS4, and CS5 treatments, and (b) simulated vs. observed point comparision for all of the treatments ($r = .93$, $P < .01$)

CS2, which only differed from CS1 in the use of N and P fertilizers, lost ~20% of the original SOC and tended to stabilize in the last 10 yr when no till was introduced. Finally, the simulations of CS5, the cropping system that included a crop–pasture rotation, gained SOC during the pasture stages and lost SOC during the crop stages (Figure 5a). As shown in Figure 5b, the general correspondence of the observed with the simulated SOC was high ($r = .93$, $P < .01$). The results from the CS4 treatment (validation treatment) showed that model did a similar job for simulating soil C dynamics as shown in the other treatments (correlation between observed and simulated SOC in CS4 was .75, $P < .01$).

Figure 6 shows the simulated time changes of modeled annual C inputs for the four treatments, which show large differences in treatments and large changes with time. Results show that C inputs are lowest for CS1, and 40% higher for CS2 compared with CS1, whereas CS4 and CS5 (pasture rotation treatments) have much higher C inputs than CS1 and CS2 (300–500% higher). A detailed analysis of the results shows that annual crop C inputs for all treatments are highest for sorghum, followed by wheat, and is lowest for sunflower. The highest annual C inputs occur after the plowing of the pastures prior to planting the annual crops for CS4 and CS5. The high soil C inputs for CS4 and CS5 are a result of C inputs from the pasture component of the rotations. Analysis of observed soil C (5-yr average values from 2006 to 2015) with the simulated C input shows that soil C is highly correlated to plant C inputs ($r = .84$, $P < .01$).

Comparison of field-measured and simulated soil microbial biomass and soil respiration rates (Figure 7a) shows a good performance of the model with lowest values for the CS1 treatment, intermediate for CS2, and much higher values CS5. Figure 7b shows that observed soil respiration rates increase with increasing soil temperatures for all treatments. These patterns are consistent with the simulated large increases in C inputs to the system going from CS1 to CS5 treatments. Theoretically, we would expect that soil respiration rates and microbial biomass increase with increasing soil C input rates. The simulated increases in plant C inputs are a result of the increases in plant production going from CS1 to CS5 treatments.

The Century model was also able to simulate the soil N dynamics, demonstrated by the high correlation found between observed PMN and the model simulated annual net N mineralization rates (Figure 8, annual accumulator of net mineralization for N from all compartments in g N m^{-2} yr^{-1}). Both observed N mineralization and model results show that the lowest N mineralization rates are found in CS1 and highest rates are found in the CS5 treatments. As expected, the simulated N mineralization rates in CS1 and CS2 were low, whereas the values for CS5 were higher. However, the observed and simulated mineralization rates were significantly correlated for all cropping systems ($r = .80$, $P < .05$). The model results suggest that the increase in net N mineralization from CS1 to CS2 are a result of adding fertilizer to the CS2 treatment, whereas the high net N mineralization rates for CS5 are caused by N fixation associated with growing grass–clover pastures. Recent model studies (Palmer et al., 2017) show that the main impact of increasing soil C is to increase plant production and soil N mineralization rates. Results from this study show that the observed field net N mineralization is highly correlated with soil C respiration ($r = .8$, $P < .05$, Figure 8b) and that plant production increases with increasing net N mineralization (CS1 < CS2 < CS5, Figure 8).

We calculated the net annual C inputs and losses simulated by the Century model to evaluate the change in system C from the start of the experiment (1963) until 2015. Figure 9a shows the average annual inputs (net C inputs due to plant production) and net C losses (heterotrophic microbial respiration plus soil erosion) for the three treatments, whereas Figure 9b shows the partitioning of average annual C loss between erosion and respiration. Total system C inputs and losses increases from the CS1 treatment (lowest values) to the CS5 treatment (highest values). The CS1 and CS2 treatments have negative long-term changes in soil C (i.e., C losses

