Soil & Tillage Research 170 (2017) 53–65

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis

Roberto Alvarez[a,b,*], Haydee S. Steinbach[a], Josefina L. De Paepe[a,b]

[a] Facultad de Agronomía,Universidad de Buenos Aires, Av. San Martín 4453(1417) Buenos Aires, Argentina
[b] CONICET, Buenos Aires, Argentina

ARTICLE INFO

Article history:
Received 9 September 2016
Received in revised form 22 February 2017
Accepted 9 March 2017
Available online xxx

Keywords:
Cover crops
Pampean region
Meta-analysis

ABSTRACT

Cover crops are a valuable management option for reducing soil erosion and nitrogen losses from agroecosystems. They improve soil quality but the impacts on crop yield depend on the type of cover crop, the commercial crop considered and the climate. In the Argentine Pampas the introduction of cover crops in rotations is being extensively studied by official institutions. We performed a meta-analysis with results of 67 local field experiments in which winter cover crop effects on soils and crops were analyzed. Soil physical properties improved after cover crops. Bulk density was minimally affected, structural stability and water infiltration increased, while soil penetration resistance decreased. Soil organic carbon content of the 0–20 cm layer rose ca. 4% in fine-textured soils and 9% in coarser ones. Nitrate-N decreased after cover crops by 30% regardless if the cover crop species was or was not legume. Soil available water at crop sowing was not affected by cover crops in the upper meter of the profile but when the cumulative water content was measured at depth (ca. 2 m) it decreased by around 20%. Soybean (*Glycine max*) yield was barely affected by the previous cover crop or fallow treatment. Conversely, corn (*Zea mays*) yield tended to decrease when the cover crop was a non-legume (- 8%) or significantly increased after legume species (+7%) when compared to a fallow. In the Pampas, cover crops have multifunctional benefits and their adoption will depend on the balance between these benefits, the sowing cost and some possible negative effects on corn yield. For this latter crop, legume cover crops are recommended.

1. Introduction

It has long been recognized that the replacement of a bare fallow period by a cover crop is a suitable tool for decreasing runoff and soil erosion in many agroecosystems (Reeves, 1994; Langdale et al., 1991). As cover crops reduce soil nitrate-N accumulation they can also substantially reduce nitrogen leaching (Constantin et al., 2015; Valkama et al., 2015). One unique application is the use of catch crops; a non-harvested cover crop with the primary function being control of leaching (Thorup-Kristensen et al., 2003). Another well known effect of cover crops is their function as green manure for the subsequent commercial crop in some cases through the introduction of nitrogen to the agroecosystem by atmospheric fixation (Fageria et al., 2005; Li et al., 2015) or by increasing the mineralization from cover crop residues during the grain crop growing cycle (Thorup-Kristensen et al., 2003). This results in a nitrogen credit for the commercial crop (Fageria et al., 2005; Ketterings et al., 2015) and a positive feedback on yield (Fageria et al., 2005; Miguez and Bollero, 2005; Sainju and Singh, 1997). Weed control is another possible benefit of cover crop use (Cherr et al., 2006; Harrwing and Ulrich Ammon, 2002). These positive environmental and agronomic effects of cover crops can offset the cost of its seeding (Reeves, 1994; Snapp et al., 2005).

The introduction of cover crops in rotations can bring along some other desired or undesired effects in agroecosystems. The soil physical status may be improved by cover crops but conflicting results have been reported in different experiments. Soil organic carbon commonly increases some years after the introduction of cover crops (Poeplau and Don, 2015) and this may be related to the improved structural condition of some soils under cover crop treatment (Fageria et al., 2005; Harrwing and Ulrich Ammon, 2002). In some experiments, however, no structural improvement was reported (Mendes et al., 1999). Bulk density was minimally impacted by cover crops (Hubbard et al., 2013; Zhu et al., 2012) or it did not differ significantly in comparison to soils with fallow periods (Chen et al., 2014; Hubbard et al., 2013). Soil penetration resistance may decrease (Folorunso et al., 1992) or not be affected

---

[*] Corresponding author at: Facultad de Agronomía,Universidad de Buenos Aires, Av. San Martín 4453(1417) Buenos Aires, Argentina.
E-mail address: ralvarez@agro.uba.ar (R. Alvarez).

http://dx.doi.org/10.1016/j.still.2017.03.005
0167-1987/

(Chen et al., 2014) by cover crop cultivation. Similarly, controversial data were published on the impact of cover crops on infiltration, with increases in some situations (Lal et al., 1978) or no effects in others (Steele et al., 2012). In low rainfall areas (<800 mm annual rainfall) cover crops can lead to soil water depletion reducing commercial crop yield (Blanco-Canqui et al., 2015; Reeves, 1994). Consequently, cover crops are multifunctional crops with multiple impacts on ecosystem services (Blanco-Canqui et al., 2015) and their adoption must be decided based on an overall evaluation of their advantages and disadvantages.

Modern meta-analytic techniques were developed for averaging means across different studies with heterogeneous variation and to permit a sound statistical comparison (Hedges and Olkin, 1985). These techniques are currently replacing review papers from which average effect size cannot be summarized. Some meta-analysis on the impact of cover crops on soil carbon (Poeplau and Don, 2015), nitrates (Tonitto et al., 2006) and grain crop yield, mainly corn (*Zea mays* (L.)) (Miguez and Bollero, 2005) were performed. In these studies results generated mainly in experiments carried out in the Northern Hemisphere and under temperate climate conditions were used. Other effects of cover crops on the agroecosystems have not been assessed yet by meta-analysis.

The Argentine Pampa is a vast plain of ca. 60 Mha which has been considered one of the main grain crop production areas of the world because of its extension and yield potential (Satorre and Slafer, 1999). This region is distinct from other important agricultural areas because of its warm-temperate climate and extensive use of soybean in crop rotations. Winter cover crops are being adopted by farmers gradually and many experiments were performed by official institutions to evaluate their suitability as a common production practice. A first attempt to analyze part of the available information reported a great increase in soil organic carbon when a fallow was replaced by cover crops (>5 t C ha^{-1} equivalent to ca. 15% increase of carbon content in the 0–20 cm layer), with no clear effect on soil water content and no impact on summer crop yields (Rimski-Korsakov et al., 2015). Our aim was to perform a meta-analysis of available information on winter cover crop effects on physical and chemical soil properties, soil available water content and soybean and corn yield in order to generate possible management recommendations based on an overall evaluation of the impact of this type of crops on local agro-ecosystems.

2. Materials and methods

2.1. Study area

The Argentine Pampa is located between 28°S and 40°S and 57°W and 68°W. Around 90% of the grain produced in the country originates in this region. The natural predominant vegetation is grassland and natural forests account for about 7% of the surface (INDEC, 2002). Climate is warm-temperate and humid with mean temperature ranging from 14 °C in the south to 23 °C in the north and mean annual rainfall ranging from 500 mm in the west to 1200 mm in the east. The relief is flat or slightly rolling with Mollisols, formed on loess-like materials, as predominant soils (Alvarez and Lavado, 1998). Soil texture and depth vary from sandy-shallow in the west to clayey-deep in the east as the result of the aeolian origin of sediments and the predominance of SW to NE winds, and the west-east climatic gradient (Alvarez and Lavado, 1998; Berhongaray et al., 2013). Illite is the predominant clay mineral (Alvarez and Lavado, 1998). In many places along the west and the south ends of the region a petrocalcic horizon appears within the upper 1 m of the soil profile (Teruggi, 1957). Soil organic carbon shows a strong association with rainfall (Alvarez and Lavado, 1998; Berhongaray et al., 2013) and pH is not associated with climate, ranging from 6 to 7 in well drained agricultural soils (Berhongaray et al., 2013). High pH values are associated with hydromorphic soils mainly devoted to livestock production (Hall et al., 1992).

