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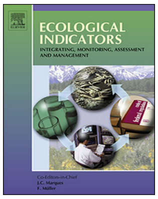

How does soil organic carbon mediate trade-offs between ecosystem services and agricultural production?

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ABSTRACT

The basis and essence of life on earth depends on soil health, and its main indicator is the soil organic carbon (SOC) content. Hence, SOC stock is a key component for the supply of many ecosystem services (SOC-mediated ES), such as erosion protection, nutrient cycling, water regulation, and climate regulation. Land use changes from natural ecosystems into agricultural systems generally deplete SOC stocks. Therefore, agricultural production usually involves trade-off relations with SOC-mediated ES supply. This paper assessed the trade-offs between agricultural production and SOC-mediated ES supply in six sub-regions of Argentina: East Southern Pampa, West Southern Pampa, Flooding Pampa, Central Pampa, Rolling Pampa and Semiarid Chaco.

In the Semiarid Chaco, overall SOC-mediated ES supply had the highest sensitivity to SOC changes, and the lowest sensitivity to natural cover removal. In East Southern Pampa, overall SOC-mediated ES supply had the lowest sensitivity to SOC changes and the highest to natural cover removal. The differences in sensitivity of overall SOC-mediated ES supply to the changes in SOC could be explained by soil texture, which is finer at East Southern Pampa. The differences in sensitivity of overall SOC-mediated ES supply to natural cover removal could be associated with the initial SOC stocks, which is lower in the Semiarid Chaco. The high sensitivity of SOC-mediated ES to SOC change and the low levels of SOC-mediated ES supply found in the Semiarid Chaco sub-region suggests that it is a highly fragile environment.

The agricultural expansion over natural areas led to trade-offs between production and SOC-mediated ES supply. However, increasing crop yields would lead to win-win situations, by positive effects on agricultural production and SOC-mediated ES supply. Hence, agricultural production should be increased by increasing crop yields rather than expanding cropland and/or pasture over natural areas.

1. Introduction

The links between ecosystem functions and human needs are often described by the ecosystem services (ES) approach. This approach offers a holistic view of the social and natural dimensions and it is proclaimed as a way to generate useful information in decision-making (TEEB, 2010). However, the implementation of the ES approach in a real-life case has been a great challenge, especially in developing countries (Balvanera et al., 2012). The coexistence of different frameworks (Mastrángelo et al., 2015), the disagreement between purposes and procedures used for ES assessments (Nahuelhual et al., 2015), and the unknown ecosystems contributions to different aspects of human well-being are among the causes to explain that challenge. Furthermore, several soil scientists stated that soil contributions to human needs are not entirely understood neither recognized within the ES framework (Wall et al., 2004, Robinson et al., 2009; Dominati, et al., 2010; Adhikari and Hartemink, 2016).

The basis and essence of life on earth depends on soil health, and its main indicator is the soil organic carbon (SOC) content (Lal, 2014). Hence, SOC stock is a key component for the supply of many ES, such as erosion protection, nutrient cycling, water regulation, and climate regulation (Palm et al., 2007; Powlson et al., 2011; Lorenz and Lal, 2016). Soil organic carbon stocks are mainly defined by climatic variables (temperature and precipitation) (Post et al., 1982), soil texture, and vegetation type (Jobbágy and Jackson, 2000). Land use changes from natural ecosystems into agricultural systems generally deplete SOC stocks (Guo and Gifford, 2002; Villarino et al., 2017). However, agricultural products (food and fibers) are needed to sustain modern societies and that implies trade-off relations between agricultural products and SOC-mediated ES. Agricultural potential production is also

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strongly influenced by edaphic and climatic variables, such as soil texture, temperature, and precipitation (van Ittersum et al., 2013). Therefore, changes in the environmental variables modify the trade-offs between agricultural production and SOC-mediated ES.

Trade-off analysis allows us identifying the amount of the ES supply lost to gain certain level of agricultural production. Agricultural production is easily measurable in physical and economic terms. However, ES supply quantification is difficult and complex, both in ecological and in economic terms (Gómez-Baggethun et al., 2010). Due to the complexity of ES models for supporting land use decisions, more simple and reliable indicators are needed. Given SOC content is intimately related to almost all soil functions and it is easily measurable, it would be a suitable indicator of soil ES supply capacity (Powlson et al., 2011; Lorenz and Lal, 2016). In addition, a large number of models that connect SOC stocks to ecosystem functions were generated outside the ES framework (Loveland and Webb, 2003). Since SOC stock is a key intermediate ES (Fisher et al., 2009), these models could be useful tools to ES assessments.

The projected population increase for 2050 will double food requirements and pressure on natural resources will be immense (Foley, 2011). As a result, the great challenge would be to increase food production by maintaining ES supply (Balmford et al., 2012). In Argentina, agricultural expansion over natural ecosystems began to be relevant at the end of the 1960s, with its main focus in the Pampean Region, but also with an epicenter in the Chaco Region (Viglizzo et al., 2011). The Pampean Region is a vast plain located in the center-east of Argentina, with temperate grasslands as native vegetation (Soriano et al., 1992). In 1990, most of those natural grasslands were already converted into croplands or cultivated pastures (Hall et al., 1992). At that time, croplands and pastures began to expand at high rates in the northern region of Argentina, especially in the Semiarid Chaco Region (Viglizzo et al., 2011). This region also comprises a vast plain but with native dry forests growing in a sub-tropical climate. Since 1976, deforestation rates in the Semiarid Chaco increased exponentially, reaching the maximum between 2006 and 2012 (2.5%, Vallejos et al., 2014). Average deforestation rates in Latin America and in the world in that period were 0.51% and 0.20%, respectively (Seghezzo et al., 2011).