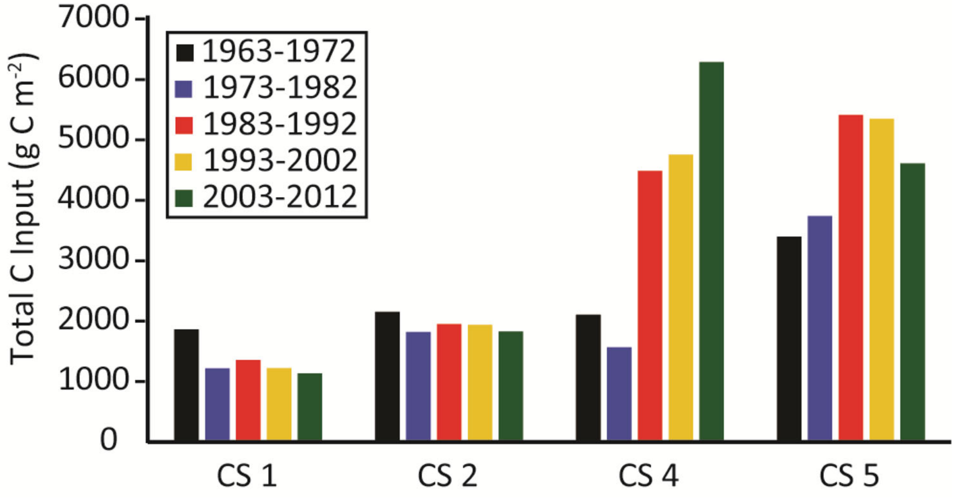

FIGURE 6 Century model simulated annual C inputs (g C m^{-2} yr^{-1}) for CS1, CS2, CS4, and CS5 treatments

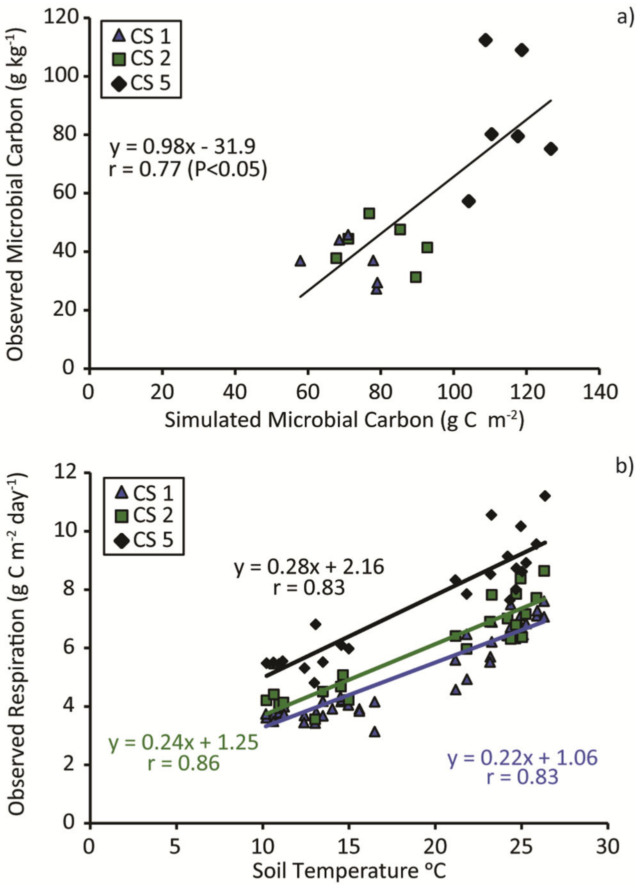

FIGURE 7 (a) Observed microbial biomass vs. Century-simulated microbial biomass. (b) Relationship of soil temperature with observed field estimated soil respiration rates