In the semiarid and humid areas, with annual rainfall above 600 mm, rain-fed crops are cultivated (Hall et al., 1992; Alvarez and Lavado, 1998). Since 1970 grain crop production has expanded on previously grazing areas (Alvarez et al., 2014c,d) and soybean (*Glycine max* (L.) Merr.) has been widely adopted as the main component of rotations (Viglizzo et al., 2001, 2011). At present, around 60% of the pampean area is under cropping with soybean, wheat (*Triticum aestivum* (L.)), corn and sunflower (*Helianthus annuus* (L.)) being the main crops (MinAgri, 2016). Soybean accounts for 60% of the area devoted annually to crops (MinAgri, 2016). The expansion of grain crops was attributed to rainfall increases and technological improvements (Magrin et al., 2005; Viglizzo et al., 1997), which also led to a 2 to 3-fold yield increase depending on the crop, which resulted in a strong rise in regional grain production (Alvarez et al., 2015). In the past, grain crops were commonly rotated with livestock production and a low-external input agriculture (Viglizzo et al., 2001, 2011). Currently, continuous cultivation of grain crops is common and pastures or annual forages tend to disappear from rotations (Alvarez et al., 2014c,d). Since 1990 no-till has had a widespread adoption including low fertilization rates mainly for cereal crops (Alvarez et al., 2015). In the last 20 years winter cover crops have been slowly adopted by farmers as a possible tool for improving soil quality.

2.2. Data acquisition and processing

We searched for published results of field experiments in which cover crop effects were evaluated on soils and crops in the Pampas. All possible information sources were taken into account. Information used came from peer reviewed journals, experimental station technical bulletins and scientific congress proceedings in which full length papers were available. Search in peer review journals was performed using Scopus and Google Scholar. Combinations of the words cover crops or catch crops or green manure and Argentina or Pampas or Pampean Region were used as search terms. A local scientific journal devoted to soil science available on line (Ciencia del Suelo) was entirely reviewed. An on line search was performed of technical bulletins from the experimental stations of the Instituto Nacional de Tecnología Agropecuaria, an official institution devoted to field experimentation and agricultural extension. Proceedings of the National Soil Science Congress for the last 26 years (9 proceedings) were also revised.

To be included in our data set, an experiment had to meet the following criteria: 1) it had to be performed by an official institution under field conditions, 2) management practices had to be similar to those applied under production scenarios, 3) a control treatment under bare fallow had to be compared against at least one cover crop treatment, 4) the cover crop species had to be identified, 5) treatments could differ only in fallow-cover crop management and all other factors (grain crop, varieties, fertilization, etc.) had to be similar, 6) the experimental design had to be clearly described (in three cases we contacted the authors of the experiments for some additional missing information), 7) average and number of replications of the control and the cover crop treatments had to be reported for at least one of the following variables: soil bulk density, soil penetration resistance, structural stability, infiltration, organic carbon content, nitrate-N level, available water content, or yield of soybean or corn, 8) experiment duration and time of measurement had to be indicated, 9) sampling depth of soil properties had to be specified. Report of treatment variances was not considered as a requisite in this selection because these were not included in many sources and this would have made the *meta*-analysis impossible. In around 12% of cases (across all variables and experiments) standard deviation or standard errors were available for the control and cover crop treatments, in which case they were extracted. Usually, variability of the reported means was included in one or two studies for each addressed variable. Data were extracted from tables and figures, in the latter case a program for data acquisition was used (Get Data Graph Digitizer 2.24).

As a result of the search we compiled data from 67 experiments done across the Pampas (Fig. 1). Each experiment was performed in a different site. Usually, a publication reported data from one single experiment but in some cases results from two or more experiments were included. Climate data from the experimental sites are means of a 40 year period (1967–2006) from a previously elaborated database (De Paepe and Alvarez, 2016). Except in one site, annual rainfall was always above 700 mm, usually ranging from 800 and 1000 mm (Table 1) and mean annual temperature ranged between ca. 14 and 18 °C. The soils were Mollisols in 92% of the cases. Experiment duration ranged from 1 to 15 years and in 89% of cases had 3–4 replicates. In five experiments, one single plot by treatment was used but pseudoreplication was performed with 3–4 pseudoreplicates by plot. Because of the similarity of experimental design between most of the experiments great differences between the variances were not expected as variance is commonly inversely correlated to sample size (Gurevitch and Hedges, 1999).

Crop rotations could be split into those that included cereal crops (wheat or corn) and those with soybean monoculture. Usually each experiment had a control and a cover crop treatment, but in some cases various cover crops were compared. In these cases the effect of each cover crop treatment was assessed independently by comparison with the control. In some experiments time of cover crop kill and different nitrogen fertilization rates were implemented, or measures were performed at different times. All these sub-treatments were also assessed as independent measures when comparing the cover crop treatment with the corresponding control treatment (see Supplementary material Tables A–I), as reported results were the averages of, usually, 3–4 plots. The majority of the tested graminaceous cover crops were rye (*Secale cereale* (L.)), oat (*Avena sativa* (L.)), triticosecale (wheat x rye), ryegrass (*Lolium multiflorum* (Lam)), barley (*Hordeum vulgare* (L.)), rescue grass (*Bromus unioloides* (Kunth)), wheat and corn. Only in a few cases, rape (*Brassica napus* (L.)) and forage radish (*Raphanus sativus* (L.)) were used. These data, because of their small number, were pooled together with graminaceous cover crops as non-legume. Legumes were hairy vetch (*Vicia villosa* (Roth)) and common vetch (*Vicia sativa* (L.)). Clover (*Trifolium resupinatum* (L.)) was tested in one experiment. In all the experiments the commercial crops were soybean or corn and always sowed after the cover crop.

Soil bulk density was measured by the cylinder method (Blake and Hartge, 1986), usually in layers of 5 to 6 cm, taken from the upper 20 cm of the soil profile. Data were split into two categories: measures from the 0–5 or 0–6 cm soil layer and measures corresponding to the 0–20 cm soil layer. As these measures are associated the results from the two layers were analyzed by separate. Soil penetration resistance was assessed by cone penetrometer readings in the field (Bradford, 1986) at different depths. Records were averaged for calculating the mean resistance of the 0–10 cm and the 10–20 cm soil layers that were analyzed separately. Structural stability was measured on surface samples taken at different depths, usually 0–5 or 0–10 cm by wet sieving (De Boodt et al., 1961) or one of its variants (Kemper and Rosenau, 1986). Some papers presented results as percentage of stable aggregates to water and others as the change in aggregates mean weight diameter. To make these readings comparable, the first variable was normalized assigning a value of 100% to the highest recorded value and calculating all other values as percentages of the highest one. Change in mean weight diameter was transformed to the inverse and normalized in the same way. Infiltration was assessed by simple or double ring infiltrometers (Bouwer, 1986). Soil carbon was determined by wet combustion (Nelson and Sommers, 1986) on surface samples from the 0–20 cm layer. In 3% of the measured samples data came from the 0–15 cm or 0–18 cm layer, and in these cases carbon content was corrected to 0–20 cm using a local stratification model (Berhongaray et al., 2013). In 73%