Therefore, it is expected that different trade-offs between agricultural production and ES supply would emerge in different ecoregions. Thus, this paper aims to explore the spatial variation of trade-offs between agricultural production and SOC-mediated ES in the main agricultural regions of Argentina. Knowledge of the spatial variation of these relations is crucial to plan the use of the territory in order to maximize both ES supply and agricultural production.

2. Materials and methods

2.1. Study area

The study comprised 161 counties covering 614,348 km^2. The counties correspond to six sub-regions: East Southern Pampa, West Southern Pampa, Flooding Pampa, Central Pampa, Rolling Pampa and Semiarid Chaco (Fig. 1). Sub-regions were divided according to vegetation composition, soil, and climate features (Morello et al., 2012) and adapted to counties limits (Viglizzo et al., 2011). In the Pampean sub-regions, grassland was the native vegetation and the climate is temperate, with mean annual precipitation similar to the mean annual evapotranspiration (Table 1). In contrast, in the Semiarid Chaco, the native vegetation is dry forest, and the climate is warm, with lower mean annual precipitation than mean annual evapotranspiration (Table 1).

2.2. Land use change and soil organic carbon stocks

Soil organic carbon stocks at 0–20 cm soil depth, and land use areas of each county were obtained from Villarino et al. (2014) for Pampean sub-regions, and from Villarino et al. (2018) for Semiarid Chaco. In the Semiarid Chaco, SOC stocks at county scale were estimated for three different years: 1976, 1996, and 2012, and for three land uses: cropland, pasture, and forest. Dry forests were the dominant natural cover in this sub-region. In the Pampean sub-regions, SOC data at county scale was available for three years: 1960, 1988, and 2006, and for two land uses: cropland and grassland. These years were chosen because they represent contrasting periods of the land use history. Cropland included pastures in these sub-regions, since pastures rotate with annual crops and SOC stocks did not differ between annual crop and pasture phases (Berhongaray et al., 2013). Grasslands were the dominant natural cover in this region.

It was assumed that the sum of cropland, grassland, pasture and forest areas of each county is equal to the total county area. Therefore, SOC stock for each county was calculated as weighed SOC average through the area occupied by each land use. Moreover, a decrease in natural cover area (forest in Semiarid Chaco and grassland in Pampean sub-regions) always corresponded to an increase in cropland and/or pasture area.

2.3. Agricultural production and SOC-mediated ES supply

Soil functions and attributes mediated by SOC stocks that underpin the potential supply of ES (SOC-mediated ES) were assessed. The selected SOC-mediated ES were nutrient cycling, erosion resistance, climatic regulation, and water regulation. Agricultural production was estimated as the sum of crop and livestock production in energy units (Mj ha^{-1}).

2.3.1. Nutrient cycling service

Nitrogen (N) and phosphorous (P) are the two major macronutrients most important for crop production. In developing countries, such as Argentina, N is the main nutrient that limits crop yields (Echeverría and García, 2015; Lassaletta et al., 2016). Therefore, this nutrient was selected as an indicator of the nutrient cycling service.

Potentially mineralizable N (N$_0$) is a fraction of soil organic N that may contribute to crops nutrition. The ammonium released during a short anaerobic incubation (anaerobic N, AN) (Waring and Bremner, 1964) is an accurate predictor of N$_0$ (Eq. (2), Echeverría et al., 2000), and it is closely related to SOC (Reussi Calvo et al., 2013, 2014; Studdert, 2014). The relations between SOC and AN (Eq. (1)), and between AN and N$_0$ (Eq. (2)) were applied to estimate N$_0$ from SOC stocks.

$$\mathrm{AN} = 24.8 + 1.59\,\mathrm{SOC} \tag{1}$$

$$\mathrm{N_0} = 83.17 + 1.37\,\mathrm{AN} \tag{2}$$

Reussi Calvo et al. (2014) equation (Eq. (1)) was developed for the Pampean Region, exclusively. Nevertheless, in order to get an illustrative indicator, it has been also used in the Semiarid Chaco Region.

2.3.2. Erosion resistance service

Soil erodibility (K), defined as soil susceptibility to be eroded, was considered an indicator for erosion resistance ES. Soil erodibility against wind and precipitation may be estimated by models that require soil texture and SOC stock as predictor variables (Song et al., 2005). Eq. (3) (Wischmeier, 1976) was used to estimate K:

$$\mathrm{K} = 2.766\,((\%\,\mathrm{silt} + \%\,\mathrm{fine\,sand})(100 - \%\,\mathrm{clay}))^{1.14}\,10^{-6}\,(12-\mathrm{MO}) \tag{3}$$

where K is soil erodibility (Mg j^{-1}) and MO, percentage of soil organic matter.

2.3.3. Water regulation service

Soil is a key contributor to water regulation ES, mainly due to its ability to absorb and retain rainwater (Powlson et al., 2011). When rainfall intensity exceeds soil water infiltration rate, or soil water