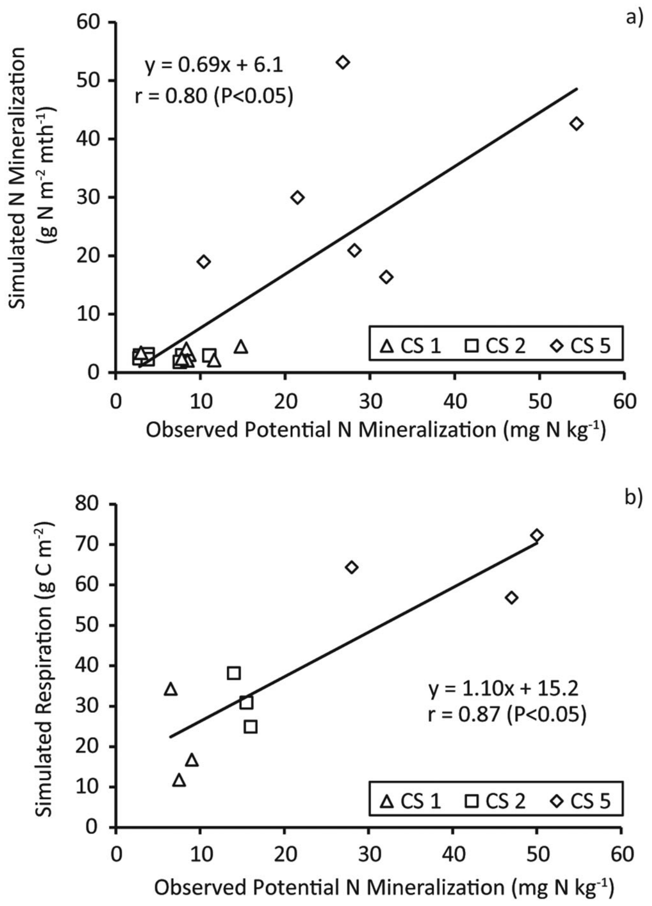

FIGURE 8 (a) Observed field N mineralization rates vs. Century simulated annual N mineralization rates and (b) observed potential net N mineralization vs. Century-modeled soil respiration from 2009 to 2014

are greater than C inputs), whereas CS5 has a slight positive increase in C (higher C inputs compared to C losses). The increasing values of heterotrophic respiration C loss going from CS1 to CS5 is a result of increasing C inputs from plant production with highest C inputs from the pasture component of the CS5 rotation. The C erosion losses (Figure 9b, Table 2) are highest for the CS1 treatment with 34% of the

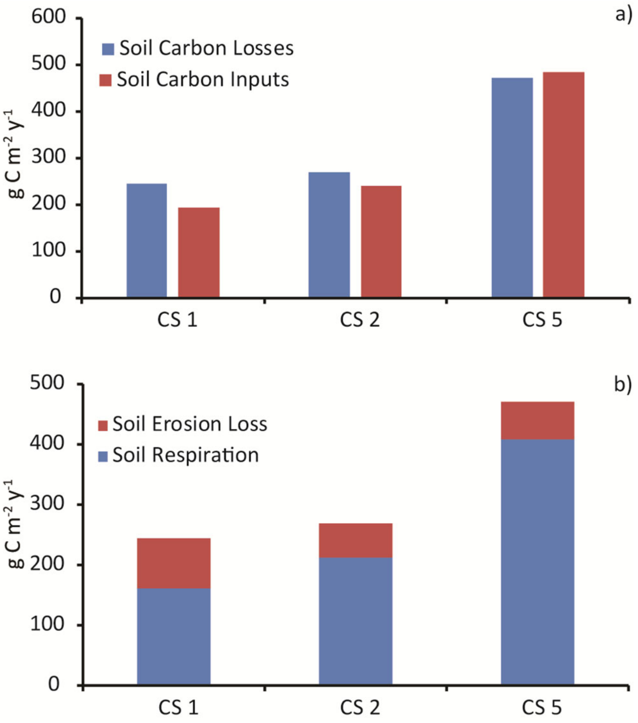

FIGURE 9 (a) Century-simulated total C balance per year for CS1, CS2, and CS5 treatments. (b) Century-simulated respiration and erosion losses per year for CS1, CS2, and CS5 treatments

