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Review

Soil Quality Impacts of Current South American Agricultural Practices

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Abstract: Increasing global demand for oil seeds and cereals during the past 50 years has caused an expansion in the cultivated areas and resulted in major soil management and crop production changes throughout Bolivia, Paraguay, Uruguay, Argentina and southern Brazil. Unprecedented adoption of no-tillage as well as improved soil fertility and plant genetics have increased yields, but the use of purchased inputs, monocropping *i.e.*, continuous soybean (*Glycine max* (L.) Merr.), and marginal land cultivation have also increased. These changes have significantly altered the global food and feed supply role of these countries, but they have also resulted in various levels of soil degradation through wind and water erosion, soil compaction, soil organic matter (SOM) depletion, and nutrient losses. Sustainability is dependent upon local interactions between soil, climate, landscape characteristics, and production systems. This review examines the region's current soil and crop conditions and summarizes several research studies designed to reduce or prevent soil degradation. Although the region has both environmental and soil resources that can sustain current agricultural production levels, increasing population, greater urbanization, and more available income will continue to increase the pressure on South American croplands. A better understanding of regional soil differences and quantifying potential consequences of current production practices on various soil resources is needed to ensure that scientific, educational, and regulatory programs result in land management recommendations that support intensification of agriculture without additional soil degradation or other unintended environmental consequences.

Keywords: soil degradation; erosion; soil organic matter; no-till; agricultural intensification

1. Introduction

Our global population is anticipated to be 8.1 billion in 2025 and 9.6 billion by 2050, with most of the growth occurring in developing countries [1] and urban settings [2]. In addition to population growth, the global Gross Domestic Product (GDP) is expected to grow at a rate of 2.1% year^{-1} from 2005/2007–2050 [3]. Collectively, population growth, increased per capita income, and the resultant anticipated dietary changes (*i.e.*, more meat and dairy consumption) are expected to increase global crop demand by 100%–110% by 2050 [4].

Meeting this global crop demand may be challenging because agricultural production, which grew 2.2% year^{-1} between 1987 and 2007, is projected to increase at only 1.3% yr^{-1} between 2005/2007 and 2050 [3]. This estimate was supported by Ray *et al.* [5] who studied long-term yield trends for maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* (L.) Merr.). Those four crops represent two thirds of the total agricultural calorie demand. Their study [5] analyzed crop yield data from 1989–2008 and projected yields to 2050 using 2008 as the baseline year. The projections indicated global average increases of 1.6%, 1.0%, 0.9% and 1.3% year^{-1} for maize, rice, wheat, and soybean, respectively. These values are well below the 2.4% year^{-1} crop yield increase needed to double current production by 2050.

Fortunately, there are several ways to increase agricultural production. Crop yields can be increased through genetic improvement and perhaps by increasing the amount and types of chemical input. Total production can be increased through more intense land use by reducing the amount of fallow, increasing the number of crops grown per year, and by cultivating new agricultural land. These options were supported by an FAO study [3] that predicted 80% of the future crop production increases will come from developing countries, with 71% of the increase coming from yield increases, 8% through higher cropping intensity and 20% by the addition of arable land.

A portion of the increasing global demand for oil seeds and cereals has been met by increasing the cropping area and converting from conventional tillage (CT) to no-till (NT) throughout Argentina, Bolivia, southern Brazil, Paraguay and Uruguay during the past 50 years. Increases in cropping area have been accompanied by changes in land tenancy, tillage practices, and greater overall productivity, but it has also contributed to a loss of crop diversity (*i.e.*, conversion of long-term perennial pastures to grain crop rotations or even monocultures). The transition from CT to NT throughout the region was initially characterized as a tremendous soil management success, but more recently it has been challenged because of the unprecedented expansion of cropland, devoted solely to soybean production, into marginal areas. Our hypothesis is that current agricultural practices are having unanticipated negative effects on soil quality in addition to the impacts associated with the loss of crop diversity.

2. Regional Soil Resource Characteristics

This review focuses on an area of approximately 195 million hectares in South America. The area includes the Pampas and Gran Chaco regions of Argentina and Uruguay, the southern highlands of eastern Paraguay, the eastern lowlands of Bolivia, as well as the Rio Grande do Sul, Santa Catarina and Parana states of Brazil. Several soil associations are found in this region. Mollisols are dominant throughout the Pampas-Chaco plains and Uruguay [6] and are among the best suited for agriculture because of their high natural fertility. Alfisols are also widespread in the Pampas-Chaco region. Alfisols are generally fertile, with high concentration of nutrient cations. Ultisols and Oxisols are the main soils in southern Brazil and eastern Paraguay; these soils have good physical qualities, but require high lime and phosphorus inputs. Vertisols are located in Entre Rios province at Argentina and Uruguay, with good fertility levels but soil physical properties that demand a careful soil management. Alluvial soils dominate the eastern lowlands of Bolivia, and also have good natural soil fertility.

The development of current agricultural practices throughout the region required the transformation of natural ecosystems into agroecosystems with reduced structural and functional complexity. The agroecosystems are also continuously evolving as the result of natural factors and human actions [7–10]. At the global scale, agroecosystems have been evolving towards oversimplification characterized by low efficiency of inputs, loss of resilience, intensification of outputs (grains plus stocks, nutrient removal and leaching and soil erosion), increased carbon consumption by the dependence on fossil energy (fertilizers, pesticides and fuel) and loss of soil quality and ecosystem services [11–13].

The capacity of agroecosystems to provide ecosystem services mainly depends on the adequate functioning of the soil [9,14]. Soil provides the media for root anchoring and healthy plant growth. In addition, soil health affects availability and transport of water, air and nutrients, the resistance to degradation and erosion, soil temperature, and water and air pollution [14,15]. Soil organic matter (SOM) constitutes one of the most affected soil components by agricultural management practices. SOM depletion is associated with alteration of important soil properties (*i.e.*, fertility, porosity, aeration-water dynamics, resistance to erosion and compaction, among others [16], and to the reduction of the capacity of soil to reorganize and restore its functionality after use or a stressful event [17]. Therefore, the capacity of soil to provide other expected environmental services (*i.e.*, supports biodiversity, regulate water partition and purification, and sequester carbon), is affected [18,19]. Other soil properties important for the adequate functioning of soil as aggregate stability and penetration resistance are impacted. Aggregate stability indicates how aggregates will react to and how porosity will be impacted by environmental events (*i.e.*, precipitation, wetting and drying cycles), while soil penetration resistance indicates the degree of difficulty for roots to grow into the soil, which is related to soil compaction and salinization processes among others that affect nutrient and water use efficiency.

3. Cropping System Changes

The primary cropping systems changed throughout the study area during the past 50 years in response to market globalization and the need to develop an internationally competitive agriculture that was beneficial for the countries, farmers, and society in general [20].

Soybean, maize and wheat have become the primary grain field crops in Argentina, Bolivia, Paraguay, Uruguay and southern Brazil (Rio Grande do Sul, Santa Catarina, and Parana states). These crops represented 63%, 19%, and 12%, respectively, of the total cropped area in 2012 according to FAOSTAT, IGBE and CONAB data [21–23]. In the last 54 years, total grain production from those three crops has grown from 14.5 million Mg (16 million tons) in 1961 to over 142 million Mg (156 million tons) in 2013 or roughly a 10-fold increase (Figure 1). Average grain yields for soybean, maize and wheat increased from 1493–2309, from 1489–5485, and from 1114–2386 $kg \cdot ha^{-1}$, respectively, during this period. According to Manuel-Navarrete *et al.* [20], agricultural expansion in Argentina has been supported by the adoption of new technologies (*i.e.*, genetic resources, chemical inputs, and agricultural machinery), an increase in grain prices, a relative decrease in input costs, regional agricultural research, active farmer participation, and relatively good and stable climatic conditions [24,25].

The rates of change in cropped area, grain yield, and total production have been different for the various crops and countries within the region (Table 1). In general, soybean has expanded at the expense of other crops and through land use change [26], increasing production at an annual rate of 5.9% from 1961–2013. Most of the increase can be attributed to an increase in production area (5%), with an additional 0.8% attributed to increased grain yield. The largest recent increases in crop area and total soybean production within the study area have occurred in Argentina, Bolivia, Paraguay and Uruguay. Increases in southern Brazil have been more moderate, primarily because a significant area in that country was already devoted to soybean in 1961 (Table 1). Wheat production also increased in all the countries except Argentina, mainly due to increased grain yield in southern Brazil and Uruguay, and increased area within Paraguay and Bolivia. For maize, there was a large increase in regional production, primarily due to increased area in southern Brazil and Paraguay and higher grain yield in Uruguay and Argentina. During the 1990s and early 2000s, NT stimulated an increase in soybean/maize rotations which increased diversity, reduced insect pressure, restored SOM, and increased crop residue input and nutrient cycling.

The most significant cropping system changes throughout the region since the mid-1990s were the release and rapid adoption of glyphosate-tolerant (GT) soybean varieties and the unprecedented expansion of NT. Since 1994, soybean production has increased at an annual rate of 6.3%, primarily due to area expansion (+5.5% $year^{-1}$) at the expense of grasslands, maize, sunflower (*Hellianthus annuus* L.), and sorghum (*Sorghum bicolor* (L.) Moench). By 2012, soybean, maize, and wheat accounted for 67%, 20%, and 13% of the region's total cropland. With regard to yield, maize showed the highest rate of increase throughout the entire region. Wheat yield increased most rapidly in southern Brazil and Paraguay, while soybean yield increased most rapidly in Paraguay and Uruguay, but overall, yield for both crops increased at a slower pace than maize throughout the region. More recently and despite increases in potential maize yield, the soybean/maize rotation was replaced by a soybean-dominated cropping system. The driver for this change was neither agronomic nor technically based, but simply an economic one. Maize is generally a more expensive crop to grow than soybean. It is also more vulnerable to short drought during critical phenological growth stages and within the region, the commodity price was lower than for soybean.