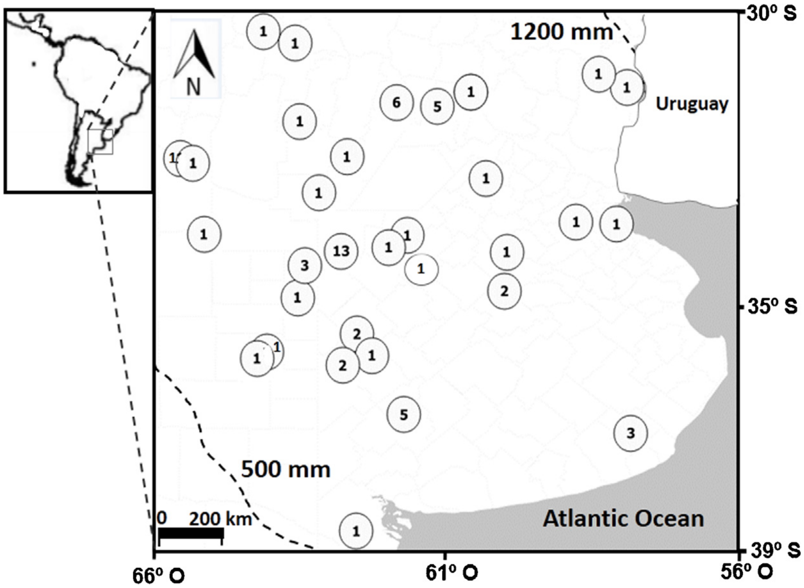

Fig. 1. Map of the Argentine Pampa showing the location of the experiments. Circles indicate experimental locations and numbers inside the amount of experiments performed at each location.

Table 1
Main characteristic of the experiments compiled.

Reference	Experiment	MAR (mm)	MAT (°C)	MAR/ETP (mm/°C)	Soil	Duration (years)	Design	Rotation	Cover crop	Grain crop
1	1	1014	17.5	0.99	VA	2	1		V	C
2	2	805	18.0	0.73	TA	6	RCB-3	S-S, S-C	(T + Cv)	S, C
3, 10	3	818	17.5	0.77	EH	15	FD-3 or 4	S-S, S-C	T, DGS	S, C
4, 7	4	826	16.3	0.84	EH	1	RCB-3	Su-C	R	Â C
	5	826	16.3	0.84	EU	1	RCB-3	Su-C	R	C
	6	826	16.3	0.84	EH	1	3	Su-C	R	C
5, 29	7	859	16.3	0.88	TH	7	RCB-3	S-S	T	S
6	8	970	16.2		EH	5		S-S	O, Ry	S
	9	702	16.0	0.61	TU	1	1	S-C	R	C
8	10	915	17.4	0.87	TA	1	RCB-3		T	S
9	11	859	16.3	0.88	TH	9	RCB-3	S-S	R	S
11	12	859	16.3	0.88	TH	8	RCB-3	S-S, S-C, C—C	R	S, C
12	13	915	17.4	0.87	TA	1	RCB-3		T, R, Cv, Hv	
13	14	856	17.1	0.83		3	2	S-C	V	C
14, 16, 17	15	892	16.0	0.97	TH	4	RCB-3	S-S	O, R, Ry	S
	16	725	17.5	0.74	THs	1	RCB-3	S-S	R, O, Ry	S
15	17	993	17.7	0.95	TA	3	RCB-3	S-S	W, (Cv + O), O, Cv	S
	18	993	17.7	0.95	TA	1	RCB-3	S-S	Hv, O	S
	19	993	17.7	0.95	TA	1	RCB-3		Hv, (Hv + O)	S, C
	20	993	17.7	0.95	AA	1	RCB-3		Hv, (Hv + O)	S, C
	21	993	17.7	0.95	TA	1	RCB-3		Hv	C
18, 27	22	915	17.4	0.87	TA	15	RCB-3	W/S-S-C	O, T, W	
19, 21	23	918	14.3	1.28	TA/PP	2	RCB-3	C—C	O, Hv, (Hv + O)	C
20	24	1030	16.8	1.11	TA	1	RCB-3	W/S	O	S
22	25	892	16.0	0.97	TH	1	RCB-3		R	S
23	26	908	17.4		TH	1	1	W/S-C	Cv, T	C
24, 25	27	725	17.5	0.74	EH	1	RCB-3	S-C	R	C
26, 30, 56, 60	28	859	16.3	0.88	TAH	8	RCB-3	S-S	R, Ry, O	S
28	29	1003	16.3	1.09		2	RCB-3	W/S	R	S
31	30	859	16.3	0.88	TH	1	RCB-3	S-C	W	S
32, 33	31	918	14.3	1.28	TA/PP	3	RCB-3	S-S	O	S
34	32	859	16.3	0.88	TH	1	RCB-3		Hv	
35	33	859	16.3	0.88	TH	1	RCB-3	S-C	R	C
36, 55	34	859	16.3	0.88	TH	1	RCB-3		R	C
	35	859	16.3	0.88	TAH	1	RCB-3		R	C
37	36	859	16.3	0.88	TH	1	RCB-3	S-S	O, R, Ry	S
38	37	1152	18.1	1.08	AP	1	RCB-3		Ry, (Ry + O), (Ry + C), C	S
39	38	896	17.4	0.85	EH	1	RCB-3		Vc	S
	39	915	17.4	0.87	TA	1	RCB-3		Vc	S
	40	860	16.7	0.85	UH	1	RCB-3		Vc	S
40, 41	41	1022	16.8	1.05	TA	5	RCB-3	W-C-S	Rg, O, Ba, Ry, (O + Cv), Cv, Ra, Fr	C
42	42	947	17.6	0.87	TA	1	RCB-5	W/S-C-S	O	S
43	43	987	16.0	1.10	EHl	5	3	S-S	O, Ry	S
	44	987	16.0	1.10	EHl	5	3		Cv	C
44	45	1037	16.9	0.78	VA	1	RCB-3		Ry	C
45	46	915	17.4	0.87	TA	1	RCB-3	C—C	Hv	C
46	47	1152	18.1	1.08	AP	1	RCB-3	S-C	Ry	S
47, 48	48	805	14.3	1.02	TA	1	RCB-3	W-C	O, Cv, (O + Cv), Cg, Cng	C
	49	805	14.3	1.02	TA	1	RCB-3	W-C	O, Cv, (O + Cv), Cg, Cng	C
	50	805	14.3	1.02	TA	1	RCB-3	W-C	O, Cv, (O + Cv), Cg, Cng	C
	51	805	14.3	1.02	TA	1	RCB-3	W-C	O, Cv, (O + Cv), Cg, Cng	C
	52	805	14.3	1.02	TA	1	RCB-3	W-C	O, Cv, (O + Cv), Cg, Cng	C
49	53	670	15.7	0.62		1	1		R	
	54	663	16.0	0.61		1	1		T	
50	55	993	17.7	0.95	TA	3	RCB-3	C-S-W/S, S-S	W	S

51	56	725	17.5	0.74	EH	1	RCB-3	W-So	O	So
52	57	859	16.3	0.88	TA	1	RCB-3		O, R, Ry	S
	58	859	16.3	0.88	TAH	1	RCB-3		O, R, Ry	S
53	59	878	16.2	0.92	TA	2	RCB-4		O, R, Ry	S
54	60	917	16.4	0.96	TA	2	RCB-4		R	S
	61	859	16.3	0.88	TAH	2	RCB-4		R	S
	62	848	16.3	0.86	EH	1	RCB-4		R	S
57, 58	63	918	14.3	1.28	TA	2	RCB-4	W/S-C	W, Cv	C
59	64	627	14.9	0.73	EH	2	RCB		Hv, (Hv + O)	C
61	65	800	15.5	0.89	EH	1	RCB-3		Hv, R	C
	66	800	15.5	0.89	TU	1	RCB-4		Hv, R	C
62	67	915	17.4	0.87	TA	1	RCB-3	C—C	Hv	C