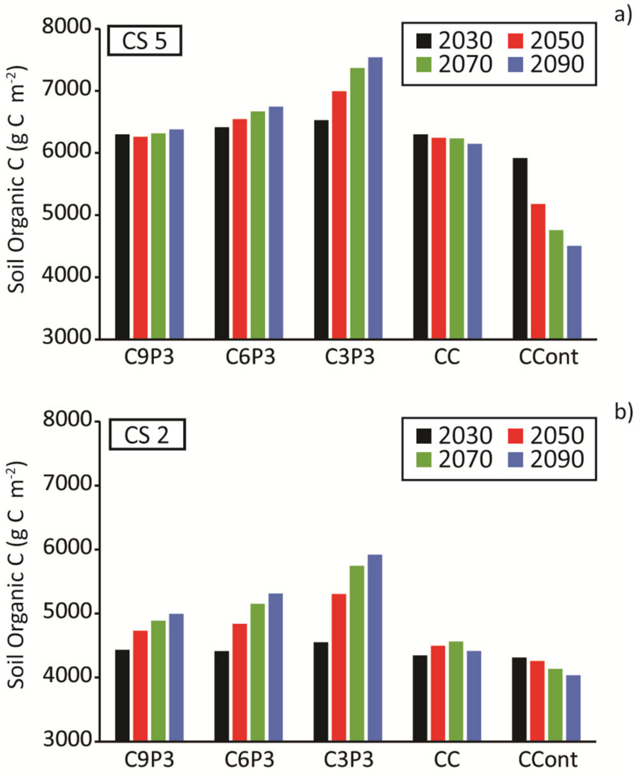

FIGURE 10 Century-simulated soil organic C (2015–2100) for CS5, with 50% of the time in pastures and 50% in crops (Panel a), and for CS2 (Panel b), where no pastures had been included in the field experiment, leading to degraded soil conditions. We tested four future scenarios: a sequence with 3 yr of pastures followed by 3 yr of annual crops (C3P3); a sequence of 3 yr of pastures and 6 yr of crops (C6P3); a sequence of 3 yr of pastures and 9 yr of crops (C9P3); and using a sequence of annual crops alternating with cover crops (“green manure”) (C5CC2). All systems under no-till and annual crops are fertilized with N and P, and all pastures are fertilized with P

net C loss coming from erosion, whereas for the CS5 treatment, only 13% of the C loss comes from erosion. Key results from this analysis indicate that most of the C inputs to the system are lost due to heterotrophic respiration and that C losses from soil erosion have a substantial impact on the C budget for the CS1 treatment.

3.2 | Scenario simulations

We simulated changes in soil C and crop yields in two contrasting cropping systems (CS5 and CS2—high and low initial soil C levels) when the proportion of time under pasture vs. annual crops was changed, and cover crops were added to the crop rotations. Simulated scenarios (Figure 10, Table 3) extending the model results for CS5 indicate that soil C increased slowly (C3P3 results for CS5), whereas increasing the frequency of annual crops from 50 to 75% showed that soil C was lower compared with the rotation of equal number of years of annual crops and pastures. Eliminating the

TABLE 2 Estimated erosion losses, C gains, and balance in five decades of the experiment

	CS[a] 1			CS 2			CS 5		
Decade	**Erosion**	**Gains**	**Balance**	**Erosion**	**Gains**	**Balance**	**Erosion**	**Gains**	**Balance**
	g C m^{-2}								
1960–1970	843	177	−666	574	93	−480	364	279	−85
1970–1980	1227	459	−768	979	423	−556	945	712	−234
1980–1990	872	306	−565	663	310	−353	398	671	273
1990–2000	778	361	−417	363	158	−205	700	634	−66
2000–2010	477	185	−293	240	28	−212	392	548	157

[a] CS, Cropping system treatment.

TABLE 3 Century model simulation for 100 yr in CS2 and CS5, for five scenarios: (a) using a sequence with 3 yr of pastures followed by 3 yr of annual crops (C3P3); (b) using a sequence of 6 yr of crops and 3 yr of pastures (C6P3); (c) using a sequence of 9 yr of crops and 3 yr of pastures (C9P3); (d) using a sequence of 4 yr of crops including cover crops (CC); and (e) using a sequence of only annual crops (CONT—no pastures and no cover crops). Results are shown for the average grain yields during grain producing years, total grain production during a 100-yr time period, total C inputs from aboveground plant biomass during a 100-yr time period, and total C inputs from belowground biomass during the 100-yr time period