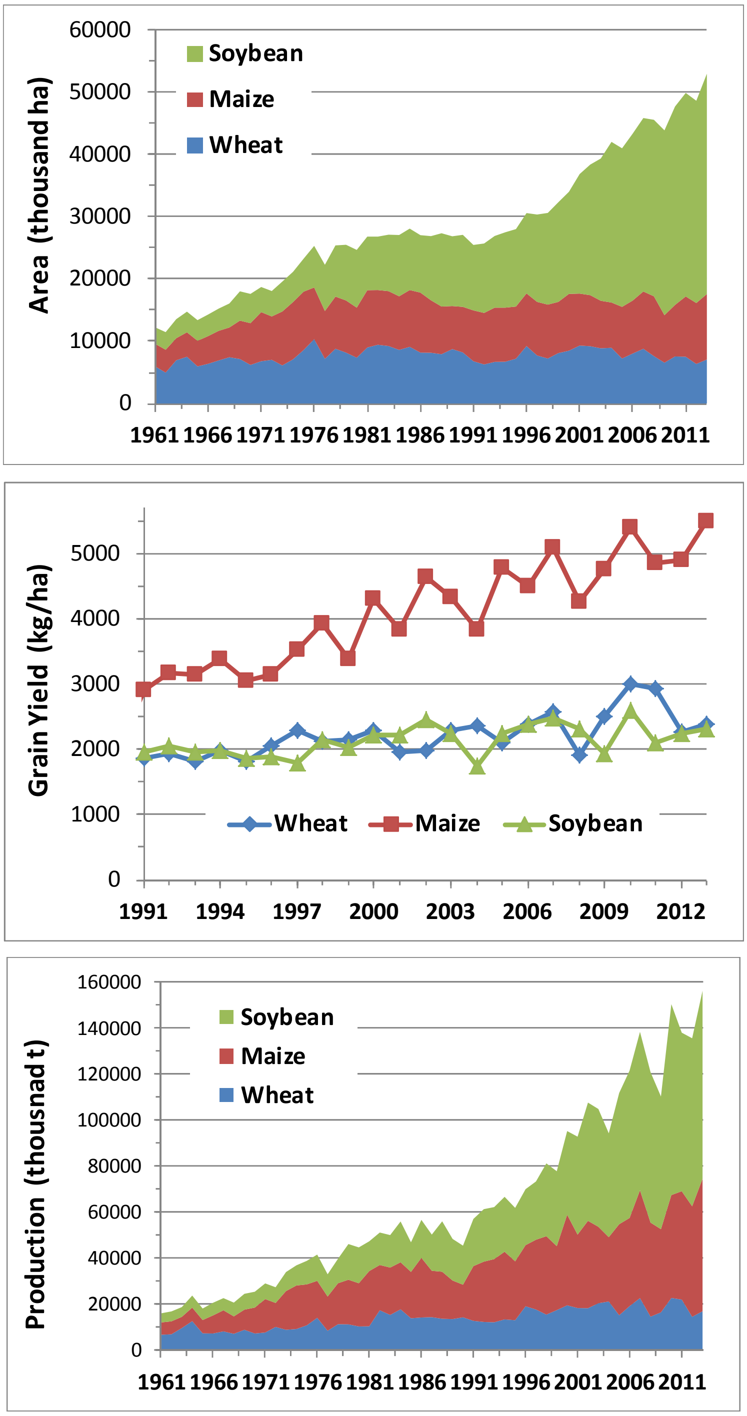


Figure 1. Fifty-year changes in planted area, grain yield, and total production of wheat, maize, and soybean in Argentina, Bolivia, southern Brazil, Paraguay, and Uruguay. Elaborated with data from FAOSTAT, IBGE and CONAB databases [21–23].

Table 1. Rates of change in area, yield, and production for wheat, maize, and soybean in Argentina, Bolivia, southern Brazil, Paraguay, and Uruguay.

Period	**Area**			**Grain Yield**			**Total Production**		
	Wheat	**Maize**	**Soybean**	**Wheat**	**Maize**	**Soybean**	**Wheat**	**Maize**	**Soybean**
Argentina									
1961–2013	−0.6%	1.1%	20.5%	1.3%	2.5%	1.8%	0.6%	3.6%	22.7%
1994–2013	−2.5%	3.5%	6.3%	0.8%	2.2%	1.1%	−1.7%	5.8%	7.4%
Bolivia									
1961–2013	1.7%	1.4%	16.9%	1.3%	1.3%	1.3%	3.1%	2.7%	18.4%
1994–2013	3.1%	2.3%	7.1%	2.0%	1.5%	−0.8%	5.1%	3.9%	6.2%
Southern Brazil (PR-SC-RS)*									
1961–2013	1.8%	5.0%	2.6%	3.2%	3.3%	1.2%	5.0%	8.4%	3.8%
1994–2013	5.0%	−1.7%	3.4%	3.3%	3.1%	1.0%	8.5%	1.4%	4.5%
Paraguay									
1961–2013	8.3%	4.7%	15.8%	2.0%	2.3%	1.1%	10.5%	7.1%	17.1%
1994–2013	6.0%	8.1%	7.7%	3.9%	3.2%	0.7%	10.1%	11.6%	8.4%
Uruguay									
1961–2013	0.6%	−1.6%	14.3%	2.1%	3.8%	1.9%	2.7%	2.2%	16.4%
1994–2013	5.9%	4.1%	26.4%	0.0%	6.4%	2.9%	5.9%	10.8%	30.1%
Total									
1961–2013	0.3%	2.0%	5.0%	1.4%	2.5%	0.8%	1.8%	4.6%	5.9%
1994–2013	0.3%	1.0%	5.5%	0.9%	2.4%	0.8%	1.2%	3.4%	6.3%

Elaborated with data from FAOSTAT, IGBE and CONAB databases [21–23]. * PR = Parana; SC = Santa Catarina; RS = Rio Grande do Sul States, Brazil.

Adoption of conservation tillage, including NT, has been a leading practice in South America (Table 2, Figure 2). The initial North American experience with NT (*i.e.*, Shirley Phillips and the University of Kentucky) became an important reference for the first South American experiences with NT during the early 1970s. Pioneer farmers in Brazil and Argentina recognized the importance of maintaining crop residues on the surface to protect against water erosion and to compensate for rapid residue decomposition under high temperature and moisture regimes prevalent throughout the summer cropping season. Although the adoption of NT was relatively slow from the 1970s to 1990s, it increased exponentially following the release of GT soybean varieties. The success of NT in southern Brazil and Argentina became an important reference for its widespread adoption throughout South America. Currently, NT is being used on 70%–90% of the grain crop area in Paraguay, Brazil, Argentina, Bolivia, and Uruguay. Government and farmer associations throughout the region promote adoption of NT for several reasons including its economic benefits, higher or more stable yields through improved water use efficiency, erosion control, saving on fuel and labor/time, and improved soil quality attributes (AUSID, MAGyP) [27,28].

The expansion of GT soybean and NT practices are highly correlated (e.g., 0.90 and 0.73 for Argentina and southern Brazil, respectively) and have been supported by higher soybean prices when compared to other grains within the region (Figure 3). For example, soybean grain prices increased by 196% between 1991 and 2012, compared to increases of 54%, 77%, 59%, 77%, and 96% for barley

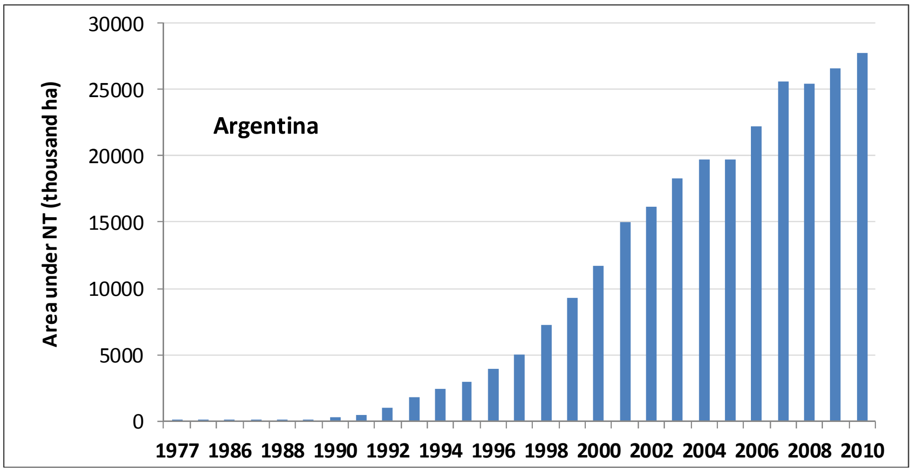
(*Hordeum vulgare* L.), maize, sorghum, sunflower, and wheat, respectively. Therefore, the main driver for increased soybean production has been the higher price when compared to other grain crops.

It is important to stress that the economic impact of soybean has not only been very positive for farmers but also for the economies of the countries in the region and society as a whole. However, to fully examine the sustainability of this cropping system change, it is important to also examine how it has affected soil resources and overall soil quality.

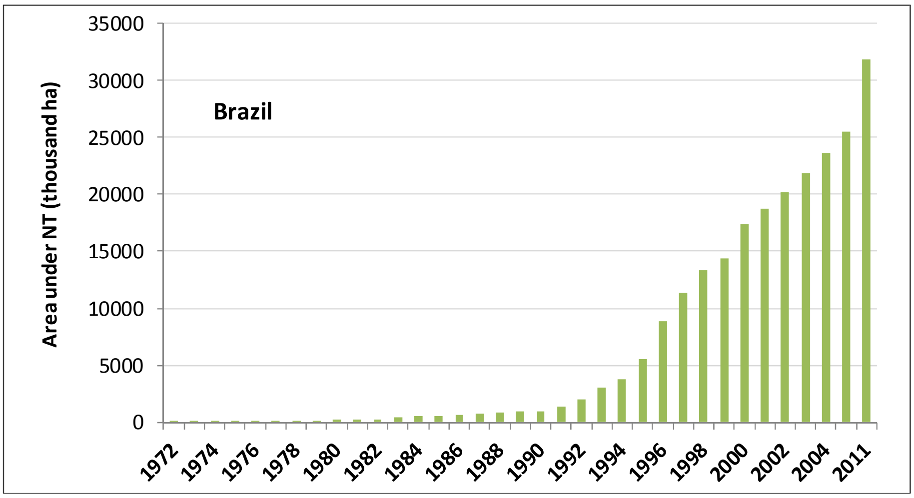
Table 2. Area under no-tillage in selected South American countries.

Country	Area under No-Tillage (ha) 2008/2009	Percentage of Total Cropped Area
Brazil	25,502,000	58
Argentina	25,553,000	70
Paraguay	2,400,000	90
Bolivia	706,000	72
Uruguay	655,100	82

Data source is Friedrich *et al.* [29].