Reference: 1: Agosti et al., 2014, 2: Alessandría et al., 2013, 3: Alvarez et al., 2014b, 4: Alvarez et al., 2013, 5: Alvarez et al., 2008, 6: Alvarez et al., 2016c, 7: Alvarez et al., 2014a, 8: Baigorria et al., 2014, 9: Barraco et al., 2016, 10: Basanta et al., 2013, 11: Beltrán et al., 2014, 12: Bertolla et al., 2013, 13: Boeiro et al., 2013, 14: Brambilla et al., 2012, 15: Capurro et al., 2013, 16: Carfagno et al., 2014b, 17: Carfagno et al., 2014a, 18: Cazorla et al., 2010, 19: Corral et al., 2014, 20: Costa et al., 2014, 21: Diez et al., 2016, 22: Eiza et al., 2014, 23: Fargioni et al., 2012, 24: Fernández et al., 2012, 25: Fernández et al., 2013, 26: Giron et al., 2014, 27: Gudelf et al., 2016, 28: Klein, 2013; 29: Lardone et al., 2012, 30: Lardone et al., 2014, 31: Mandrini et al., 2012, 32: Martínez et al., 2012, 33: Martínez et al., 2013, 34: Miranda et al., 2016, 35: Miranda et al., 2015, 36: Miranda et al., 2014, 37: Miranda et al., 2012, 38: Müller et al., 2008, 39: Ortiz et al., 2012, 40: Restovich and Andriulo, 2013, 41: Restovich et al., 2011, 42: Ridley, 2013; 43: Rillo et al., 2013, 44: Rimski-Korsakov et al., 2013, 45: Rinaudo et al., 2012, 46: Ronconi et al., 2008, 47: Sá Pereira et al., 2013, 48: Sá Pereira et al., 2014, 49: Saénz and Colazo, 2013, 50: Salvagiotti et al., 2013, 51: Sardiña et al., 2008, 52: Scianca et al., 2006, 53: Scianca et al., 2008, 54: Scianca et al., 2010, 55: Scianca et al., 2012, 56: Scianca et al., 2013, 57: Tourn et al., 2014, 58: Tourn et al., 2012, 59: Vanzolini et al., 2013, 60: Varela et al., 2010, 61: Varillas et al., 2014, 62: Vilches et al., 2012. Note: Studies can be obtained from the authors upon request.

MAR: mean annual rainfall.

MAT: mean annual temperature.

PET: potential evapotranspiration.

Soil = VA: Vertic Argiudoll, TA: Typic Argiudoll, TH: Typic Hapludoll, EH: Entic Haplustoll, EU: Entic Ustisament, AA: Acuic Argiudoll, THs: Typic Haplustoll, TAH: Thapto Argic Hapludoll, TA/PP: complex Typic Argiudoll and Petrocalcic Paleudoll, AP: Argiudolic Peluderte, UH: Udorthentic Haplustoll, EHI: Entic Hapludoll, TU: Typic Ustisament.

Design = RCB: randomized complete block design, F: factorial, numbers denote amount of replications. Different treatments in the same experiment are separated by a comma.

Rotation treatments = S-S: soybean-soybean, S-C: soybean-corn, Su-C: sunflower-corn, C—C: corn-corn, W/S: two crops in a year wheat/soybean, W: wheat, So: sorghum

Cover crop treatments = V: unspecified vetch, (T + Cv): triticosecale + common vetch, R: rye, T: triticosecale, DGS: different graminaceous species alternate (oat, wheat, and triticosecale), Cv: common vetch, Hv: hairy vetch, O: oat, W: wheat, Ry: ryegrass, (Ry + C): ryegrass + corn, C: corn, Rg: rescue grass, Ba: barley, (O + Cv): oat + common vetch, Ra: rape, Fr: forage radish, Cg: clover grazed, Cng: clover no grazed.

Grain crop treatments = C: corn, S: soybean, So: sorghum.

of cases carbon stock was reported or could be calculated with measured values of bulk density for each treatment. In order to include as many data as possible in the analysis, in the remaining cases we used a procedure similar to that employed by Poeplau and Don (2015) that evaluated cover crop effect in a global meta-analysis. We estimated soil bulk density based on organic carbon content. We tested the common Adams-Stewart model (Tranter et al., 2007) for bulk density estimation using a typical value of 1.64 g cm^{-3} for mineral bulk density (Post and Kwon, 2000) against a data set of 1418 samples taken under different land uses and depths in the Pampas (Alvarez et al., 2016b). The modeling efficiency (*EF*) was calculated following Poeplau et al. (2011):

$$EF = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}w_i\left(O_i - \overline{O}\right)^2} \qquad (1)$$

where O_i are observed values, $\overline{O}$is the observed mean and P_i are values predicted by the model. When the mean is used as predictor *EF* is zero. If model predictions were worse than when using the mean, *EF* is less than zero and for better predictions it is bigger. The Adams model severely overestimates bulk density in Pampean soils. Modeling efficiency was −0.85 and the R^2 between observed and estimated values 0.30. Variability of bulk density in Pampean soils was small; the mean value was 1.26 g ml^{-1} with a 95% confidence interval ranging from 1.25 to 1.27 g ml^{-1}. This allowed an acceptable estimation of bulk density using only the mean value in cases where carbon concentration needed to be transformed into carbon stocks. As an alternative, we chose a local model for bulk density estimation that was fitted with the data set of 1418 samples indicated above (bulk density (g ml^{-1}) = – 0.13 carbon (%) + 1.4; R^2 = 0.32) (Alvarez et al., 2016b). Despite the model had low R^2 its *EF* was 0.22 obtaining a better performance than when using the mean bulk density. Nitrate-N was determined by colorimetric methods, usually the Griess-Ilosvay or the cromotropic acid method (Mulvaney, 1986). In 61% of the cases data for the 0–60 cm soil layer were presented but in 39% of the cases only results corresponding to the 0–100 cm soil layer were available. Because in the Pampas nitrate-N contents at different soil layers are highly correlated, it was possible to estimate the level of nitrate-N in a layer using data from another (Alvarez et al., 2001). We used a local coefficient (nitrate-N 0–60 = nitrate-N 0–100 * 0.7) (Romano et al., 2014) to transform data from the 0–100 cm layer to 0–60 cm to include all data in the analysis. Soil available water content was determined by the gravimetric approach. Although not reported in the papers, the water tensions usually used in the Pampas for assessing plant available water are −0.033 and −1.5 MPa. Gravimetric water content was transformed to stored water (mm) in a soil layer using bulk density information. Plant available stored water content in different soil depths was calculated as the sum of the stored water of the soil layers considered. As different papers reported water content to different sampling depths the number of data aggregated differed between different soil depths. Corn and soybean yield was determined by mechanical or hand harvest the experimental plots. Yields were presented with 14% water content in some cases. When not specified we also assumed a 14% grain water content. Due to the amount of experiments involved and the pairs of available data compared in each case, our data set was especially robust for the analysis of bulk density, structural stability, chemical soil properties, stored available water and crop yield (Table 2). The penetration resistance data set extracted was small but we also analyzed it because there is a lack of information of the effect of cover crops on this variable.

Table 2
Grouping categories of the studied soil and crop variables accounting for the number of experiments and pairs of data grouped in each case and the average values (between brackets = standard deviation between studies) calculated for the control.