Scenario	Avg. grain yield	Total grain production	Total C input aboveground[a]	Total C input belowground[b]
	$g\ C\ m^{-2}\ yr^{-1}$	$g\ C\ m^{-2}$ in 100 yr		
CS2 (a)	175	8,750	23,000	14,600
CS2 (b)	142	9,514	19,238	11,508
CS2 (c)	136	10,200	18,575	10,750
CS2 (d)	140	10,220	19,114	8,003
CS2 (e)	96	9,600	12,400	6,600
CS5 (a)	196	9,798	24,725	15,849
CS5 (b)	161	10,769	21,174	12,589
CS5 (c)	143	10,713	19,295	11,166
CS5 (d)	146	10,658	19,862	8,337
CS5 (e)	100	10,002	9,856	2,448

[a] Crop stover + pasture + cover crops (i.e., all biomass that remained on soil) in 100 yr.

[b] Total root biomass produced in 100 yr.

pastures (CCont model run for CS5, Figure 10) caused soil C levels to decrease rapidly, whereas adding the cover crops (CC) maintained similar levels of soil C comparable with model runs with 67% crops/33% pastures, or 75% crops/25% pastures. The results for the CS2 runs showed that adding pastures greatly increased soil C (Figure 10), with larger increases for higher pasture frequency (C3P3). Also, adding cover crops in CS2 (CC) maintained soil C levels, whereas soil C slowly decreased for the model run without pastures (CCont). Adding grass–clover pastures either 33 or 50% of the time to the CS2 (the system that included only fertilized crops and no pastures) increased soil C by >2,000 g C m^{-2}. Decreasing the frequency of pastures from 50 to 0% for the CS5 runs (high initial soil C levels) caused a decrease in soil C levels with substantial losses of soil C for the no-pasture rotation run.

Table 3 shows the impact of five cropping practices (CCont, CC, C3P3, C6P3, and C9P3) on average grain yields during cropping years, total grain yields for 85-yr runs, and total C inputs from aboveground and belowground sources for the 85-yr runs for CS2 and CS5. The results show that increasing pasture frequency causes >50% increases in average grain yields during cropping years for CS2 and CS5 runs and that adding cover crops (CC) to the CCont run (no pastures or cover crops) results in >50% increases in average grain yields during grain production years for both CS2 and CS5 runs, with average crop yields being similar for CC and C9P3 runs. Increased crop yields associated with adding grass–clover pastures are caused by higher N inputs associated with pasture N fixation. Maximum total grain production (expressed as 100-yr cumulative values) occurs for the CC and C9P3 runs for the degraded soils (CS2), whereas total grain production increases with decreasing pasture frequency from 50 to 25% for the CS5 runs. The results for the total aboveground and belowground C inputs to the system for CS2 and CS5 greatly increase (>100%) with increasing pasture frequency from 0% to 50%, and including cover crops greatly increases (30 to 200%) both belowground and aboveground carbon inputs to the system. Surprisingly, increasing pasture frequency for degraded fertilized crop rotations (CS2) not only increased soil C but also increased total accumulated grain crop production despite a reduction in the frequency of years when crops are grown in the rotation. Also, reducing the frequency of grass–clover pastures for the high initial soil C run (CS5) from 50 to 25% results in greater total grain production because of the higher frequency of growing crops. As stated before, the higher proportion of pastures in the rotation would also improve the soil physical properties, and this probably would contribute to increased grain yields in the scenarios that we simulated.

4 | DISCUSSION

The Century model was used to simulate the ecosystem dynamics of a long-term agricultural experiment at La Estanzuela site in Uruguay (1963–2015). The simulated plant production and soil C results were compared with the observed data from treatments CS1, CS2, CS4, and CS5. The results (Figures 2, 3, and 4) show that the model performed well in simulating soil C (Figure 5, $r = .93$, $P < .01$), pasture production (Figure 4), and crop yields ($r = .85$, $P < .01$, Figure 2). The correlations between observed and simulated crop production and soil C for CS4 (not used to calibrate the model) were similar to those of the treatments used to calibrate the model (CS1, CS2, and CS5). Both model results and observed data showed that the plant production and soil C were lowest for CS1, intermediate for CS2, and highest for CS4 and CS5. The general agreement of simulated crop yield data with observed data indicates that the model correctly simulated the relative treatment increases in soil C inputs going from CS1 to CS5.