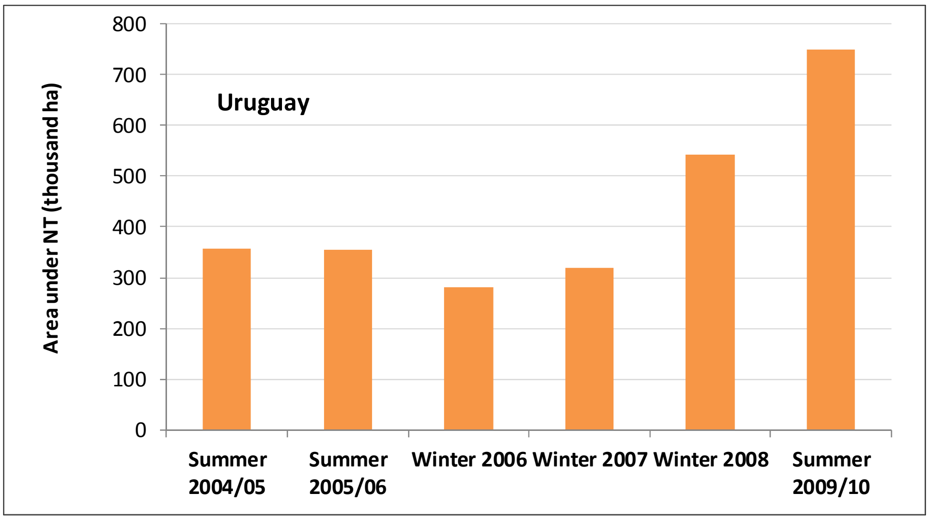


(**a**)



(**b**)

Figure 2. *Cont.*



(**c**)

Figure 2. No-tillage adoption rates in Argentina (**a**); Brazil (**b**); and Uruguay (**c**). Elaborated with data until 2011 for Argentina [30], 2012 for Brazil [23,31], and 2010 for Uruguay [27].

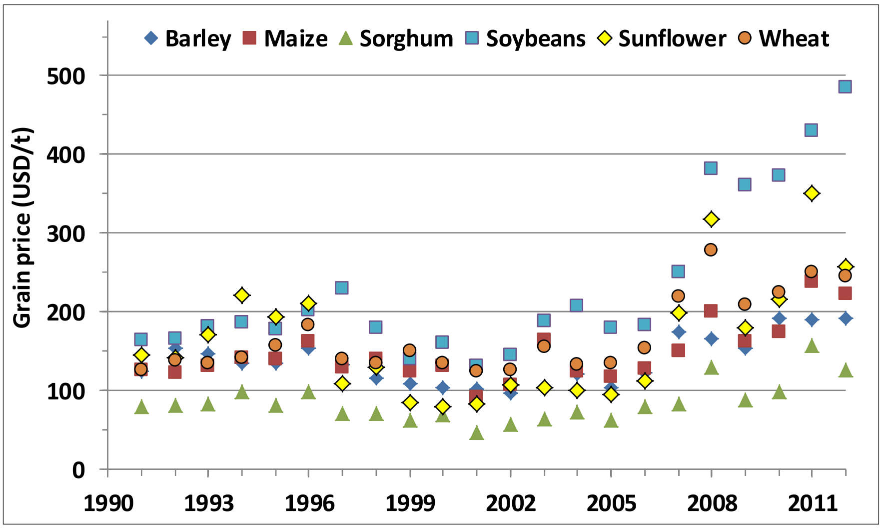


Figure 3. Twenty-year grain price averages for the primary field crops in Argentina, Bolivia, Brazil, Paraguay and Uruguay. Elaborated with data from FAOSTAT [21].

4. Soil Quality Impact of Agricultural Expansion

Assessment of soil quality indicators, including SOM content, N supply, P availability, aggregate stability, bulk density, pH, and others, has received increased attention during the last decade throughout the Pampas and extra-Pampas regions of Argentina as well as in Brazil, Uruguay, Bolivia, and Paraguay. These assessments have indicated that the cropping system changes, which have generally included removal of pasture from crop rotations, decreased crop diversity with the increased frequency of soybean, and the conversion of marginal land into cropland, are imposing a threat to soil quality [20].

In Argentina, comparisons of soil quality indicators for pristine and agricultural soils show a general reduction in SOM content and aggregate stability and an increase in bulk density with agricultural use (Table 3). Soils with less than 10 years of continuous agriculture had 83%, 62%, and 106% of the pristine

SOM content, aggregate stability and bulk density, respectively, while soils 10–20 years of continuous agriculture had 64%, 48% and 116% of the pristine values, respectively (Table 3). These measurements indicate that SOM decreased by approximately 18% per decade of agricultural use.

Table 3. Aggregate stability (AS), soil organic matter (SOM) content, and bulk density (BD) of agricultural and pristine soils in the Pampas region after various years of Agriculture (YOA) and for different soil depth increments.

Zone	Soil	YOA	Depth (m)	AS	SOM	BD	Soil pH	Soil pH	Reference
				% Relative to Pristine Conditions			Pristine	Cultivated	
Extra- pampas	O	>20	0–0.1	-	59	143	-	-	[32]
Extra-pampas	O	>20	0.1–0.2	-	83	126	-	-	[32]
Extra-pampas	O	>20	0.2–0.3	-	74	128	-	-	[32]
Pampas center	M, Argiudolls	12	>0.08	37	57	121	-	-	[33]
Pampas center	M, Argiudolls	12	0–0.08	44	56	111	-	-	[33]
Pampas center	M, Argiudolls	>20	>0.08	64	83	103	-	-	[33]
Pampas center	M, Argiudolls	>20	0–0.08	29	81	105	-	-	[33]
Pampas center	M, Argiudolls	>20	0–0.2	37	73	-	6.3	5.9	[34]
Pampas center	M, Argiudolls	>30	0–0.2	23	77	-	6.3	6.1	[34]
Pampas center	M, Argiudolls, Natralbolls	<10	>0.08	53	80	106	-	-	[33]
Pampas center	M, Argiudolls, Natralbolls	<10	0–0.08	43	72	122	-	-	[33]
Pampas center	M, Argiudolls	24	0–0.20	26	65	-	-	-	[35]
Pampas center	M, Haplustolls, Hapludolls	<10	>0.08	42	73	102	-	-	[33]
Pampas center	M, Haplustolls, Hapludolls	<10	0–0.08	39	68	110	-	-	[33]
Pampas center	M, Haplustolls, Hapludolls	>40	>0.08	37	75	112	-	-	[33]
Pampas center	M, Haplustolls, Hapludolls	>40	0–0.08	39	71	118	-	-	[33]
Pampas center, W	M, Hapludolls	13	0–0.20	40	61	-	-	-	[35]
Pampas N	I, Haplustept	4–23	0–0.025	115	75	-	6.4	7.3	[36]
Pampas NE	M, Argiudolls	>10	0–0.12	23	62	116	6.5	6.4	[37]
Pampas NE	M, Argiudolls	>20	0–0.05	57	45	109	-	-	[38,39]
Pampas NE	M, Argiudolls	>20	0.05–0.15	60	84	110	-	-	[38,39]
Pampas NE	M, Argiudolls	>20	0.15–0.3	-	86	-	-	-	[38,39]
Pampas NE	V, Hapluderts	>20	0–0.05	57	45	109	-	-	[38,39]
Pampas NE	V, Hapluderts	>20	0.05–0.15	60	84	110	-	-	[38,39]
Pampas NE	V, Hapluderts	>20	0.15–0.3	-	86	-	-	-	[38,39]

Table 3. *Cont.*

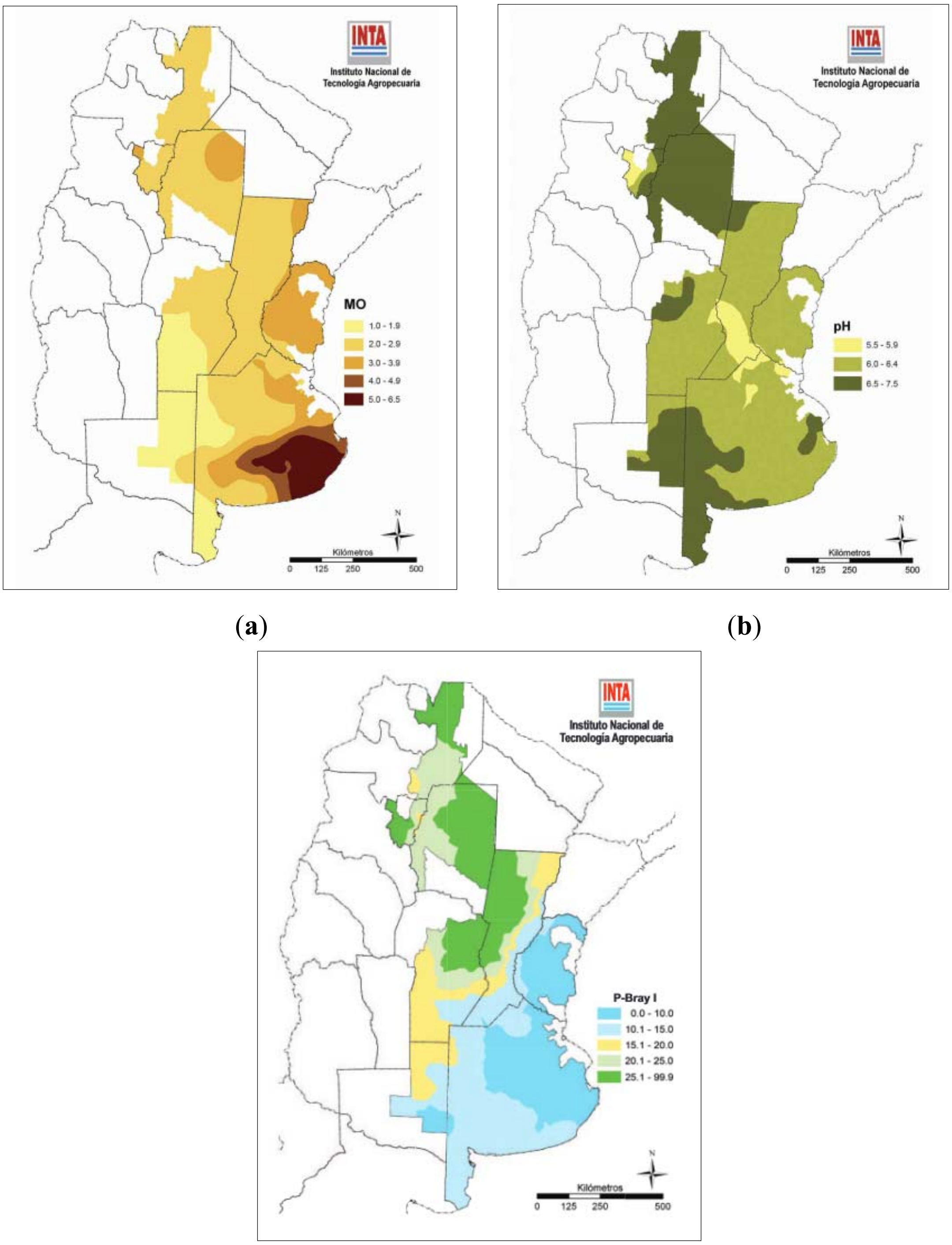
Zone	Soil	YOA	Depth (m)	AS	SOM	BD	Soil pH	Soil pH	Reference
				% Relative to Pristine Conditions			Pristine	Cultivated	
Pampas NW	M, Haplustolls	20	0–0.1	39	71	113	7.1	6.7	[40]
Pampas NW	M, Haplustolls	1–4	0–0.20	53	73	100	7.5	7.1	[41]
Pampas NW	M, Haplustolls	1–4	0.20–0.50	71	72	102	6.9	7.4	[41]
Pampas NW	M, Haplustolls	2–7	0–0.20	95	85	86	6.9	7.0	[41]
Pampas NW	M, Haplustolls	2–7	0.20–0.50	88	86	100	7.7	7.5	[41]
Pampas NW	M, Haplustolls	4–9	0–0.20	91	89	125	6.8	6.8	[41]
Pampas NW	M, Haplustolls	4–9	0.20–0.50	66	122	108	7.5	7.2	[41]
Pampas NW	M, Haplustolls	3	0–0.1	63	89	105	5.7	6.5	[42]
Pampas NW	M, Haplustolls	>10	0–0.1	37	63	120	5.7	6.6	[42]
Pampas SE	M, Argiudolls	10	0–0.20	43	83	-	-	-	[35]