Variable	Grouping categories	Experiments	Pairs of comparisons	Control
Bulk density ($g\,ml^{-1}$)	0-5/0–6 cm layer	7	38	1.14 (0.084)
	0–20 cm layer	4	31	1.30 (0.073)
Soil penetration resistance (kPa)	0–10 cm layer	3	7	1.62 (0.71)
	10–20 cm layer	3	7	2.29 (0.72)
Structural stability (%)		6	44	39.9 (21.4)
Infiltration ($mm\,h^{-1}$)		8	22	97.5 (149)
Soil organic carbon ($t\,ha^{-1}$)	Coarse textured soils	12	58	34.1 (10)
	Fine textured soils	3	35	40.7 (2.9)
	Cereal rotations	7	49	35.9 (8.1)
	Soybean monoculture	8	44	37.0 (9.3)
N-nitrate ($kg\,ha^{-1}$)	Legume CC	9	16	58.1 (33.1)
	Biculture CC	2	5	67.4 (45.4)
	Non legume CC	21	68	66.4 (39.0)
Available water (mm)	30–40 cm depth	14	44	34.3 (20.2)
	60–70 cm depth	16	68	65.9 (24.9)
	80–90 cm depth	14	51	91.7 (38.0)
	100–120 cm depth	17	83	133.6 (34.6)
	140–160 cm depth	18	67	157.5 (61.7)
	180–250 cm depth	17	41	235.0 (88.6)
Yield ($kg\,ha^{-1}$)	Corn after legume CC	16	68	9740 (2550)
	Corn after biculture CC	6	14	8210 (1750)
	Corn after non legume CC	12	48	7020 (2020)
	Soybean after legume CC	7	14	3670 (1190)
	Soybean after biculture CC	5	14	3360 (1130)
	Soybean after non legume CC	20	132	3630 (1010)

2.3. Meta-analysis

Meta-analytic methods were employed for determining cover crop effect on all the assessed variables. The *meta*-analysis was performed using three different weighting functions. In the first case, and due to the lack of a suitable variance estimator in most of the selected studies, an unweighted *meta*-analysis was performed following the criterion proposed by Gurevitch and Hedges (2001) and Rosenberg et al. (2000), assigning a value of 1 to the variance of both control and cover crop treatments of all the compiled studies. In the second case, means were weighted by sample size giving more weight (w) to means calculated with more replicates and using the equation (Adams et al., 1997):

$$w = \frac{n_T.n_c}{n_T + n_C} \quad (2)$$

where: n_T is the sample size of the treatment (cover crop) and n_C is the sample size of the control. The third weighting function used was the inverse of the pooled variance (Rosenberg et al., 2000) in which weights are calculated as $w = 1/V$, where:

$$V = \frac{V_T}{n_T(\overline{X}_T)^2} + \frac{V_C}{n_c(\overline{X}_c)^2} \quad (3)$$

V is the pooled variance of each study, V_T and V_C are variances of the treatment and control respectively, and $\overline{X}_T$ and $\overline{X}_C$ the means of treatment and control of that study. As in most studies the pooled variance could not be calculated, we developed a substitution procedure using a calculated mean standard deviation (Wiebe et al., 2006). The whole data set included 1950 means covering all selected variables and experiments, and 232 standard deviations could be extracted. We pooled all available standard deviations/means ratios and calculated the sample mean and the 95% confidence interval. The sample mean was 0.129 with a confidence interval ranging from 0.117 to 0.142. As the confidence interval was narrow we used the sample mean to estimate variance across the entire data set. It was estimated that standard deviations were equivalent to 0.129 of the means. This procedure was more conservative than the usual assumption that standard deviations are equal to 0.1 of the means (Gattinger et al., 2012; Luo et al., 2006; Zhao et al., 2015). As effect size we calculated the response ratio (*RR*):

$$RR = \frac{\overline{X}_T}{\overline{X}_C} \quad (6)$$

The *RR* is a unitless measure of the effect size of the treatment calculated as a fraction of change in relation to the control (Hedges et al., 1999). It allows combining different units of a variable and it has been widely used in ecological research (Hedges et al., 1999). A *RR* of one indicates no effect of treatment related to the control. Values greater than one correspond to a positive treatment effect and, conversely, values smaller than one indicate a negative effect. The RR was used for summarizing cover crop effects on all variables assessed by meta-analysis. When RR is subjected to statistical analysis it is convenient to transform it to the natural logarithms (Eq. (7)). The transformation linearizes the metric and nearer to the normal distribution than *RR* (Hedges et al., 1999):

$$In(RR) = In(\overline{X}_T) - In(\overline{X}_C) \quad (7)$$

The statistical significance of the cover crop effect was determined using *In(RR)*. A bias-corrected for skew 95% confidence interval was estimated by bootstrapping resampling methods (Adams et al., 1997) performing 1000 iterations. The overall RR ($\overline{In(RR)}$) was obtained as the mean of individual study's RR values as:

$$\overline{In(RR)} = \frac{\sum_{i=1}^{n} In(RR_i) * w_i}{\sum_{i=1}^{n} w_i} \quad (8)$$

The $\overline{In(RR)}$ was considered to be significant ($P < 0.05$) if its confidence interval did not overlap with one (Rosenberg et al., 2000). When the confidence interval of two different $\overline{In(RR)}$ did not overlap they were also considered significantly different ($P < 0.05$). Average effect size and their corresponding confidence intervals were calculated using MetaWin 2.0 (Rosenberg et al., 2000). The average response ratio ($\overline{RR}$) was transformed to percent change for presentation of results:

$$Percent\ change = (\overline{RR} - 1) * 100\%$$

As we were also interested in determining possible differences in the impact of cover crops on soil properties and grain crop yields depending on soil type, rotations and cover crop species, we tested if the $\overline{RR}$ presented heterogeneity between classes (i.e. different soil types) by means of the Q values (Eq. (9)) (Hedges and Olkin, 1985):

$$QT = QB + QW \quad (9)$$

where: QT = total heterogeneity, QB = heterogeneity between classes and QW = heterogeneity within classes. QT, QB and QW were calculated following the procedure proposed by Hedges and Olkin (1985) using MetaWin 2.0 and represent a partitioning of heterogeneity similar to the partition of the sum of squares in analysis of variance. The total heterogeneity is the sum of the heterogeneity between classes (equivalent to treatments) and the heterogeneity within classes (equivalent to the error). Q values had an approximate Chi-squared distribution. If QB was greater than the 95% Chi-squared critical value with k–1 degrees of freedom (k = number of classes), the different classes did not share a common effect size and the response ratio with its confidence interval was calculated for each class separately using a random effect model (Rosenberg et al., 2000). We assumed that a random effect model would fit our data set better based on the hypothesis that effect sizes were not fixed across all studies (Gurevitch and Hedges, 1999). When the pooled variance was less than or equal to zero a fixed effect model was used (Rosenberg et al., 2000). Classes were defined based on 1) soil type (coarse-textured and fine-textured soils), 2) rotation vs. soybean monoculture, 3) cover crop type (legume, biculture or non-legume), and 4) cover crop species. As the textural composition of soils was not reported in the most of the studies we grouped them into: fine-textured (Argiudolls, Paleustolls, Peluderts) and coarse-textured (Hapludolls, Haplustolls, Ustisaments). A hierarchical approach was used for selection of categorical variables with significant effect on average effect size in a two step process (Nave et al., 2010). First, we ran a meta-analysis on the whole data set to determine which categorical variable had the lowest P value. Second, in cases where two categorical variables had significant effects we divided the data set into groups defined by the variable with the lowest P value and re-ran the meta-analysis within each sub-set testing the second significant categorical variables. It was not necessary to do more than two iterations in this variance-partitioning analysis. To avoid over-reduction of groups and to decrease the probability of confounding factors the restriction of using no less than 10 values integrated in a class had been proposed (Kallenbach and Grandy, 2011). We were more conservative as more than one single RR was extracted from some experiments (i.e. different cover crop species tested in the same experiment). For that reason we did not split the data set into classes that included less than 20 data values regardless of the number of experiments or 10 data generated in at least 5 experiments. Because of this restriction, some possible effects (classes) were not tested as time of cover crop desiccation or nitrogen fertilization from which small sample sizes were available. When the structure of the data did not allow splitting into classes, but the effect size relationship with a continuous variable (i.e. time) needed to be assessed for a meta-regression, the latter was performed using weighted least squares (Hedges and Olkin, 1985). A fixed effect model or a random effect model was used (using MetaWin, Rosenberg et al., 2000), depending if the pooled variance was less than or equal to zero in the first case or greater than zero in the second.