The observed dataset from the Uruguay site includes process-oriented observations of microbial biomass, soil C respiration rates, and soil N mineralization. The model results and observed data show that microbial biomass makes up less than 2–3% of the total soil C, and that microbial biomass increases with fertilizers (CS1 vs. CS2) and is highest when pastures are included in the rotation (CS5). The field measured soil respiration and model respiration results show a similar increase from CS1 to CS5 treatments. The model results suggest that the increase in microbial biomass and soil respiration are a consequence of the increase in soil C inputs from plant production. The observed and simulated net N mineralization rates increased with increasing inputs of C and N, with lowest values in CS1, intermediate in CS2 because of added fertilizer, and highest in CS5 because of fertilizer N inputs and symbiotically fixed N from the pasture component of the rotation. The results also suggest that the Century model correctly simulates the impact of increasing soil C and N inputs on soil N mineralization, microbial biomass, soil respiration rates, and plant production. This ability to simulate components of the soil C and N dynamics increases the robustness of the model results and the suitability for using Century to simulate scenarios that are different from those used for its calibration (e.g., changing the cropping intensity, years with pastures, etc.).

Total C input in CS5 (that included pastures) were twice as large as the corresponding to treatments with no pastures: 484 g C m^{-2} yr^{-1} in CS5 vs. 193 and 239 g C m^{-2} yr^{-1} in CS1 and CS2, respectively. The total C losses (sum of respiration and soil erosion) were also much higher in CS5 than in CS1 and CS2 (471, 245, and 269 g C m^{-2} yr^{-1}, respectively). Thus, only CS5 showed a net mean C gain of 13 g C m^{-2} yr^{-1}, whereas CS1 and CS2 had net C losses of 30 and 52 g C m^{-2} yr^{-1}, respectively (Figure 9a). Observed erosion rates (García Préchac, 1992; García Préchac & Baethgen, 1982; Pérez Bidegain et al., 2010) were used as inputs for the different treatments, and C loss from erosion in the CS1 treatment was almost twice as large as that in treatments CS2 and CS5 (Figure 9). The erosion losses in CS2 and CS5 were similar due to the soil preparation for sowing pastures in CS5 under conventional tillage that required the use of many tillage operations to produce a fine seedbed and resulted in high risk of soil erosion losses. The model results reveal that the fraction of C loss from erosion was greater than 30% for the CS1 treatment and less than 15% in the CS5 treatment. The net C balance from the Uruguay experiment after 53 yr (net changes from 1963 to 2015) indicates that there is a net C loss from CS1 and CS2, and a slight gain in C in CS5. The results for CS5 suggest that there are large C inputs from pasture biomass production, but most of that C is lost due to soil microbial respiration.

Also noteworthy are the results of general higher soil erosion losses in the decade 1970–1980 as compared with the rest of the study period. Two factors have probably contributed to those increased losses in the 1970s. On the one hand, the winter trimester is the time of the year with highest risk of erosion because, under conventional tillage, soils have little or no residues covering the surface—that is, evapotranspiration is low and water runoff is high. The winter trimester of the 1971–1980 decade was the wettest of the six decades of our study (283 mm vs. the average of 220 mm). Also, in that same decade, there was an increased number of tillage operations, 26 and 16% higher than in the previous and following decades, respectively.

The results from this study are similar to other Century studies (Harden et al., 1999; Manies et al., 2001), which show that soil erosion can greatly increase soil C losses and reduce soil N mineralization rates. The results of this experiment would have been quite different if erosion losses had been reduced from the start. For example, based on the estimated soil C balances shown in Figures 8a and 8b, cutting the erosion losses by one half would have resulted in an almost neutral soil C balance in CS2 and in much higher net C gains in CS5. The unique characteristic of this paper is that the Century model was able to correctly simulate the impact of adding perennial grass–legume pastures to annual crop production systems, and N mineralization along with the impact of soil erosion on ecosystem dynamics.