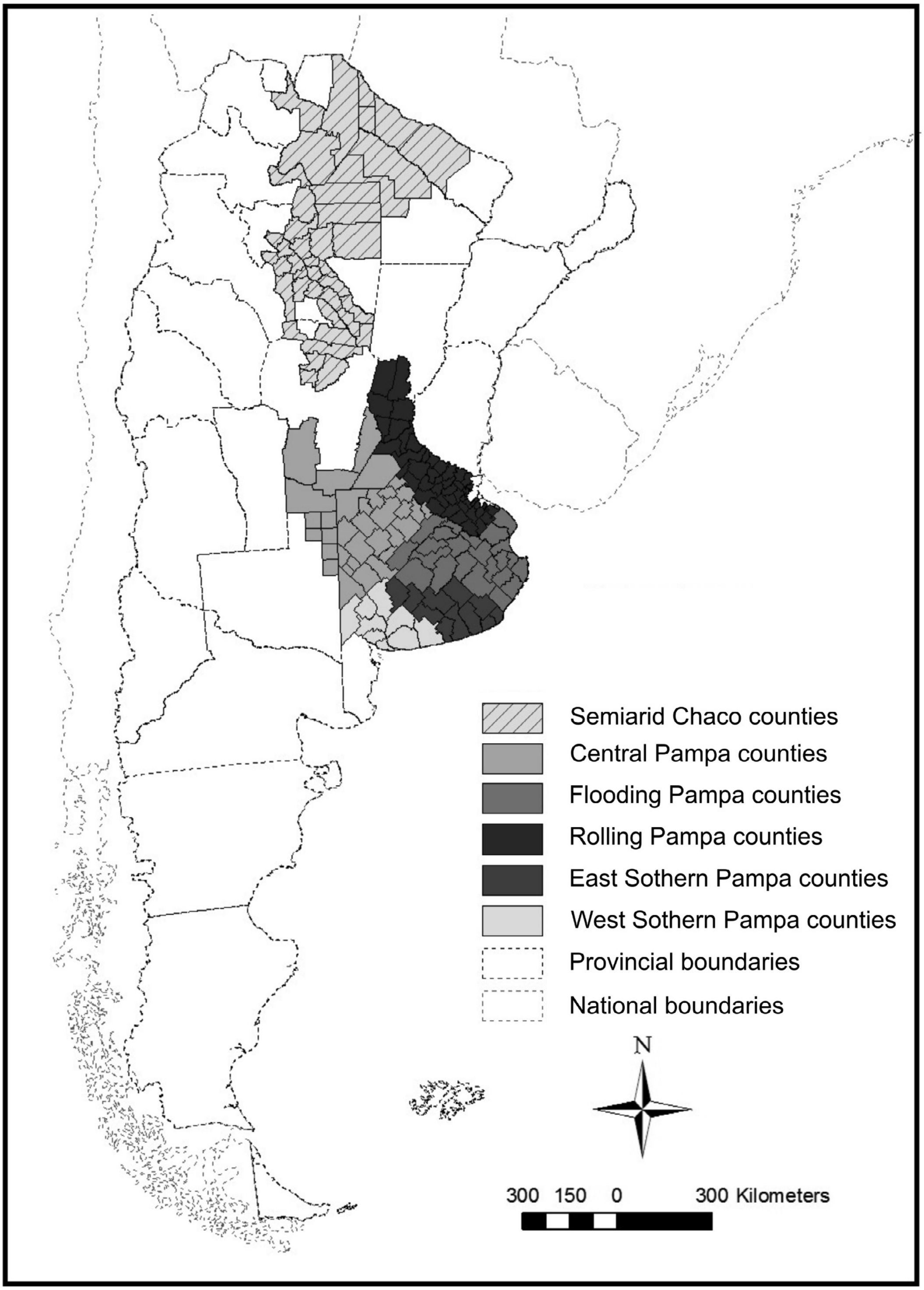

Fig. 1. Argentinean sub-regions.

storage capacity, surface runoffs and floods may occur, depending on land topography (Viglizzo et al., 2009). When soil is saturated, water infiltration rate equals saturated hydraulic conductivity (Ks) (Wu et al., 1999). Available soil water (water retained at soil water potential values between 33 kpa and 1500 kpa) is the total amount of water actively involved in the hydrological cycle (Porporato et al., 2004). Soil organic carbon is crucial to determine soil structure (Tisdall and Oades, 1982; Six et al., 2004). As a consequence, SOC affects both Ks and available soil water storage (Saxton and Rawls, 2006). These two properties were selected as indicators of water regulation ES. The equations developed by Saxton and Rawls (2006) were used to estimate them. In order to obtain a clearer understanding of the results, these two indicators of water regulation ES are shown separately.

2.3.4. *Climate regulation service*

Carbon dioxide (CO_2) is the main atmospheric gas responsible for global warming (IPCC, 2013). Soil organic C variations are associated with CO_2 sequestration (Lal, 2004). Therefore, SOC stock is considered an intermediate ES that contributes to climate regulation ES (Dominati et al., 2010; Stockmann et al., 2013).

Table 1
Variables that describe climate (Bianchi and Cravero, 2010) and soil texture (INTA, 1990) in the sub-regions under study.

Sub-region	MAT	MAP	PET	Particle size distribution (g kg^{-1})		
	(°C)	(mm)	(mm)	Clay	Silt	Sand
Semiarid Chaco	21	756	1101	118	374	508
Southern Pampa East	14	912	738	294	307	399
Southern Pampa West	14	766	739	266	380	354
Central Pampa	16	904	811	149	273	578
Flooding Pampa	15	980	776	215	330	455
Rolling Pampa	17	1010	873	242	632	126

MAT: mean annual temperature; MAP: mean annual precipitation; PET: mean annual potential evapotranspiration; E: east; W: west.

2.3.5. Supply and loss of ES

The selected indicators (N_0, K, Ks, available soil water and SOC stock) were normalized in a scale from 0 to 1; where 1 represents the highest level and 0 the lowest level of ES supply (Calzolari et al., 2016; Laterra et al., 2016). Eq. (4) was used for those normalizations, with the exception of K indicator. Since, K and erosion resistance ES are negatively correlated (i.e. as the former increases, the latter decreases), the normalization was carried out in the opposite way (Eq. (5)).

$$\text{SOC-mediated ES}_P = (Ip - Imin)/(Imax - Imin) \tag{4}$$

$$\text{SOC-mediated ES}_P = (Imax - Ip)/(Imax - Imin) \tag{5}$$

where SOC-mediated ES_p is the relative supply of SOC-mediated ES for a county in a year; Ip is the value of the of SOC-mediated ES indicator (N_0, Ks, available soil water or SOC stock) for a county and in a year; Imax is the highest value of the indicator for the data set; and Imin is the minimum value.