Soil: O: Oxisols, M: Mollisols, V: Vertisols, I: Inceptisols.

In Uruguay, the average SOM decrease in Alfisols after 10+ years of cultivation was 15% [43]. In southern Brazil, Campos *et al.* [44] reported 23% of decline of SOM in an Oxisol when measured 30 years after the conversion of pasture to grain production with CT practices. Ferreira [45] investigated long-term NT (>20 years) in southern Brazil and reported that compared to native fields, the average SOM declined 12% and 23% for the 0–0.3 and 0–1.0 m soil depths, respectively. In addition to near-surface (≤0.2 m) SOM decline, another soil quality concern is SOM decline in deeper soil layers. This can occur with the current regional cropping systems because of the difficulty in restoring SOM at those depths. The main drivers for SOM decline within the region are: elimination of perennial pasture from long-term rotations, increased soil disturbance associated with tillage, limited rooting depth due to machinery traffic and soil compaction, soil erosion, decreased crop residue input, and less crop diversity. Short-term land tenure, increases in cropland area managed by an individual farmer, and increased inputs of low C/N crop residues also contribute to land use decisions that often reduce SOM levels. Therefore, to prevent current cropping systems from further degrading soil resources, several agronomic, economic and social factors affecting soil quality need to be addressed throughout the region to better understand and improve soil and crop management.

5. Soil Quality Evaluation

The evaluation of soil quality indicators is important to avoid widespread soil degradation due to inappropriate crop management. Previous evaluations at the landscape scale have shown important changes in SOM, pH and P availability (Figure 4) [46,47], and in the soil's capacity to supply N (Figure 5) [48]. Soil quality assessment within the 0–0.2 m depth of agricultural fields throughout the Pampas and surrounding regions (*n* > 34,000 samples) indicated that current SOM values ranged from 1 to 83 $g \cdot C \cdot kg^{-1}$. The highest values were found in the southeast Pampas region and with gradual decline toward the north and west (Figure 4a) [46]. In the same study, low soil pH (<6.0) due to acidity was a concern only in the north Pampas region, while for the majority of the region, soil pH was within normal range for crop production (pH 6.0–7.5) [46]. Assessments of P availability (Bray P) showed low to very low (≤5 mg·kg^{-1}) values throughout the Pampas region (15.2 Mha) and medium to high (≥15 mg·kg^{-1}) values north of that area (12.7 Mha) [47].



(**a**) (**b**)

(**c**)

Figure 4. Median landscape values for (**a**) soil organic matter (SOM); (**b**) soil pH; and (**c**) available soil phosphorous (Bray P1) in the Pampas region of Argentina. Source: Sainz-Rozas *et al.*, 2011 and 2012 [46,47].

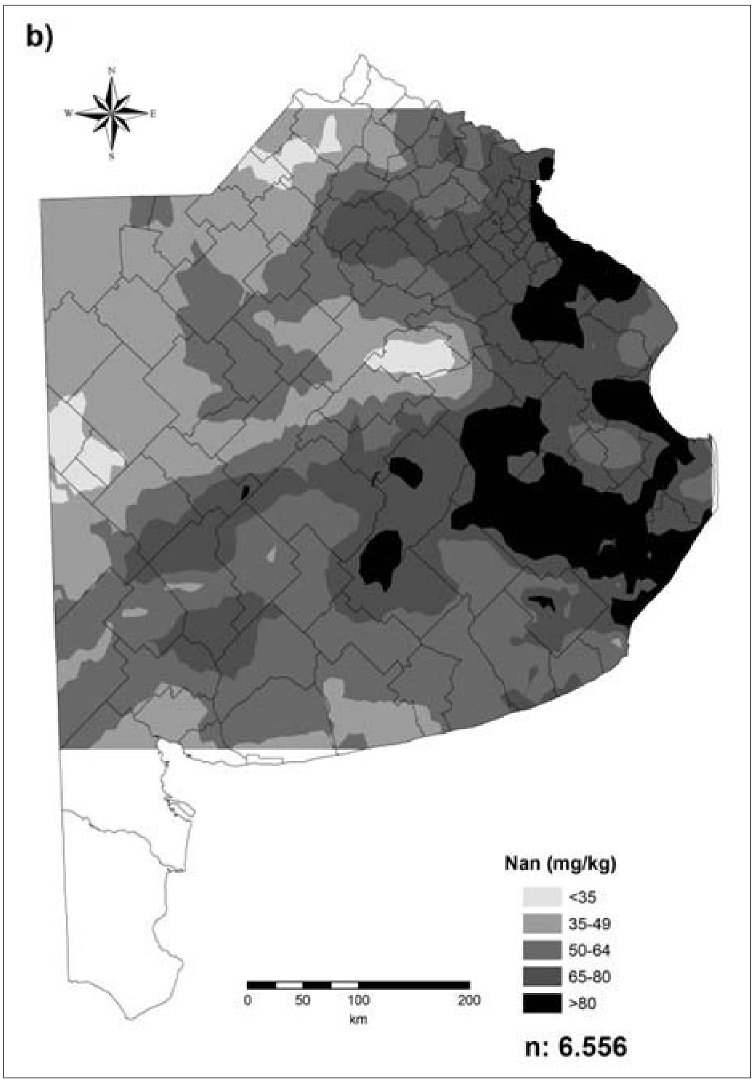


Figure 5. Surface horizon (0–20 cm) potential nitrogen supply (Nan) in cropland soils of Buenos Aires province, Argentina. *N* = number of observations. Source: Reussi-Calvo *et al.* 2014 [48].

A similar survey in the 1980s [49] showed that after 25–30 years of cropping, areas that had medium to high levels of P (west and north of the Pampas region) showed a major decrease in *p* availability due to unbalanced fertilization. On the other hand, areas such as the south of Pampas region which had low to very low levels of P (>10 ppm P-Bray I) had increased P availability due to long term balanced fertilization (Figure 4c) [47]. Nitrogen mineralization potential in Buenos Aires province of Argentina ranged from 12–260 $mg \cdot kg^{-1}$ with the majority of the fields below 65 $mg \cdot kg^{-1}$ [48]. Potential N supply showed a high relationship with SOC content and represented a reduction in potential N supply of approximately 50% compared to pristine soils [48]. The availability of these reports constitutes an important step for monitoring and characterizing soil quality indicators and how soil management affects it.

In Uruguay, NT was adopted to mitigate soil loss due to intensive water erosion [50]. This would be expected in improve soil quality and even though other soil and crop management changes are hypothesized to affect the quality of natural resources including soils, quantifying long-term effects has been considered very difficult because of the lack of baseline soil quality data [51]. Therefore, several studies have measured the impact of agricultural practices on soil quality indicators as compared to undisturbed conditions. For example, a 2009–2010 survey of commercial operations in Uruguay showed an average reduction in SOM of 20% [52]. The loss of potentially mineralizable N (PMN) was reported to be as high as 41.5%. These results are consistent with previous findings [53] and are presumed to be real because most PMN is contained in the biologically active SOM fraction which is easily degraded by agricultural operations. The variability of both parameters was very high, with 20% of locations reporting SOM increases between 1% and 20%, and 30% of locations reporting losses between 30% and 60%. This indicates there are important interactions between soil management, soil type, climate, and cropping system. Regarding PMN, 12% of the locations had increases between 1% and 14% while 30% of locations reported losses between 35% and 80% [52]. A different study [51] compared soils under dairy pasture with those from crop production fields and reported that both systems had 20% SOM losses. However, PMN losses from cropland soils were much higher (42%) than in pasture soils (26%). This difference is attributed to higher soil N input by legumes in dairy pastures compared to N removal by grain production.

In 2009, Mori [43] quantified several other soil quality indicators [SOM, PMN, total N (TN), exchangeable bases (EB) and water pH] in agricultural Mollisols within Uruguay (Table 4). The study showed SOM and NPM losses of 15% and 17%, respectively, for agricultural and native systems. Other negatively affected indicators were TN (−23.7%), EB (−10.5%) and pH (−7.3%). The study also demonstrated high correlation among some soil quality indicators (e.g., SOM, TN, EB and pH) (Figure 6) and therefore, soil management strategies that result in the simultaneous losses of C, N and EB are likely to cause a sharp decline in soil quality.

The use of CT in early 1970s in southern Brazil and in the 1980s in Paraguay resulted in severe (>50 $Mg \cdot ha^{-1} \cdot year^{-1}$) soil erosion due to intensive rainfall during the maize and soybean establishment period of September to December. It was estimated that soil loss for each Mg of harvested grain was 10 $Mg \cdot ha^{-1}$ throughout the 1970s [54,55]. The use of CT also promoted wind erosion in sandy soils and flat croplands and resulted in significant runoff from bare soil on the undulating topography of southern Brazil and Paraguay croplands [54].