3. Results

The weighting function used for the meta-analysis did not affected results, that were similar using an unweighted meta-analysis or a meta-analysis weighted by replication or by the inverse of the pooled variance.

Soil physical properties generally improved when replacing a fallow period by the inclusion of cover crops. Changes in bulk density were very small with decreases or increases not greater than $0.1\ g\ ml^{-1}$. In the 0–5/0–6 cm soil layer, bulk density decreased in 63% of cases and did not change in 8%. In the 0–20 cm layer, 49% of cases showed lower bulk density under cover crops than under fallow and in 35% of the cases changes were not detected. The meta-analysis showed only a minimal impact of cover crops on bulk density (Fig. 2). The confidence interval for the average RR of the 0–5/0–6 cm layer was close to one and a decrease of 1% in bulk density was calculated for the 0–20 cm layer. Soil penetration resistance was greatly impacted by the adoption of cover crops. Soil resistance decreased in all experiments and depths, in some cases as much as ca. 0.5-0.6 kPa. On average, it was around 15–20% lower under a cover crop than under fallow both in the 0–10 and the 10–20 cm layers (Fig. 2). Structural stability was generally greater under cover crops but it decreased in 24% of cases. The increases ranged from 1 to 18%. The overall evaluation showed a 12% average positive and significant effect of cover crops on stability (Fig. 2). Infiltration was also enhanced by cover crop use. In 82% of cases infiltration increased under cover crops with half of them exceeding $25\ mm\ h^{-1}$. The average infiltration increase was around 36% (Fig. 2). Neither of the soil physical variables were correlated to time.

Soil organic carbon stocks generally improved under cover crops. Increases ranged from 0.2 to $8.9\ t\ ha^{-1}$ and in only 10% of studied cases, decreases not exceeding $2–3\ t\ C\ ha^{-1}$ were found. These carbon decreases were observed always in experiments of less than five year duration but no carbon reduction was measured after five years. The average increase was around 7% of the carbon content in the 0–20 cm layer (Fig. 3). Increases were not correlated with time and a significant meta-regression could not be fitted. When the whole data set was partitioned into experiments performed on fine or coarse textured soils, a differential impact of cover crops on soil carbon was detected giving rise to a significant QB. The $\overline{RR}$ was greater in coarse soils than in fine textured ones (change approximately 9% vs. 4%, respectively). When testing the type of rotation (with cereal crops against soybean monoculture) within each soil class, no significant effects were detected. Nitrate-N decreased in almost all cases under cover crops. Only in 9% of cases increases were measured. The decreases were very variable ranging from -2 to $-99\ kg\ N\ ha^{-1}$ with an average decrease rounding 53% (Fig. 3). The decreases were observed when cover crops were both legumes and non-legumes. No significant QB was detected between different types of cover crops. A significant

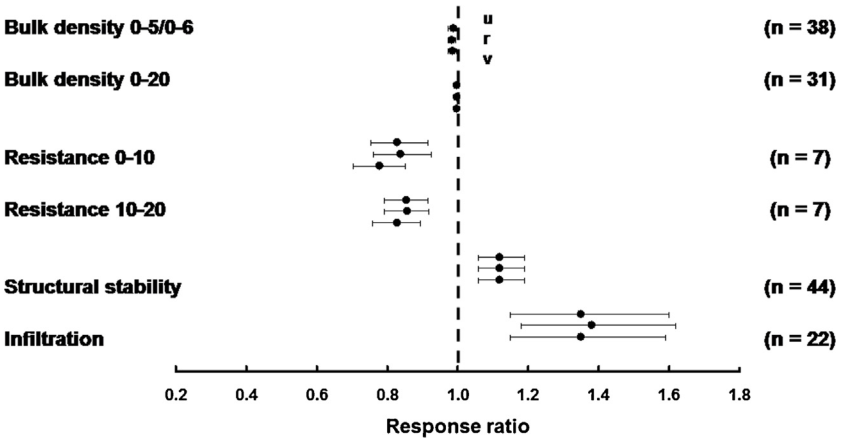

Fig. 2. Cover crop effect on soil physical properties. The meta-analysis results are presented as percent change (mean size effect and the 95% confidence interval). Numbers in brackets are the number of paired data grouped in each category. u = unweighted, r = weighted by replication, v = weighted by the inverse of the pooled variance.

meta-regression could be adjusted between the Ln(RR) and time since initiation of experiment with a negative slope value (Ln (RR) = −0.50–0.16 time). Coefficients were similar independently of the weighting function used indicating a greater depleting effect of cover crops on soil nitrate-N content along time.

The impact of cover crops on available water stored in the soils depended on the soil depth considered. In the upper soil layers changes produced by the introduction of cover crops in the rotations had both positive and negative effects but in deep soil layers this trend was clearly negative (Fig. 4). Changes were not clearly associated to the climatic condition of the site in which the experiment was located. Meta-regressions of the Ln(RR) against the rainfall/potential evapotranspiration ratio were not significant for some soil depths, showed significant positive trends in some cases or negative in others. Time was neither correlated to the Ln (RR). No significant effect of cover crops was detected when available water stored in the upper meter of the soil profile was considered. When the analysis included data from 1 to 2.5 m depth, the stored available water decrease ranged from 15% to 30% depending on the depth taken into account.

Corn yield was affected by the type of the previous cover crop. The heterogeneity analysis showed a significant *QB* for type of cover crop classes. With non-legume cover crops yield tended to decrease in average ca. 8%, although this difference was not significant (Fig. 5). Biculture cover crops did not affect corn yield while a significant increase of around 7% was obtained with a legume cover crop. Species effects within the non-legume cover crop type class could not be tested because of the lack of sufficient data for species subclasses. The biculture class was the combination of oat and *Vicia sp.* and the legume class was *Vicia sp.* Yield effects on corn were not correlated to climate or time because significant meta-regressions could not be fitted between the RR and the rainfall/potential evapotranspiration ratio or time since experiment initiation. By contrast, soybean yield was minimally affected when a fallow was replaced by a cover crop (Fig. 5). The heterogeneity analysi s indicated that cover crop type did not affected the $\overline{RR}$. Climate or time since adoption neither impacted the response of soybean to cover crops adoption.

4. Discussion

The results from our meta-analysis were generally not affected by the weighting method used. When sample size is similar, no great variability between studies is to be expected (Gurevitch and Hedges, 1999) and consequently, different weighting functions can lead to the same conclusion. This was the case in our study. Previous comparisons of different weighting functions in soil science studies arrived to similar results (Hungate et al., 2009; van Groenigen et al., 2011).