Soil organic C-mediated ES loss was estimated as relative to SOC-mediated ES supply with soil under natural cover (SOC stock under forest in Semiarid Chaco (Villarino et al., 2018) and under grassland in Pampean Region (Villarino et al., 2014)) (Eq. (6)).

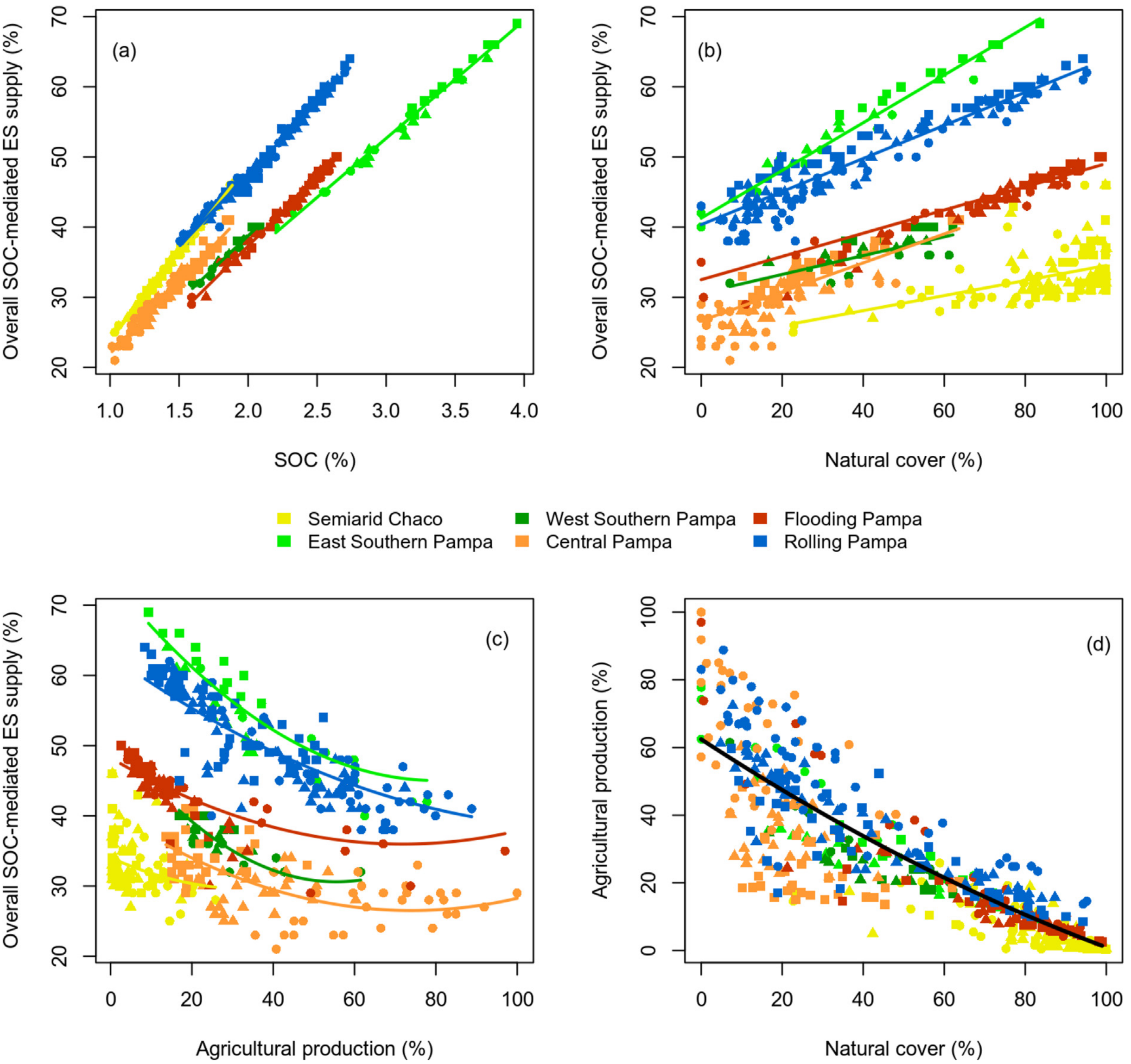

Fig. 2. Relations between ecosystem services mediated by soil organic carbon (SOC-mediated ES supply) and percentage of soil organic carbon (SOC) (a), percentage of natural cover (b), and agricultural production (c), and relation between agricultural production and percentage of natural cover (d). Squares, triangles and circles match with 1960, 1988, and 2006 for the Pampean Region, respectively; and, 1976, 1996, and 2010 for the Semiarid Chaco, respectively. The black line (d) matches to the fitted model for all sub-regions.

Table 2
Summary of models showed in Fig. 2.