Table 4. The range and average change (agricultural *versus* undisturbed conditions) in selected soil quality indicators of 15 Argiudolls from Uruguay.

Average	**SOM**	**TN**	**PMN**	**EB**	**pH**
Young	−16.4%	−25.0%	−21.6%	−6.0%	−5.7%
San Manuel	−14.0%	−22.7%	−12.8%	−14.4%	−8.6%
All	−15.1%	−23.7%	−16.9%	−10.5%	−7.3%
			Range		
Min	−37.0%	−41.9%	−54.3%	−38.2%	−17.1%
Max	1.8%	−1.4%	51.0%	15.8%	5.9%

Elaborated with data from Mori [43]. SOM: Soil organic matter; TN: total nitrogen; PMN: potentially mineralizable nitrogen; EB: exchangeable bases; pH: water-pH.

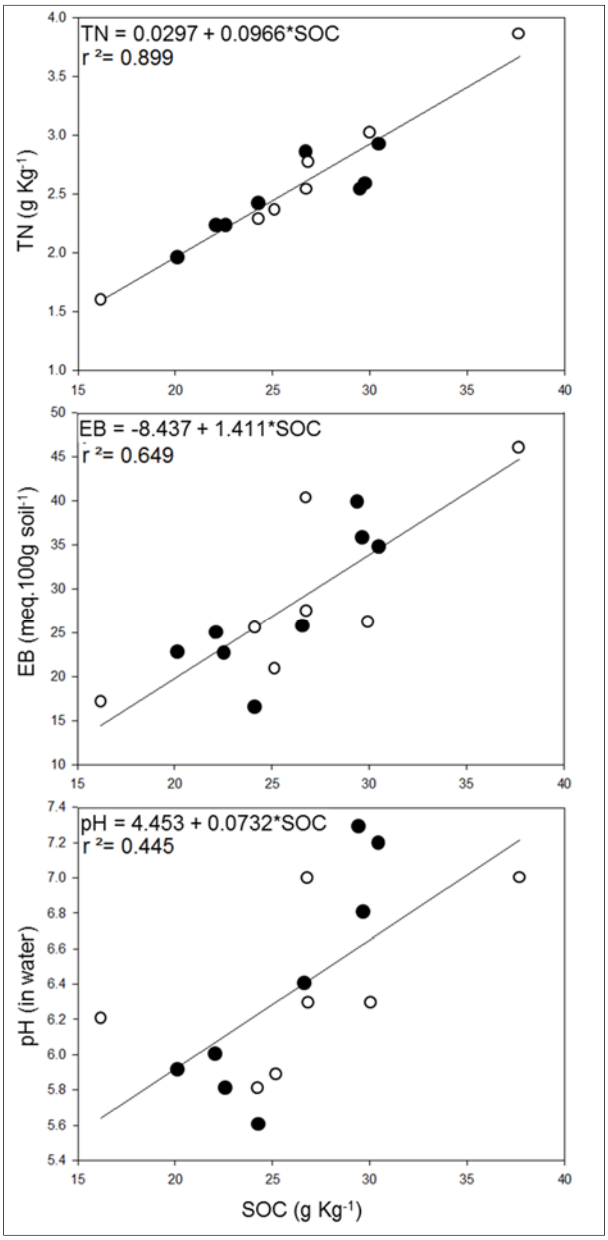


Figure 6. The statistical relationship between soil quality indicators (SOC, NT, EB and water-pH) in San Manuel (closed) and Young (open) soils from Uruguay. Regression results based on pooled data from both sites. Elaborated with data from Mori [43].

The intense soil disturbance of Oxisols by CT also resulted in decreased soil aggregate size and, as a consequence, labile fractions of SOC that were previously occluded inside aggregates were exposed to microbial processes. Soil erosion also removed the top soil carrying with it SOM and clay fractions, thus resulting in a sharp decline in soil quality. Biological oxidation of SOM was also stimulated by tillage, mixing of crop residues, and high temperature and moisture conditions during the summer. It was estimated that with CT, crop residue input as high as 16 Mg·ha^{-1}·year^{-1} would be necessary to maintain SOC content [55]. Needless to say, achieving such a level of crop residue is very difficult with grain crops. For southern Brazil and Paraguay, the first steps toward improving soil quality were associated with reducing soil disturbance by conversion from CT to NT and by increasing crop residue inputs to maintain soil protection throughout the year. Long-term experiments with agricultural grain crop rotations indicated that even under NT it is necessary to design crop systems with high amounts of crop residue input in order to balance the fast SOM decay associated with high temperature and moisture conditions in subtropical and tropical environments of southern Brazil and Paraguay [56]. Furthermore, adoption of higher crop diversity and incorporation of pastures with well-developed root systems will help restore soil structure and relieve soil compaction issues associated with the large soybean expansion area. Equilibrated soil fertilization, lime and use of soil amendments as gypsum, should also be considered as tools to sustain high crop residue input, especially on the naturally acid and low fertility soils of southern Brazil [57].

6. Developing Cropping Systems for Sustained Grain Yield, Maintenance of Soil Quality, and Environmental Protection

In southern Brazil, a recent study carried out by Ferreira [45] in six different croplands showed that there was an average SOM decline of 23% in the 0–100 cm soil layer after 25 years of CT. On-farm research showed SOM values that were similar to those observed in the few long-term experiments carried out in Rio Grande do Sul [44]. On the other side, restoration of SOM with NT in southern Brazil has been shown to be a long term process (>20 years) with increases ranging from 61%–117% (Figure 7) depending upon climate, clay content and crop rotation. With continuous soybean crops in summer and black oat (*Avena strigosa* Schieb.) or wheat in the winter, there was only a slight increase in SOM under NT in relation to CT. Conversely, crop rotations that included soybean alternated with maize as summer crops and cover crops during winter showed enhanced SOM restoration in the range of 85%–116%. In the region, it is possible to grow crops all year along since there is only a very short window of frost, and rainfall is generally well distributed. Typically, successful farmers use cover crops mixtures that include black oat + vetch (*Vicia sativa* L.) + oilseed radish (*Raphanus sativus* var. *oleiferus* Metzg.) before maize, which is then followed by oilseed radish during a short 3 month window after which wheat followed by soybean are grown. This crop rotation is designed to increase crop residue input, increase crop diversity and sustain high grain yields. In the scenario of long-term soybean as the main summer crop, special attention must be given to the use of cover crops and pastures in the short windows in order to maintain soil quality.

In Argentina, studies on SOM dynamics in Mollisols within the southeast of the Pampas region showed a quick decline in SOC (Figure 8a) and its particulate fraction (POC) when soils under pasture were converted to cropland regardless if they were managed using CT (moldboard plow) or NT management [58–60]. Crops used in the rotation had a significant impact on the rate of SOC loss [46] which was primarily associated with the amount of C returned through crop residues input [61,62]. Under continuous grain cropping, adoption of NT resulted in reduced losses, or even increases in SOC and POC in shallow soil layers (0–5 cm) regardless of fertilizer management [60,62–65], or agricultural intensification levels [66]. However, none of these studies reported improvements in SOC or POC due only to the adoption of NT or to fertilization when the 0–20 cm depth soil layer was taken into account. Nonetheless, the inclusion of a 3-year pasture in the rotation after 7–8 years of grain crops restored SOC (Figure 8a) and POC contents to original contents before cropping after pasture [58,60]. These results suggest that for the naturally rich SOM Mollisols of the southeastern Pampa, restoration and maintenance of SOM content within sustainable levels would require a combination of NT and pasture in rotation with grain crops.

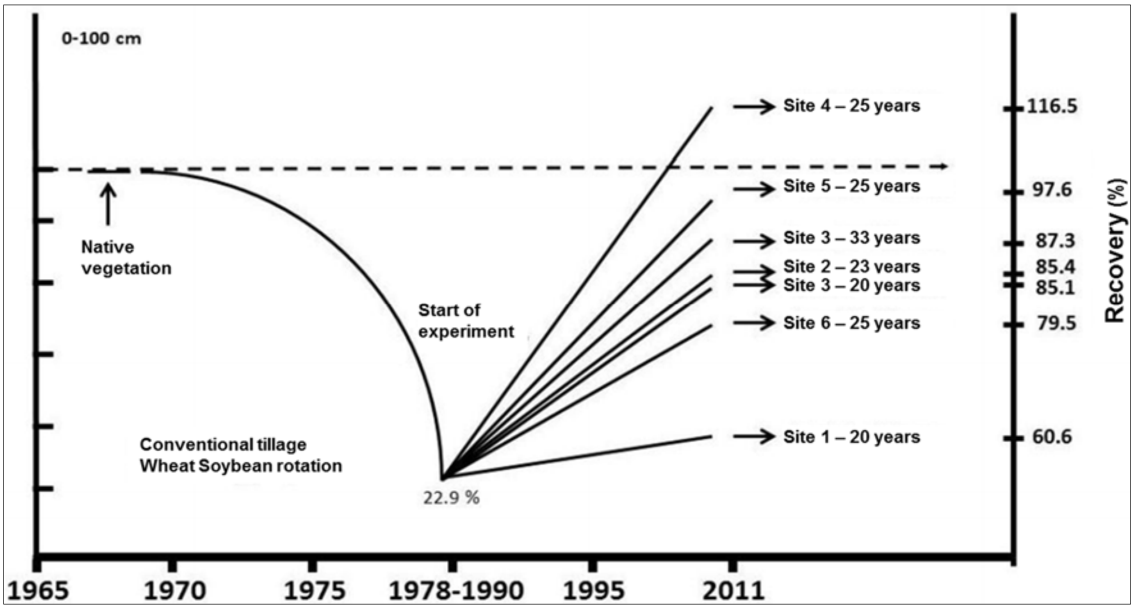


Figure 7. Soil organic matter in the 0–100 cm soil depth following the use of conventional tillage to replace native pasture with grain crops and after conversion to no-till with different soybean-based crop rotations. Source: Ferreira (2014) [45].