Recent model results (Palmer et al., 2017) suggest that the main impact of increasing soil C in agricultural systems consists of increasing N mineralization and plant production. The field and model results from this study support these conclusions with observed field N mineralization, soil respiration rates, and crop yields all increasing with increasing soil C. The results in this study are among the first to show the strong correlation of soil C to net N mineralization using field observed N mineralization data. Rasmussen and Parton (1994) found that one of the major controls on agricultural soil C is the amount of C added to the soil with a positive correlation of C inputs to soil C. The results from this study confirm these results showing a strong correlation of observed soil, soil respiration rates, and microbial biomass to C inputs (primarily caused by adding grass–clover pastures to crop rotation systems). We expect that, in addition, the impact of increased C on improving soil structure, root development, and water holding capacity also contributed to increased crop productivity in the cropping systems that included grass–clover pastures.

The simulations of the scenarios presented in Figure 10 have important practical implications for Uruguay and the entire RPG region (see Figure 1). In the mid-2000s, grain prices increased drastically and farmers increased the area sown to annual crops. This was especially true for soybeans in Uruguay that increased from about 10,000 ha sown area in 2000 to more than 1,000,000 ha by 2015 (DIEA, 2017). This increased cropped area resulted in changes in the crop–pasture rotations, and some farmers started systems with continuous crops. The scenarios we simulated show that in well-managed soils (CS5 treatment), increasing the fraction of years with crops from 50 to 75% of the time (with grass–clover pastures during the other years) causes soil C to be unchanged with a 9% increase in total crop production even when average crop yields are decreased by 27%. These results contrast with our simulations for degraded soils such as that in CS2 with a history of >50 yr of continuous crops, where we find large (>40%) increases in average crop yields, and concomitant increases in soil C resulting from increasing the frequency of grass–clover pastures to 33 or 50% of the time. Thus, in CS2, we observe an absolute increase of 17% in total accumulated crop production and a 180% increase in mean annual crop yields in the rotations that include grass–clover pastures 50% of the time. These results lead us to suggest that adding grass–clover pastures to degraded cropping system will increase crop production in Uruguay, with the added positive impact of increasing soil C and N mineralization rates. The results also show that it would require about 60 yr of a cropping system with equal amounts of pastures and annual crops (maize, soybeans, sorghum, wheat, and barley) to recover the soil C content that was present at the beginning of the experiment for the CS2 treatment.

Many of the regions in the Rio de la Plata cropping zone do not have the ability to add grass–clover pastures because of the lack of grazing animals. Our results from the cover crop runs show that adding cover crops greatly increases crop yield by about 45% for both the CS2 runs (low initial soil C) and the CS5 runs (high initial soil C), when compared with continuous crops. Adding cover crops both increases crop yields and maintains soil C at the levels observed at the beginning of the model runs. These results suggest that adding cover crops to regions where it is not practical to add multiyear grass–clover pastures is a viable way to increase grain crop yields and maintain soil fertility.

5 | CONCLUSIONS

The Century model effectively simulated observed soil C in four contrasting cropping systems in an experiment with more than 50 yr of annual observed data. Several measures of soil C dynamics (soil microbial biomass, total soil C, soil C mineralization rates, N mineralization, and crop and pasture yields) were also successful, supporting the robustness and credibility of the simulations. Our results highlight the importance of including grass–clover pastures in crop rotations in Uruguay and in similar environments of the Rio de la Plata Grasslands (RPG), with large increases in C and N inputs and concomitant increases in crop yields, soil N mineralization rates, and soil C. Even in degraded cropping systems, crop production can be increased in RPG by adding grass–clover pastures. The results also show that in RPG regions where it is not feasible to add grass–clover pastures, cover crops can increase crop yield and maintain soil C. This research was conducted in the oldest ongoing field experiment of Latin America and highlights the value of maintaining long-term experiments for calibrating and testing simulation models such as Century that can then be used to assess the sustainability of different options for agricultural intensification that would otherwise require decades of field experimentation.

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AUTHOR CONTRIBUTIONS

Walter E. Baethgen: Conceptualization; Formal analysis; Investigation; Writing-original draft; Writing-review & editing

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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