Independent variable	Sub-region	Dependent Variable											
		SOC-mediated ES supply						Agricultural production					
		α		β1		β2		α		β1		β2	
		Estimated	SE	Estimated	SE	Estimated	SE	Estimated	SE	Estimated	SE	Estimated	SE
Soil organic carbon (%)	SC	−1	0.3	24.9	0.2								
	ESP	2.2	1.1	16.8	0.4								
	WSP	1.5	1.4	18.6	0.8								
	CP	1.4	0.7	20.6	0.5								
	FP	−1.6	0.7	19.5	0.3								
	RP	6.4	0.5	20.6	0.3								
Natural cover (%)	SC	23.8	1.4	0.1	0.02			62.4	2.2	−0.8	0.06	0.002	0.0004
	ESP	41.3	1.6	0.3	0.02								
	WSP	30.6	2	0.1	0.03								
	CP	26.6	1.5	0.2	0.03								
	FP	32.5	1.5	0.2	0.02								
	RP	40.3	1.5	0.2	0.02								
Agricultural production	SC	34	0.4	−0.3	0.1	0.004	0.003						
	ESP	73.7	4.1	−0.7	0.2	0.004	0.004						
	WSP	51.6	3.2	−0.8	0.2	0.007	0.004						
	CP	40.6	1.2	−0.4	0.1	0.003	0.003						
	FP	48.3	0.8	−0.3	0.1	0.002	0.003						
	RP	62.9	1.4	−0.4	0.1	0.002	0.003						

α: intercept of the fitted model; β1: linear component of the fitted model; β2: quadratic component of the fitted model; SE: standard error; SC: Semiarid Chaco; ESP: East Southern Pampa; WSP: West Southern Pampa; CP: Central Pampa; FP: Flooding Pampa; RP: Rolling Pampa.

$$\text{Loss of SOC-mediated ES} = 1 - (\text{SOC-mediated ES}_P)/(\text{SOC-mediated ES}_{nc}) \tag{6}$$

where SOC-mediated ES_p is the relative supply of SOC-mediated ES for a county in a year; SOC-mediated ES_{nc} is the relative supply of SOC-mediated ES under natural cover for a county.

Assuming that agricultural production is an ecosystem benefit and that SOC-mediated ES loss a consequent ecosystem cost, cost-benefit ratio was estimated according to the classical economy theory (Hanley and Spash, 1993). The overall supply of SOC-mediated ES was calculated as the average of all SOC-mediated ES (Carreño et al., 2012) and then was multiplied by 100 to express values in percentage units (%).

2.3.6. Agricultural production

Agricultural production was calculated as the sum of crop and livestock production. Crop production per county was taken from the Agricultural Integrated Information System (SIIA, 2015). Regarding livestock, there are two types of production systems in the Pampean Region: reproduction oriented or “cow-calf” systems, and meat production systems (Modernel et al., 2016). It was assumed that “cow-calf” production was between 80 and 150 kg ha^{-1}, and meat production between 200 and 500 kg ha^{-1} (Rearte, 2007). In the Pampean Region, livestock production grew from 1960 to 2006 (Modernel et al., 2016). Hence, the lowest production levels correspond to 1960, the highest to 2006, and the average between the maximum and the minimum was assumed in 1988. The “cow-calf” production system was assigned to the Flooding Pampa sub-region and the meat production system to the other sub-regions (Rearte, 2007). In the Semiarid Chaco Region, it was assumed 10 kg ha^{-1} for livestock production in native forest (Rearte, 2007; Mastrángelo and Gavin, 2012), and 150 kg ha^{-1} for livestock production in pastures (Mastrángelo and Gavin, 2012).

Physical production per hectare was turned into energy units to be able to sum up crop and livestock productions. For this purpose, gross energy was assumed as 4.2 Mcal kg^{-1} in crops products (grains), and 3.9 Mcal kg^{-1} in meat (Merrill and Watt, 1973). Finally, agricultural production was normalized in a scale from 0 to 1; where 1 represents the higher and 0 the minimum production level, in the same way as for SOC-mediated ES supply (Eq. (4)), and then was multiplied by 100 to express values in percentage units (%).

2.4. Statistical analysis

The relations between SOC-mediated ES supply, SOC, percentage of natural cover, and agricultural production were described by fitting general linear models. Such models were fitted with the gls function from nlme package of the R software (R Core Team, 2013). A general correlation structure was adjusted for errors throughout the years in the same county (Pinheiro et al., 2015). When the variance homogeneity of errors assumption was violated, variance heterogeneity was incorporated in the model. The final models that met the assumptions were selected through the residual plot analysis.

3. Results and discussion

3.1. Agricultural production and overall SOC-mediated ES supply

The relations between SOC and overall SOC-mediated ES supply were different among sub-regions (Fig. 2a). Overall SOC-mediated ES supply sensitivity to changes in SOC concentrations is described by the slopes of the corresponding models (Fig. 2a, Table 2). The model in Semiarid Chaco showed the highest slope (Fig. 2a, Table 2). Therefore, overall SOC-mediated ES supply in this sub-region had the greatest sensitivity to SOC changes. The opposite was observed in East Southern Pampa, where the model showed the lowest slope (Fig. 2a, Table 2). Moreover, the lowest sensitivity of overall SOC-mediated ES supply to natural cover removal was observed in the Semiarid Chaco (lowest slope of model, Fig. 2b). Once again, the opposite was observed in the East Southern Pampa, where overall SOC-mediated ES supply had the highest sensitivity to natural cover removal (Fig. 2b). Summarizing, in the Semiarid Chaco, overall SOC-mediated ES supply had the highest sensitivity to SOC changes, and the lowest sensitivity to natural cover removal. In East Southern Pampa, overall SOC-mediated ES supply had the lowest sensitivity to SOC changes and the highest to natural cover removal.