Direct consequences of SOC and POC loss under cropping systems include the reduction of soil N and S supplying capacity [48,67–70] and an increased dependence on N [71,72] and S [73] fertilizers to maintain crop yields. Under continuous cropping, potential N supply within 85% of farmer fields in the southeast of Pampas region was <100 $mg \cdot N \cdot kg^{-1}$ while only 35% of soils under crop rotations including short term pastures were below that level [74]. Regarding aggregate stability, both physical breakdown of aggregates and loss of SOM due to soil disturbance contributed to the reduced aggregate stability of soils under agriculture [58,75,76] The use of NT delayed the reduction in aggregate stability compared to CT, but ultimately, aggregate stability reached similar values for both systems [77]. Furthermore, within the 0–20 cm soil depth, aggregate stability under continuous cropping did not improve with the conversion of CT to NT [77]. Aggregate stability was highly related to POC content [78] and particularly with POC content in macro-aggregates [79]. However, the introduction of a pasture in the rotation not only resulted in recovery of SOC and POC contents but also improved aggregate stability (Figure 8b) [58,77,78]. Based on these studies, we conclude that cropping systems need to be designed and developed regionally. For Mollisols in Argentina under temperate climate conditions, crop rotations including pastures were more critical to aggregate stability and SOC content than tillage systems or fertilization. However, for tropical and subtropical environments in southern Brazil and Paraguay, the role of minimum soil disturbance, lime and fertilization were more critical.

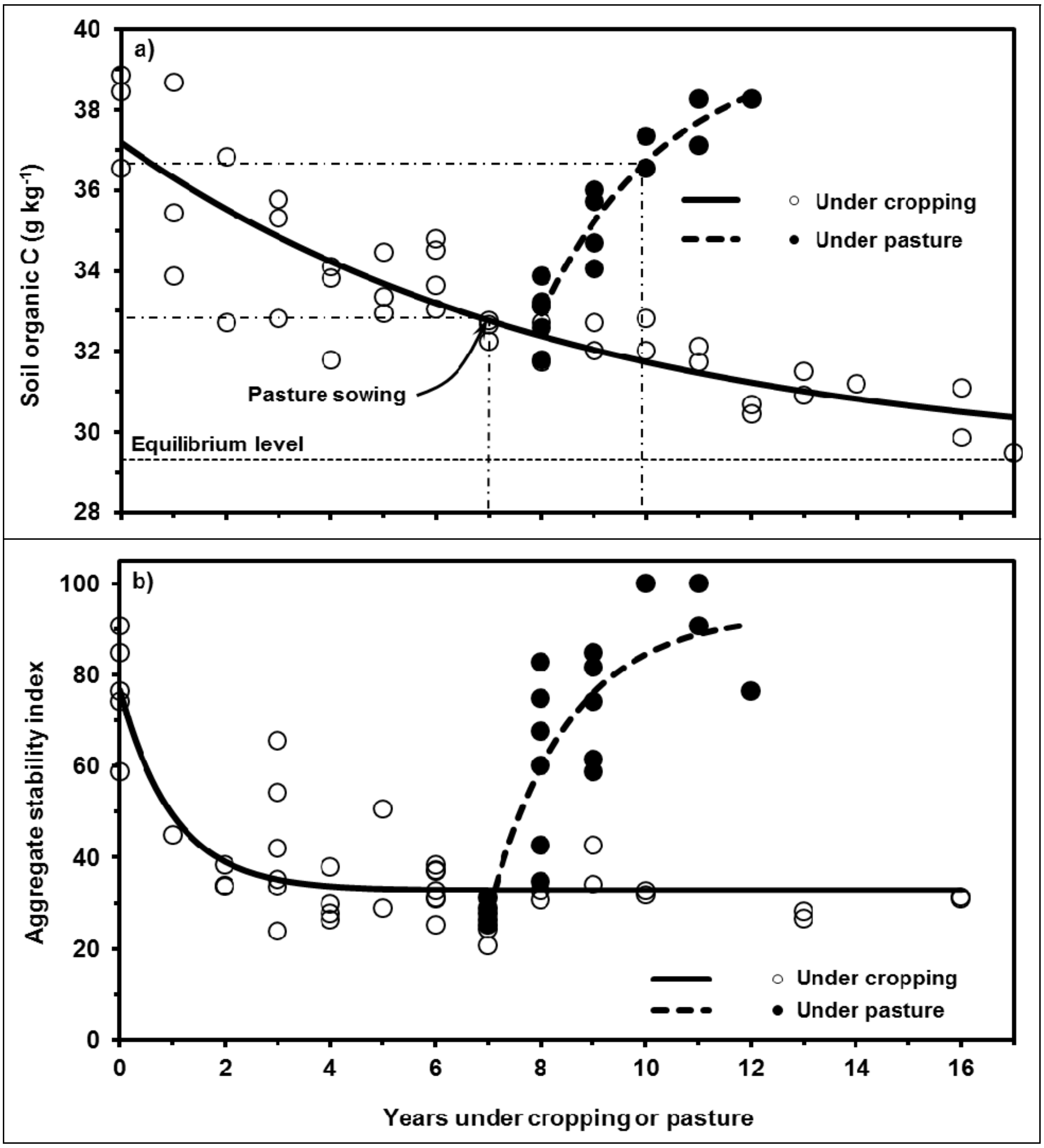


Figure 8. Changes in (**a**) soil organic C; and (**b**) aggregate stability in the arable layer of Mollisols from the southeast Pampas region of Argentina. Elaborated from Studdert *et al.* [60] and unpublished data.

In a review of long term experiments in Uruguay, Garcia Préchac *et al.* [80] reported a six-fold erosion reduction under NT compared to CT conditions. Soil losses were similar between continuous pastures and crop rotations that incorporated pasture suggesting the efficacy of pastures to reduce soil erosion was evident even in short-term rotations. Using USLE modeling, they estimated an average annual erosion rate of less than 7 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ in a Typic Argiudoll in a soybean/wheat or in a soybean/winter cover crop rotation. This is a moderate level according to Clérici *et al.* [81]. Using Century modeling [82], the same crop rotations were projected to result in long-term SOC losses.

In another study in Uruguay, Salvo *et al.* [83] quantified changes in SOC stocks in a long term study that included CT and NT and two crop rotations (continuous grain crops, *versus* a rotation with three-years of pasture and three years of grain crops). The study was carried on a Typic Argiudoll and the measurements were taken 10 years after initiation of the experiment. The results comparing NT *versus* CT, showed a SOC increase of 29% within the 0–3 cm depth under NT. Under CT, the rotation that included pastures increased SOC content by 23% at the same soil depth. The inclusion of maize under NT and pasture-crop rotations resulted in a 12% increase in SOC as compared with the treatment with only soybean and sunflower as summer crops. The evolution of SOC and other physical properties after the incorporation of winter pastures such as ryegrass (*Lolium multiflorum* L.) and oat (*Avena sativa* L.) to continuous soybeans managed under NT was investigated by Sawchik *et al.* [84]. After six years, SOC within the 0–7.5 cm layer was 17% higher on treatments with soybean and winter pasture than under continuous soybean. Infiltration rates were also higher in treatments with soybean and winter pasture compared to continuous soybean. Thus, in Uruguay, the recommendation for maintaining a stable SOC content requires inclusion of pastures and alternating C3 and C4 summer crops instead of using only C3 summer crops as soybean.

Soil management effects on soil quality in two long-term experiments carried out on Alfisols in Rio Grande do Sul were evaluated by Amado *et al.* [85]. They found that CO_2 respiration, aggregate stability and infiltration rates were the most effective soil quality indicators to discriminate between cropping and tillage systems. In general, the adoption of NT and use of cover crops increased CO_2 respiration suggesting higher biological activity (Table 5). Adoption of NT also resulted in enhanced aggregate stability, increased infiltration rates, and reduced soil erosion. In this study, the decline of SOC was associated with decreased CO_2 respiration, aggregate stability and infiltration suggesting a loss of soil quality with CT and in association with lack of crop rotation. They also reported that the soil quality kit from USDA/ARS was an efficient tool to evaluate soil quality under contrasting soil management scenarios in the region. From the two long-term experiments, it was determined that improved cropping systems should have legume cover crops or pasture in the crop rotation in order to increase both crop N and C inputs to soil. Therefore, the treatments under NT that have hairy vetch in consortium with black oats, maize in consortium with cowpea (*Vigna unguiculata* (L.) Walp.), or tropical legume cover crops such as pigeon pea (*Cajanus cajan* (L.) Millsp.), lab-lab (*Lablab purpureus* (L.) Sweet) or mucuna (*Mucuna* sp.) in consortium with maize had the best soil quality. Furthermore, in this case, mineral N fertilization applied to maize did not replace the role of a legume cover crop for improving soil quality.

Campos *et al.* [44] in a long-term experiment carried out on an Oxisol reported a linear relationship between crop residue input and SOC stock in the 0–30 cm soil depth (Figure 9). This study supports previous research suggesting an annual dry matter input of 8–10 $Mg \cdot ha^{-1} \cdot year^{-1}$ is needed to maintain or increase SOC stock under NT [55]. In addition, this experiment showed an increase of 16% in crop residue production under NT compared to CT. The increase in crop residue input under NT may be associated with the improvement in soil fertility and soil quality compared to CT [44].

Table 5. Soil respiration (CO2), aggregate stability (AS), pH, nitrate and nitrite content (N-NO3$^-$ + N-NO2$^-$), bulk density and infiltration rate for different management systems (MGMENT) and two soils using the Soil Quality Kit (SQK) and the reference method (REF).