Soil bulk density changes induced by cover crop use were very small. These changes would not affect crop root development. Accepted thresholds beyond which root growth is affected by high

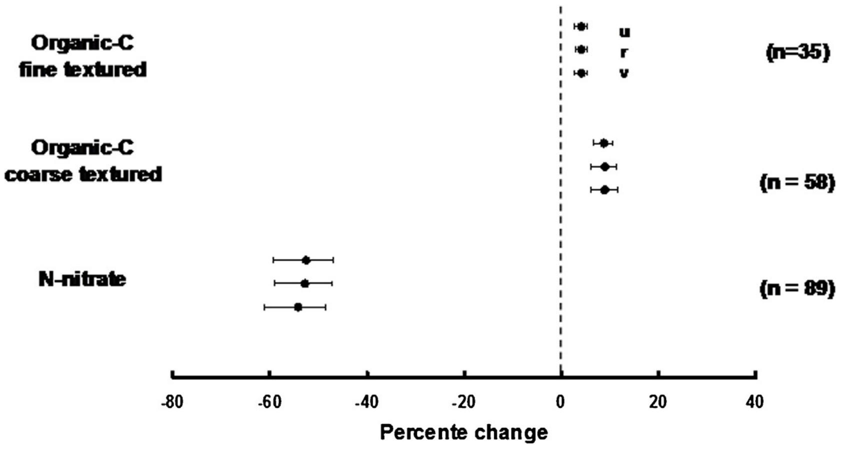

Fig. 3. Cover crop effect on soil chemical properties. The meta-analysis results are presented as percent change (mean size effect and the 95% confidence interval). Numbers in brackets are the number of paired data grouped in each category. u = unweighted, r = weighted by replication, v = weighted by the inverse of the pooled variance.

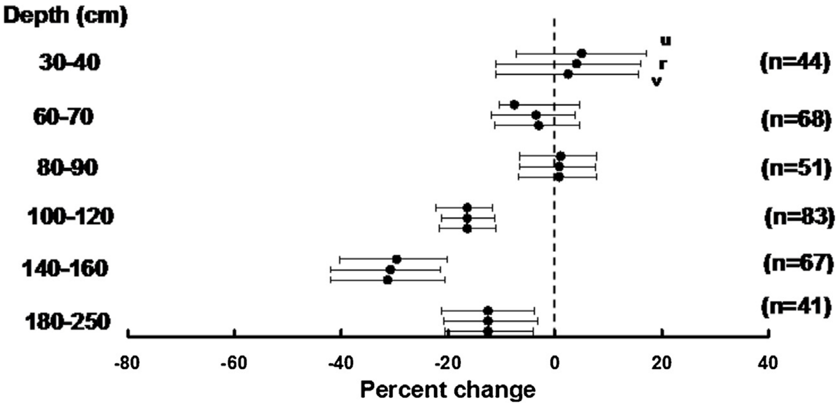

Fig. 4. Cover crop effect on stored soil available water content. The meta-analysis results are presented as percent change (mean size effect and the 95% confidence interval of stored soil available water content to the indicated depth). Numbers in brackets represent the number of paired data grouped in each category. u = unweighted, r = weighted by replication, v = weighted by the inverse of the pooled variance.

bulk density usually vary between 1.5 and 1.8 g ml^{-1} depending on soil texture (Arshad et al., 1996; USDA, 2014). Reviewed data from the surface layer (0–15 to 0–30 cm) of 750 field plots showed that, in the Pampas, average bulk density was 1.2-1.3 g ml^{-1} and <2% of sites had values >1.5 g ml-1 (Alvarez et al., 2014c,d). In our data set, only 2% of cases showed bulk density values reaching 1.5 g ml^{-1} and therefore an average decrease of around 1% (0.015 g ml-1 or less) can be considered biologically non-significant. Bulk density seems not to be substantially changed by cover crops in the region. This scenario changes when considering soil penetration resistance. The average decrease of 15–20% under cover crops calculated in our analysis can lower soil resistance below root limiting values. Root growth is restricted when resistance is greater than 2–3 kPa (Hakansson and Lipiec, 2000; Hamza and Anderson, 2005) and in 40% of the cases included in our meta-analysis the soil resistance of the control exceeded 2 kPa. In these cases, the inclusion of a cover crop would generate better conditions for roots. However, the data set used for this variable was small and more experiments should be performed in the future. Structural stability was enhanced in most cases under cover crops but we could not test if this increases were associated to organic carbon increases because carbon was not determined in most of the samples where stability was assessed. Taking into account that most of our stability data (79%) were generated in experiments of less than 2 years duration, in which carbon build up was presumably small, other mechanisms might be involved. Similarly, improvements of soil structural stability without carbon changes have been found by other authors, usually in short-term experiments (Hermawan and Bomke, 1997; Kabir and Koide, 2002; Liu et al., 2005) but in some cases also in long-term ones (Steele et al., 2012). The aggregation effect of fine roots seems the most probable cause. Although the data set was small, infiltration results were clear. Cover crops produced a greater infiltration. The increase was especially high in soils with low infiltration, in which it doubled. The greater infiltration under cover crops did not necessarily increase soil water content (Lal et al., 1978). Water consumption by the cover crops could offset infiltration increases. In some experiments the impact of cover crops on infiltration was reported to be time dependent (Steele et al., 2012). In most of our data, infiltration was measured in autumn before cover crop sowing under crop rotations managed under no-till. Further research is needed to check if these effects would still be important during the grain crop growing season.

We calculated the cover crop effect on soil carbon using both measured and estimated carbon stocks. Excluding studies in which only soil carbon concentration was reported and where we estimated bulk density for carbon stock calculation had no impact on the final results of the meta-analysis. An average change of 5.3% was calculated; a very similar value to the ca. 7% increase calculated using the whole data set. Carbon sequestration was not correlated to time since cover crop adoption in the Pampas. A previous meta-analysis with data from 37 experiments spread worldwide, in which cover crop effect on soil carbon was assessed, described a significant regression between time since adoption and the amount of carbon sequestered in the soil (Poeplau and Don, 2015). In this latter study, modeling carbon sequestration as a function of time, the authors concluded that a steady state soil organic carbon level would be attained around 150 years after the

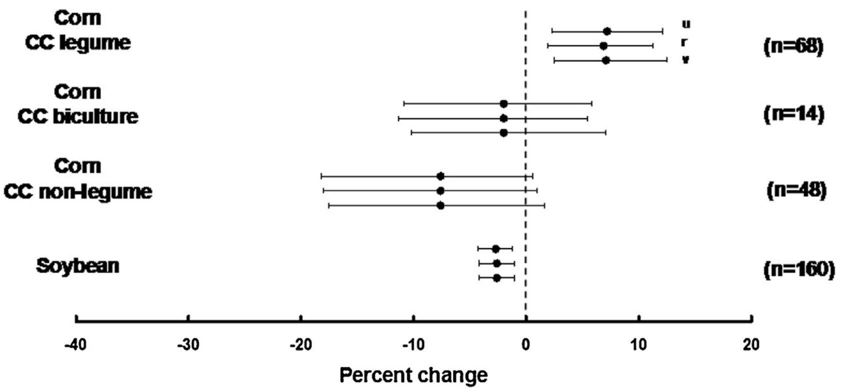

Fig. 5. Cover crop effect on crop yield. The meta-analysis results are presented as percent change (mean size effect and the 95% confidence interval). Numbers in brackets are the number of paired data grouped in each category. u = unweighted, r = weighted by replication, v = weighted by the inverse of the pooled variance.

introduction of cover crops. As nearly all our data set was obtained from experiments of less than 10 years duration it would be risky to use our average carbon increase for regional estimates of steady state conditions. The average increase of 7% in soil carbon we calculated in our meta-analysis would represent ca. 2.6 t C ha^{-1} if applied to the average carbon stock of the controls. This estimation is around half a previous estimate for Pampean soils (Rimski-Korsakov et al., 2015). We attributed this difference to the fact that our dataset was 3-times larger and so giving a more realistic result. Cover crops had more impact on soil carbon content in coarse soils than in fine textured ones. In the Pampas, this can be attributed to lower crop productivity in the former soil type (De Paepe and Alvarez, 2013) and the consequent greater relative increase of residue input.