The critical threshold of SOC concentrations (i.e. minimum amount

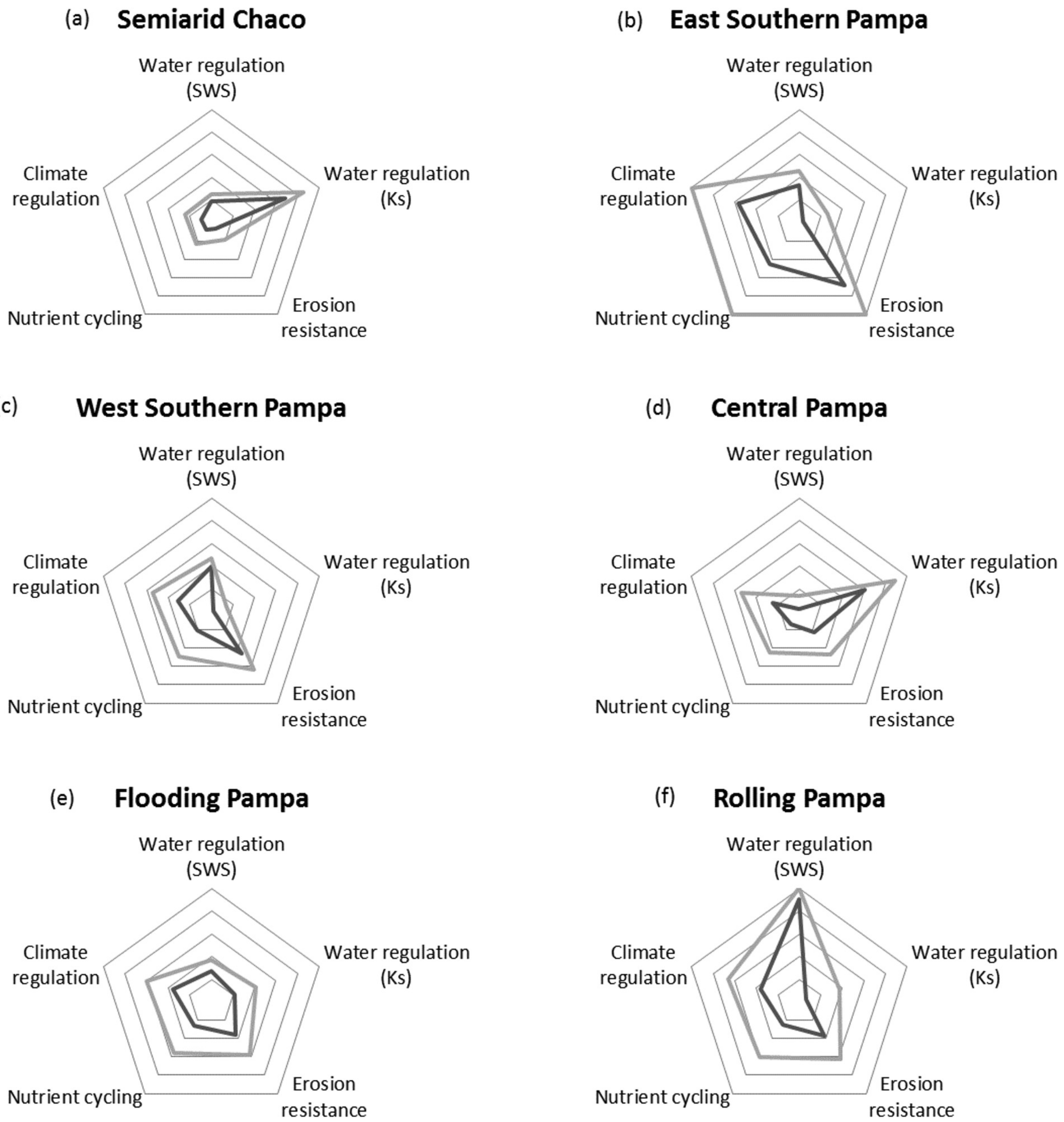

Fig. 3. Relative supply of SOC-mediated ES of soil under natural cover (light grey line) and cropland (dark grey line), in 2006 for the Pampean sub-regions, and in 2010 for the Semiarid Chaco. The scale goes from zero (center of the pentagons) to one (exterior perimeter of the pentagons) (Eq. (4) and (5)). SWS: soil water storage, Ks: saturated hydraulic conductivity.

of SOC concentrations needed for soil functioning) is unknown (Loveland and Webb, 2003). However, this threshold depends on soil texture, and it would be closer to the native SOC concentrations (soil under natural cover) in soils with high sand content and low clay content (Stockmann et al., 2013). When SOC concentration is close to the critical threshold, slight variations of SOC may imply major changes in SOC-mediated ES (Loveland and Webb, 2003; Powlson et al., 2011). This hypothesis agrees with the greater sensitivity of overall SOC-mediated ES supply to the changes in SOC observed in Semiarid Chaco, where soil texture is defined by high proportion of sand and low proportion of clay (Table 1). On the contrary, the lowest sensitivity was observed in the East Southern Pampa, where soil texture is defined by higher proportions of clay and lower proportions of sand (Table 1).

The highest sensitivity of overall SOC-mediated ES supply to natural cover removal was observed in the East Southern Pampa (Fig. 2b); that is the sub-region with the highest SOC stocks under natural cover (~107 Mg ha^{-1} at 0–30 cm soil depth (Villarino et al., 2014)). On the other hand, the lowest sensitivity of overall SOC-mediated ES supply to natural cover removal was observed in the Semiarid Chaco; that is the sub-region with the lowest SOC stocks under natural cover (~40 Mg ha^{-1} at 0–30 cm soil depth (Villarino et al., 2018)). The magnitude and direction of SOC stock variations due to land use changes depend, to a large extent, on the initial SOC stock (Berhongaray et al., 2013). In the Pampean Region, Berhongaray et al. (2013) reported that, between 1960 and 2008, soils with high initial SOC stocks (more than 95 Mg ha^{-1} at 0–100 cm soil depth) had lost SOC due to agricultural land use, and soils with low initial SOC stocks (less than 95 Mg ha^{-1} at 0–100 cm soil depth) had maintained or even gained SOC. This effect of initial SOC stock on SOC changes could explain the differences in sensitivity to natural cover observed in East Southern Pampa and Semiarid Chaco.