MGMENT	**CO$_2$**		**AS**		**pH**		**N-NO$_3^-$ + N-NO$_2^-$**		**Bulk Density**		**Infiltration Rate**	
	SQK	**REF**	**SQK**	**REF**	**SQK**	**REF**	**SQK**	**REF**	**SQK**	**REF**	**SQK**	**REF**
	kg·ha^{-1}·day^{-1}		**%**				**kg·ha^{-1}**		**Mg·m^{-3}**		**mm·h^{-1}**	
					Rhodic Paleudalf							
Bare fallow	6.7 b[1]	15.9 b	33.4	23.9 b	5.6 a	5.5 b	1.2 b	1.2	1.72 a	1.66 a	<1 c	1
NT Fw/M	23.8 b	36 b	54.9	78.9 a	5.7 a	5.6 ab	1.9 a	3.0	1.45 ab	1.34 b	75 b	50
NT P/M	21.4 b	35.3 b	61.4	76.8 a	5.6 a	5.6 b	2.0 a	2.5	1.45 ab	1.41 b	202 a	86
NT M/Lcc	54.0 a	80.9 a	64.1	77.7 a	5.8 a	5.8 a	2.0 a	2.0	1.33 b	1.35 b	190 a	195
NV	43.5 a	97.4 a	71	96.8 a	5.2 b	5.3 c	0.9 b	1.2	1.35 b	1.37 b	35 bc	23
CV (%)	12.9	16.9	23.1	7.3	1.5	0.7	5.4	23.3	4.6	2.8	15.5	99.6
p-value	0.003	0.005	0.209	0.002	0.01	0.002	0.002	0.056	0.022	0.008	0.008	0.216
R	0.95 ***		0.86 **		0.98 ***		0.69 *		0.85 **		0.60 ns	
					Typic Paleudult							
CT O/M 0N	16.2 b	26.7 e	51.5 c	52.2 b	5.4 a	5.5 ab	1.7 b	2.6 c	1.39	1.37	601 ab	392
CT O/M	17.4 b	36.6 de	55.6 bc	62.7 b	5.1 ab	5.3 ab	2.2 b	3.3 bc	1.37	1.42	570 ab	308
RT O/M	16.0 b	36.3 de	54.7 bc	63.8 b	5.4 ab	5.5 ab	5.0 b	5.1 bc	1.49	1.46	319 abc	570
NT O/M	20.5 b	51.6 cd	64.4 ab	86.9 a	5.7 a	5.7 a	5.2 b	5.9 abc	1.49	1.42	188 bc	142
NT O + V/M + CB	24.5 b	58.8 bc	64.7 ab	88.1 a	5.1 ab	5.4 ab	9.5 a	8.4 ab	1.34	1.43	461 abc	310
NT M+PB	39.9 a	73.5 ab	71.0 a	97.2 a	4.5 b	4.9 b	12.1 a	11 a	1.32	1.30	690 a	356
NV	40.4 a	87.6 a	70.0 a	93.1 a	5.1 ab	5.3 ab	1.5 b	2.1 c	1.43	1.52	40 c	6
CV (%)	18	12.5	6.5	7	5.8	4.7	27.1	32.9	6.7	6.1	42.1	108.7
p-value	0.0001	0.00002	0.0004	0.00002	0.01762	0.02846	0.00004	0.0007	0.2223	0.1278	0.0056	0.4593
R	0.85 ***		0.91		0.98 ***		0.91 ***		0.50 *		0.42 ns	

Source: Amado *et al.* [85]. [1] Means in a column followed by same letters are similar at the 0.05 probability level using Tukey. (2) ***, **, *: significant at 0.001, 0.01, and 0.05. ns: non-significant. CV (%) = variation coefficient. NV = native vegetation; CT = conventional tillage; RT = reduced tillage; NT = no tillage; P = pasture; Fw = fallow; Lcc = legume cover crop; O = oat; M = maize; V = vetch; CB = cowpea; PB = pigeon pea; 0N = no N fertilization; p-value: probability value; R: correlation coefficient.

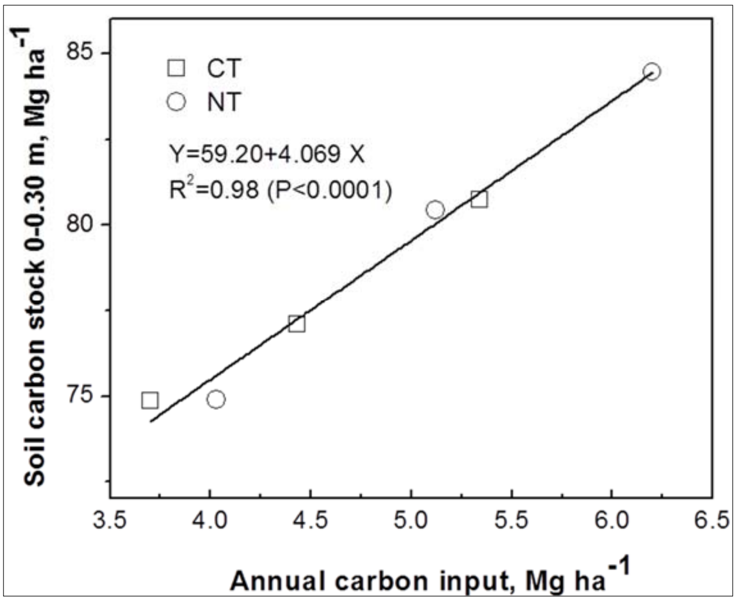


Figure 9. The relationship between annual C input and soil organic C stocks (0–0.30 m) within a subtropical Oxisol under conventional (CT) and no-till (NT) systems. Source: Campos *et al.* [44].

In a study including native vegetation, CT and NT treatments from Argentina, United States and Brazil, the role of biological activity in soil C protection was investigated [86]. The soil types were Mollisol (United States), Vertisol (Argentina) and Oxisol (Brazil) with long-term tillage system adoption. Microbial biomass, evaluated by total phospholipid fatty acids (PLFA), was higher in NT than in CT for the Mollisol and Oxisol probably due to maintained permanent soil protection and high C input by crop residues (Figure 10). Biological activity was also related to the amount of macroaggregates in topsoil (Figure 11). The relationship was stronger in the Mollisol than Oxisol, presumably reflecting the presence of iron and aluminium oxides and higher tillage intensity (eight crops in three years). The presence of macroaggregates has been suggested as an important mechanism for C protection under NT systems. With the exception of the 0–5 cm depth increment in the Oxisol, CT and NT had decreased amounts of macroaggregates and increased amounts of microaggregates when compared to native vegetation (Figure 12). These results agree with aggregate stability findings for long-term tillage experiments on Mollisols from the southeastern Pampas region and Oxisols of Brazil mentioned previously. Long-term NT adoption contributed to the improvement of some soil quality indicators in the region and was crucial for reducing soil erosion. However, quality of agricultural soils in the region has been affected despite the unprecedented adoption of this soil conservation practice. Fortunately, research findings point out that soil quality recovery throughout the region is possible with an integrated soil management approach that includes NT, crop rotations that include short term pasture, and balanced fertilization.

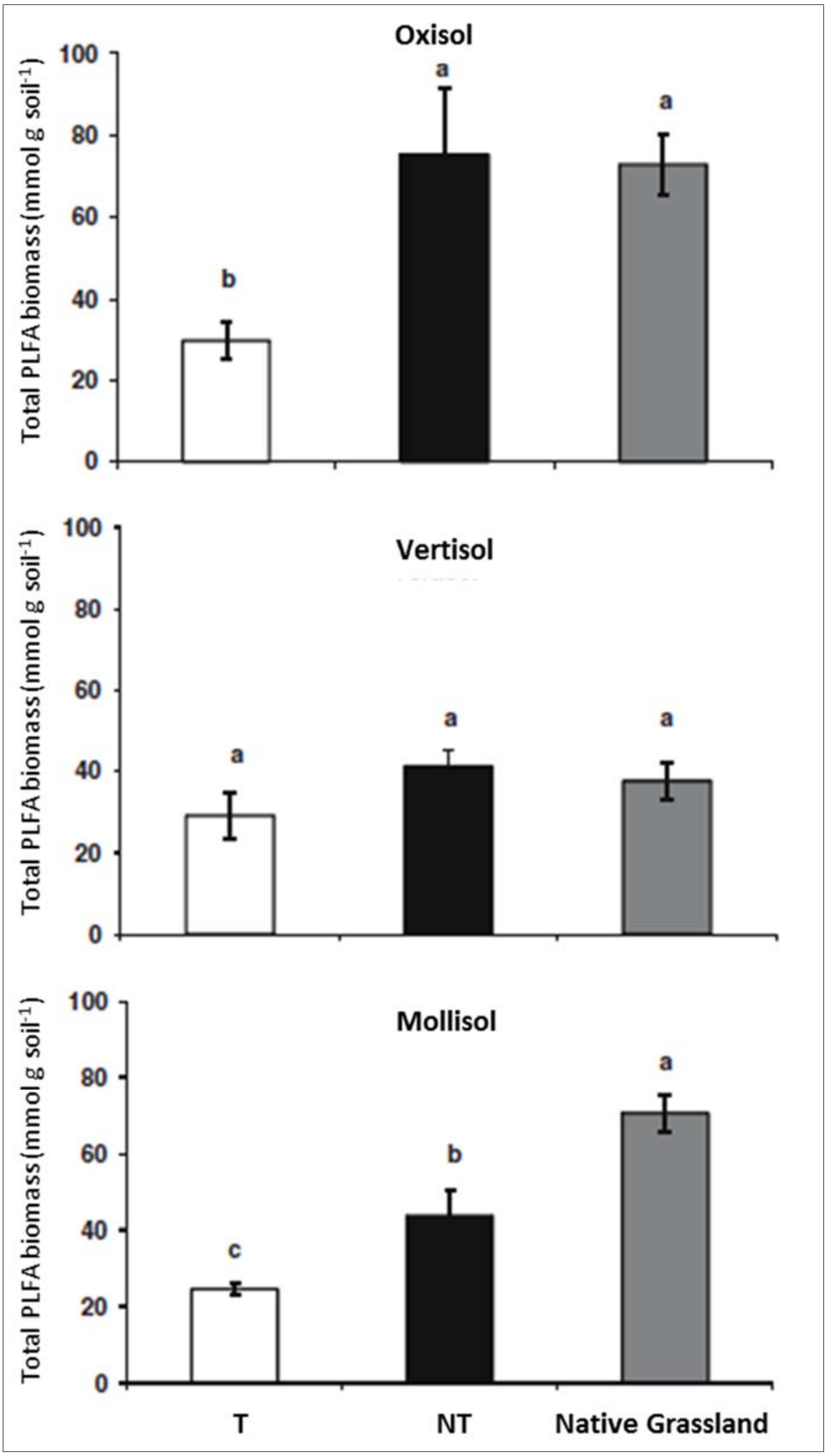


Figure 10. Mean and standard error (SE) values for microbial biomass estimated through PLFA using tilled (T), no-till (NT) and native grassland samples from the 0–0.05 m increments of an Oxisol (Brazil), Mollisol (USA) and Vertisol (Argentina). Source: Fabrizzi *et al.* [86]. Reproduced with permission from journal of Biogeochemistry.