Increases in agricultural production may be caused by increases in

Table 3
Relations between overall SOC-mediate ES loss (cost) and agricultural production (benefit) for the different sub-regions.

Sub-region	Year	Land use	Cost	Benefit	Cost-benefit
Semiarid Chaco	1976	Cropland	0.37	0.24	1.53
		Pasture	0.19	0.03	6.93
	1996	Cropland	0.48	0.43	1.11
		Pasture	0.22	0.03	8.04
	2010	Cropland	0.44	0.39	1.12
		Pasture	0.24	0.03	8.93
East Southern Pampa	1960	Cropland	0.40	0.37	1.10
	1988	Cropland	0.44	0.36	1.23
	2006	Cropland	0.49	0.51	0.96
West Southern Pampa	1960	Cropland	0.32	0.29	1.08
	1988	Cropland	0.37	0.28	1.33
	2006	Cropland	0.47	0.36	1.28
Central Pampa	1960	Cropland	0.48	0.29	1.63
	1988	Cropland	0.57	0.39	1.47
	2006	Cropland	0.59	0.56	1.06
Flooding Pampa	1960	Cropland	0.38	0.32	1.18
	1988	Cropland	0.42	0.37	1.14
	2006	Cropland	0.41	0.57	0.71
Rolling Pampa	1960	Cropland	0.38	0.46	0.83
	1988	Cropland	0.44	0.48	0.91
	2006	Cropland	0.49	0.57	0.86

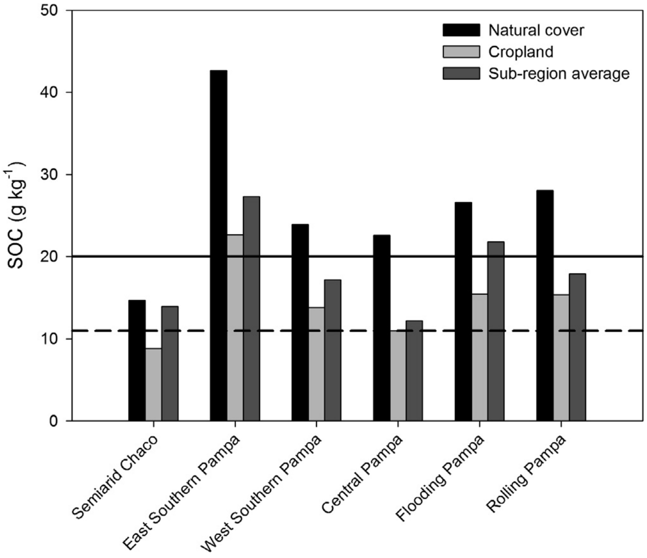

Fig. 4. Averages concentrations of soil organic carbon (SOC) for 2006 in Pampa's sub-regions (Villarino et al., 2014) and for 2010 in Semiarid Chaco (Villarino et al., 2018). Critical thresholds proposed for temperate regions (full line), and for topical regions (dashed line) (Lal, 2011).

cropland area or increases in productivity per unit area. When agricultural production increases at the expense of natural areas (Fig. 2d), overall SOC-mediated ES supply decreases (Fig. 2b). However, the relation between overall SOC-mediated ES supply and agricultural production shows that the marginal loss of overall SOC-mediated ES supply decreases as production increases (Fig. 2c). However, this relation could be different like in Central and Flooding Pampa sub-regions where, at high production levels, it is suggested a win-win situation: SOC-mediated ES supply and agricultural production increase together (Fig. 2c).

Until the 1990s, in the Pampean Region there was an expansion phase, where increases in production were mainly due to the expansion of crops and pastures on natural grassland (Hall et al., 1992). Then, on account of technological improvements, agricultural production initiated a new phase characterized by intensification and technology adoption, and production increases were mainly due to productivity increases (Viglizzo et al., 2011). Mayor initial loss of SOC-mediated ES supply can be associated with the first phase of agricultural expansion (squares in Fig. 2c), where crop yields were low (SIIA, 2015). Later minor losses (circles in Fig. 2c) can be related to the further crop yield increase (intensification phase) (SIIA, 2015), because crop yield and SOC stocks are reported to be positively correlated (Álvarez and Lavado, 1998; Studdert and Echeverría, 2000; Álvarez et al., 2011). Therefore, this positive relation between crop yield and SOC-mediated ES supply could explain this potential win-win situation. In general, trade-offs between ES supply and agricultural production are the rule (Viglizzo and Frank, 2006b; Carreño et al., 2012) and win-win situations are exceptionally found (Laterra et al., 2012). The unusual win-win situations may be explained by the lack of consideration of soil functioning within ES conceptual framework (Wall et al., 2004; Robinson et al., 2009; Dominati et al., 2010).

3.2. Disaggregated SOC-mediated ES supply

The supply of the different types of SOC-mediated ES assessed varied greatly among sub-regions, and, within them, between cropland and soil under natural cover (Fig. 3). Hence, land use change had different effect on SOC-mediated ES supply among sub-regions. In the Semiarid Chaco, cropland produced little changes on SOC-mediated ES supply, and it maintained the lowest supply levels. Water regulation SOC-mediated ES was an exception where the Ks indicator showed high values. However, available soil water storage capacity, other indicator associated with this ES, presented low values. Due to the high sand content in soils of Semiarid Chaco (Fig. 3a) and Central Pampa (Fig. 3d) a high value of Ks and a low value of available soil water storage capacity was expected (Nielsen et al., 1973; Clapp and Hornberger, 1978). On the contrary, in the Rolling Pampa (Fig. 3f) the values of Ks and of available water storage capacity were minimum and maximum, respectively. This is also associated with soil texture, which in this sub-region is much finer. In the Pampean Region it was found that the available water storage capacity is positively correlated with soil productivity (De Paepe and Álvarez, 2013). In agreement with this, the highest water storage capacity (Fig. 3f) and crop yields were found in Rolling Pampa (Table 3).

In contrast to the pattern observed in the Semiarid Chaco, cropland in East Southern Pampa greatly affected SOC-mediated ES. However, most of SOC-mediated ES kept intermediate levels of supply under cropland (Fig. 3b). In this sub-region, nutrient supply, climate regulation and erosion resistance presented maximum values, under natural cover and cropland. This suggests that, in this sub-region, soil functions in cropland are better preserved than in other sub-regions. Nevertheless, the low levels of Ks found in this sub-region, in the West Southern Pampa (Fig. 3c), in the Flooding Pampa (Fig. 3e) and in the Rolling Pampa (Fig. 3f) show that special attention should be paid to SOC-mediated ES of water regulation, mainly, considering that most of the Pampean Region constitute a plain of poor drainage system that make them vulnerable to floods (Latrubesse and Brea, 2009).

3.3. Cost-benefit ratio and SOC-mediated ES sustainability

The lower the cost-benefit ratio, the higher the advantage would be for agricultural production, since it would indicate higher production and/or lower costs. Cost depends on the base lines of each sub-region (SOC under natural cover, Eq. (6)). Therefore, comparison of costs among sub-regions is not possible. However, cost-benefit ratio could be employed to assess changes over time and to compare land uses within a specific sub-region.

In every sub-region, costs and benefits increased between the first and the last year under analysis. Generally, the increase of benefits was proportionally higher than cost increase and, as a result, cost-benefit ratio tended to decrease over time (Table 3). In the Semiarid Chaco, cost-benefit ratios of cropland and pasture were compared. Pasture resulted in lower cost and benefit than cropland. However, benefits were much lower than costs. As a result, the cost-benefit ratios of pasture were significantly larger than cropland in all years (Table 3). This suggests that pastures are not an advisable use for the Semiarid Chaco sub-region. When comparing biodiversity and agricultural production, similar results were obtained by other authors in this sub-region (Mastrángelo and Gavin, 2012; Macchi et al., 2013). On the one hand, Mastrángelo and Gavin (2012) found that pastures carry a very high cost regarding bird biodiversity loss, whereas silvopastoral systems achieve a good integration between production and bird conservation. On the other hand, Macchi et al. (2013) concluded that cropland (soybean crop) produces a more efficient cost-benefit ratio than pastures, mainly due to the fact that crop benefits double pasture ones.

It is worth noting that despite cost-benefit ratio provides some insight regarding how different levels of benefits affect SOC-mediated ES, the analysis does not consider system sustainability (i.e. maintenance of these cost-benefit ratios over time). Soil health is fundamental for maintaining ES supply over time, and SOC concentration is its main indicator (Weil and Magdoff, 2004; Powlson et al., 2011). According to current knowledge, the critical threshold of SOC is around 11 $\mathrm{g\,kg^{-1}}$ for tropical regions, and around 20 $\mathrm{g\,kg^{-1}}$ for temperate regions (Lal, 2011). Therefore, in the Semiarid Chaco sub-region, SOC concentration under natural cover is above the threshold for tropical regions and below that for temperate regions (Fig. 4). However, SOC concentrations in croplands in this sub-region, as well as in the Central Pampa sub-region, are below both critical thresholds (Fig. 4). This suggests that cropland land use in these environments seriously compromised soil health and, therefore, the supply of SOC-mediated ES over time. On the contrary, the East Southern Pampa is the only sub-region where SOC concentration is above the critical threshold for temperate regions, even for cropland land use (Fig. 4).

4. Conclusions

The agricultural expansion over natural areas led to trade-offs between production and SOC-mediated ES supply. However, increasing crop yields would lead to win-win situations, by positive effects on agricultural production and SOC-mediated ES supply. Crop yields in Argentina are near 65% of its potential yield under rainfed condition (Aramburu Merlos et al., 2015). Hence, agricultural production should be increased by reducing this gap between real and potential yield rather than expanding cropland and/or pasture over natural areas. By this strategy, trade-offs would be characterized by lower costs and higher benefits.

Opposite to the Pampean sub-regions, the Semiarid Chaco sub-region still maintains a large area of natural cover exposed to be transformed for its agricultural use. The high sensitivity of SOC-mediated ES to SOC change and the low levels of SOC-mediated ES supply found in the Semiarid Chaco sub-region suggests that it is a highly fragile environment. Thus, cropland and pasture expansion in this sub-region could not only produce low sustainability of agricultural systems, but also generate environmental degradation at a landscape scale. Dust storms (Viglizzo and Frank, 2006a) and floods (Nosetto et al., 2012) in semiarid regions are some negative externalities associated to environmental degradation at landscape scale.

Trade-off and win-win situations observed in this work emerged from the analysis of variations of SOC, an easily measurable indicator. These results reinforce the suitability of SOC as an appropriate indicator for soil management decisions, land use planning, and regulation. For that purpose, it would be fundamental to improve our knowledge regarding critical thresholds of SOC concentrations for different soil types.

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