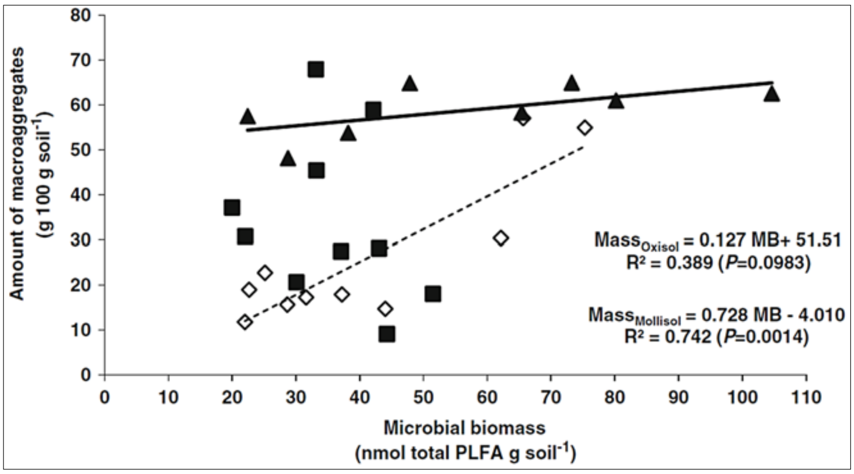


Figure 11. The relationship between microbial biomass, estimated through the PLFA technique, and the amount of macroaggregates (>250 µm) in an Oxisol (▲), Vertisol (■), and Mollisol (◊). Source: Fabrizzi *et al.* [73]. Reproduced with permission from journal of Biogeochemistry.

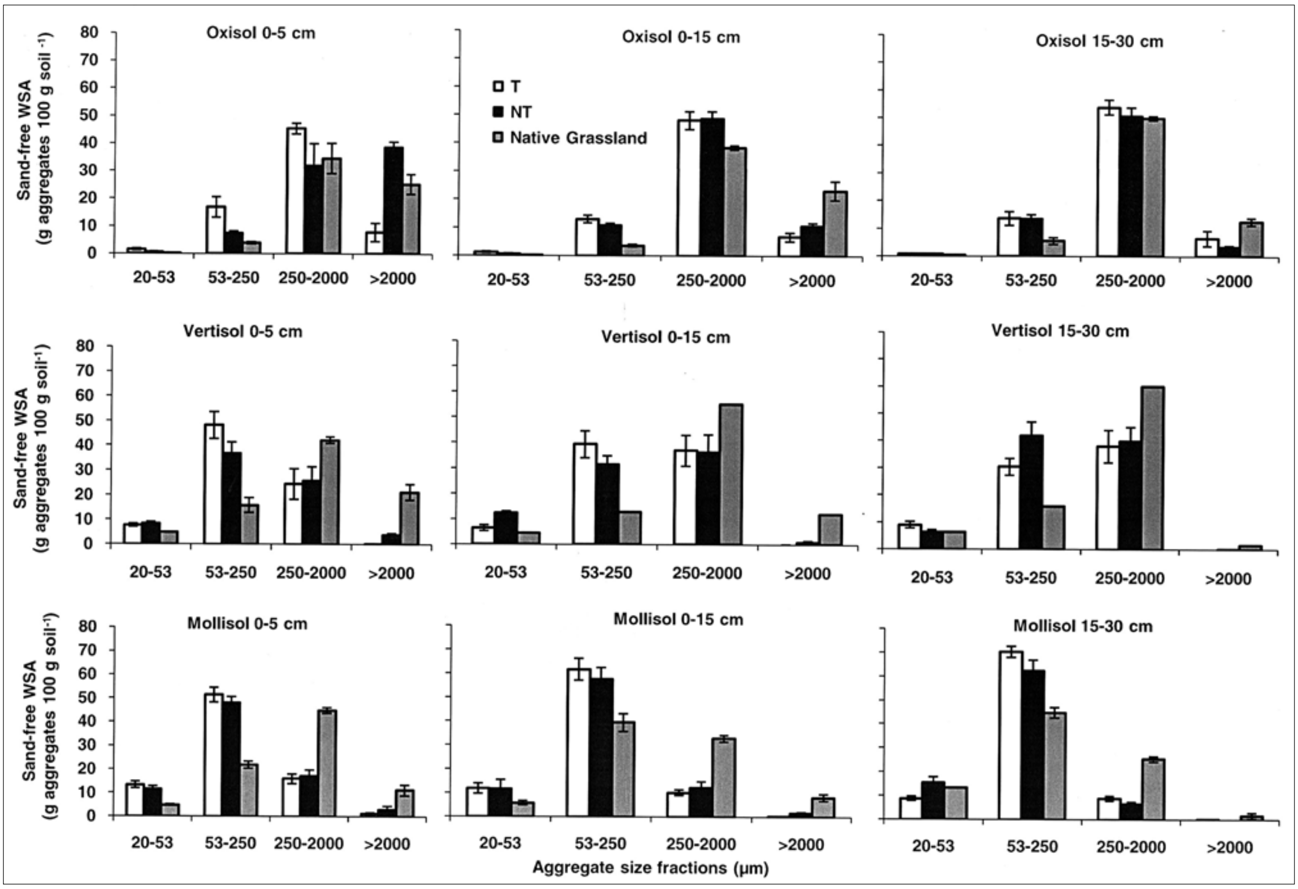


Figure 12. Distribution of sand-free water stable aggregates (WSA) under tilled (T), no-till (NT) and native grassland within the 0–5, 0–15, and 15–30 cm depth increments for the Oxisol, Vertisol, and Mollisol sites. Error bars represent the standard errors of the means. Source: Fabrizzi *et al.* [73]. Reproduced with permission from journal of Biogeochemistry.

7. Strategies for Protecting and Restoring Regional Soil Quality

Recognizing that soil is a nonrenewable resource, several legislative efforts have been initiated throughout the region to recognize, conserve, and protect both the ecosystem services and capacity for food production provided by agricultural soils. Bolivia and Uruguay have national laws of soil use and conservation under agricultural management, while in Argentina and Brazil several provinces/states have specific legislation for soil conservation. In Uruguay, farmers are currently required to develop a Land Use Management Plan with the advice of a certified agronomist for each specific field under agricultural management [87]. Each management plan is then used to determine potential soil erosion associated with the proposed management by using a software package (Erosion 6.0) based on the Universal Soil Loss Equation (USLE). For a plan to be approved, the estimated potential erosion needs to be less than the maximum allowable soil loss threshold for that soil. The Environment Protection law in Bolivia states that agricultural activities should maintain soil productive capacity and avoid soil loss and degradation [88]. To obtain and maintain a soil use license, farmers need to comply with the solicitation requirements by presenting a Management Plan and a Study of Environmental Impacts, to follow the conditions stated in the granting documentation (the Environmental Impact Declaration) of the regulatory authority, and to report the plan progress. The license is valid for 10 years if all the requirements are met. In San Luis province (Argentina), there is an enforced legislation with emphasis on peanuts (*Arachis hypogeae* L.) due to the crop's high risk for soil erosion. Similar to Uruguay, farmers that want to grow peanuts in San Luis province are required to present a five year management plan with the advice of a certified agronomist for each field under production [89]. The plans are evaluated for the potential soil loss based on soil and landscape characteristics, proposed rotations and technology. In Entre Ríos province, Argentina [90], and Parana State of southern Brazil there are specific legislative actions promoting soil conservation practices (e.g., construction of terraces). The legislation is voluntary with modest government support in Argentina, but mandatory in Brazil. The Argentinean legislation in Entre Ríos province also establishes mandatory and voluntary areas for implementation of conservation practices in the province, where farmers in mandatory conservation areas should abide to the conservation guidelines. While not widely spread in the region, these soil conservation efforts based on research findings constitute a starting point for directing the future agricultural expansion towards socially acceptable, economically viable, and environmentally sustainable systems.

8. Summary and Conclusions

This review provides an overview of research that supports our hypothesis that South America's current agricultural practices are detrimental to long-term soil quality even though NT has become a cornerstone for those practices. The analysis highlights the impact of monocultures and a general lack of biodiversity on soil degradation through wind and water erosion, SOM depletion and nutrient loss.

We found that regional economic and land tenure conditions are at odds with practices aimed at long term soil quality conservation and improvement. However, there is strong evidence that farmers embrace new practices if they understand the challenges and benefits. In the region, the adoption of NT was a voluntary reaction by farmers, agronomists and researchers in response to the unsustainable soil erosion observed under CT. The region's adoption of NT was a huge success reaching more than 54 million ha (approximately 45% of global NT area) in less than three decades without direct government financial support for the conversion from CT to NT. In the soybean cropland of the main agroecozones, NT reached adoption rates as high as 90%.

Codifying this trend, Uruguay and Bolivia, and provinces/states in Argentina and Brazil established soil conservation regulations. A couple examples include requiring soil use management plans with a crop rotation program (Uruguay and the San Luis province, Argentina) and promoting the construction of terraces (Entre Ríos province, Argentina and Parana state, Brazil). These government programs differ greatly from those in USA, Canada, and Australia, because they do not stimulate farmers economically for adopting conservation management practices and providing environmental services for the entire society.

Regional farmer adoption of NT without government support needs to be used as an example when looking for solutions to resolve soil degradation problems and the need for increased biodiversity and crop diversification. Developing and achieving adoption of alternative crop rotation systems with equivalent economic return has been a challenge for regional farmers, despite the positive and well-documented impacts of incorporating cover crops, pasture and even maize in the rotation found in agronomic research. There remains a need for multiple types of educational materials and programs that emphasize the importance of conserving the environment and enhancing soil quality. Ultimately, however, farmer compensation (direct and/or market based) for environmental services (*i.e.*, carbon sequestration, reducing nutrient runoff, and increasing biodiversity) may be required to overcome the increasing use of crop monocultures. In developed countries, consumers and retailers are requesting sustainable agricultural commodities. These demands will affect the global supply chain and producers will need to adapt to meet those requirements that often include soil quality performance indicators.

Argentina, Bolivia, southern Brazil, Paraguay and Uruguay have tremendous agricultural potential but without aggressive action and changing current crop production trends, the region will suffer soil degradation as the growing global population increases demand for food. New paradigms of agricultural production are needed to improve current soil conditions. Increased cooperation between the government, scientific community and farmers is crucial for developing effective long term solutions. Everyone's aim should be to develop more sustainable agricultural systems that balance soil quality, environmental sustainability and agricultural production while maintaining economic and social benefits for all.

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Author Contributions

Ana Wingeyer, Telmo Amado, Mario Pérez-Bidegain, Carlos Perdomo Varela, Guillermo Studdert and Fernando García were involved in the conception, discussion, and data gathering for this review. All authors contributed to the writing of the manuscript and gave thought to the conclusions. Doug Karlen edited the manuscript and provided critical final review. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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