Nitrate-N depletion after cover crops was not associated to species type. Both, non-legume or legume cover crops generally produced nitrate-N decreases and of the same magnitude. However, in some cases (9%), mainly in low nitratre-N soils, increases were measured ranging from 1 to 48 kg N ha^{-1}, which were also independent of type of cover crop species. Nitrogen input to the agroecosystem as atmospheric nitrogen by *Vicia sp*., the legume cover crop tested in nearly all Pampean experiments, may range from 50 to 180 kg N ha^{-1} (Fageria et al., 2005; LaRue and Patterson, 1981). This input did not affected nitrate-N at the time of grain crop sowing. The diminishing effects of non-legume cover crops on soil nitrate-N have been previously reported (Thorup-Kristensen et al., 2003; Valkama et al., 2015). Nitrogen not found in the nitrate pool is usually in crop biomass (Thorup-Kristensen et al., 2003). Some experiments also reported decreases in nitrate-N with legume cover crops (O'Connell et al., 2015) but a meta-analysis carried out with data from northern Europe showed opposite results (Valkama et al., 2015). In the Pampas, *Vicia sp.* acted as a catch crop as efficient as a non-legume species, despite its nitrogen fixation potential. In Pampean soils, cover crops produced an average reduction of ca. 50% of the nitrate pool in relation to a fallow. This is a strong decrease of the nitrate pool, of similar magnitude to results obtained in meta-analyses performed in other regions, which showed also important decreases of nitrogen leaching (Teixeira et al., 2016; Valkama et al., 2015). Legume species may not be effective for reducing leaching (Valkama et al., 2015) but it does not seems to be the case in the Pampas.

The use of cover crops produced a mean 15–30% decrease in available water storage in the Pampas soil profile when measured up to a depth greater than 1m. This water reduction would represent around 20–40 mm less of available water for crops when calculated over the mean water stored of the control treatment of our data set. Consumptive water use of summer crops in the region ranges from 500 to 700 mm during the growing season (Bono and Alvarez, 2016; Dardanelli et al., 2003) and this small restriction in water supply would possibly have no impact on crop productivity. Different reviews showed that in arid and semiarid environments ($<$500 mm annual rainfall) water stored in soils decreased with cover crops reducing crop yields (Cherr et al., 2006; Reeves, 1994). This negative impact on soil water is usually not observed in humid areas with annual rainfall higher than 800 mm (Blanco-Canqui et al., 2015). In the Pampas, because of the large rainfall amount, cover crops would not restrict plant water supply except during very dry years or in soils where rooting depth is limited.

Soybean yield was minimally affected (-2%) by cover crops. Neither reduction of soil nitrates or of available water, nor the possible nitrogen credit of legume cover crops had great impacts on yield. This enhances the idea that the available water content reduction produced when fallow is replaced by a cover crop did not have a negative effect on yield. This nitrogen fixing crop is usually not affected by soil nitrogen levels and fertilization in the region (Gutierrez Boehm, 2016) and the decrease of stored water under cover crops did not affect it either. Conversely, corn yield was significantly improved by *Vicia* sp. as previous cover crop. The nitrogen credit of legume cover crops can vary commonly between 30 and 150 kg N ha^{-1} (Fageria et al., 2005; Reeves, 1994; Sainju and Singh, 1997). In the Pampas, corn needs ca. 20 kg N intake to yield one ton of grain (Alvarez and Steinbach, 2016). The average yield increase of 7% calculated in our meta-analysis would result approximately in 0.65 t grain ha^{-1} when related to the mean yield of the control treatment of the dataset. This yield increase could be associated to an additional 15 kg N ha^{-1} intake after a *Vicia sp* crop. This small nitrogen credit was generated during the corn growing cycle by the release of residue nitrogen, as nitrate-N at corn sowing time was reduced by the cover crop. Although not significant, the average decrease of corn yield after a non-legume cover crop seems to be the consequence of nitrate-N depletion by the cover crops and would be a matter of concern for farmers. A meta-analysis of results from 37 experiments performed in USA and Canada showed that legume and biculture cover crops increased corn yield by 21–24%, while graminaceous species did not affect yield (Miguez and Bollero, 2005). This result was attributed to nitrogen mineralization of residues, as it tends to decrease with high nitrogen fertilizer applications. Another meta-analysis of 35 experiments, most ofthem from the USA, showed that legume cover crops did not affect corn yield under low fertilizer application rates but decreased 12% under high nitrogen rates (Tonitto et al., 2006). This negative effect of replacing fertilizer application by legume cover crop disappeared when cover crop biomass accumulated more than 110 kg N ha^{-1}. Under the Pampas low input agriculture past and present scenario, in which 50 kg N ha^{-1} average nitrogen rates were applied to corn (Alvarez et al., 2016a), *Vicia* sp. seems to be a good option for yield increase. The cost of sowing cover crops calculated using current prices (Márgenes Agropecuarios, 2016) would be equivalent to ca. 0.7 t of corn yield. Our meta-analysis indicated that if *Vicia sp*. is used, the cover crop cost would be nearly compensated by the increase in corn yield with the additional benefits of soil quality improvement. With the available information, some matters remain unanswered such as if non-legume cover-crop species produce benefits and if the introduction of cover crops before soybean are profitable practices. To asses this concerns, long term experiments should be performed.

Acknowledgements

This research was granted by the University of Buenos Aires (UBACYT 20020130100484) and CONICET (PIP 11220130100084CO).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2017.03.005.

References

Adams, D.C., Gurevitch, J., Rosenberg, M.S., 1997. Resampling tests for meta-analysis of ecological data. Ecology 78, 1277–1283.

Agosti, M.B., Peralta, G.E., Gil, R., 2014. Vicia villosa como cultivo de cobertura en el sur de Santa Fe. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 4.

Alessandría, E., Arborno, M., Leguía, H., Pietrarelli, L., Sanchez, J.V., Zamar, J.L., (ex Aequo), 2013. Introducción de cultivos de cobertura en agroecosistemas extensivos de la región central de Córdoba. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 128–137.

Alvarez, R., Lavado, R.S., 1998. Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina. Geoderma 83, 127–141.

Alvarez, R., Steinbach, H.S., 2016. Dosificación de la fertilización en maíz. In: Alvarez, R. (Ed.), Fertilidad de suelos y fertilización en la Región Pampeana. Editorial Facultad de Agronomía-Universidad de Buenos Aires, Buenos Aires, Argentina, pp. 307–331 (Chapter 15).

Alvarez, C.R., Alvarez, R., Steinbach, H.S., 2001. Prediction of soil nitrate in depth using nitrate concentration in the upper layer. Comm. Soil Sci. Plant Anal. 32, 759–769.

Alvarez, C., Barraco, M., Díaz Zorita, M., Pecorari, C., 2008. Impacto del manejo de cereales de cobertura invernal sobre propiedades edáficas y producción de soja. Proceedings of XXI Congreso Argentino de la Ciencia del Suelo 4.

Alvarez, C., Bagnato, R., Lienhard, C.P., Quiroga, A., 2013. Cultivos de cobertura: manejo y efectos sobre la nutrición de suelos y cultivos. Proceedings of Simposio Fertilidad 2013: Nutrición de cultivos para la intensificación productiva sustentable 80–87.

Alvarez, C., Bagnato, R., Lienhard, C.P., 2014a. Dinámica de agua en barbechos y cultivos de cobertura en la Región Pampeana. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 5.

Alvarez, C., Alvarez, C.R., Costantini, A., Basanta, M., 2014b. Carbon and nitrogen sequestration in soils under different management in the semi-arid Pampa (Argentina). Soil Till. Res. 142, 25–31.

Alvarez, R., Berhongaray, G., Bono, A., Steinbach, H.S., De Paepe, J., 2014c. Rangos de densidad aparente medidos en suelos pampeanos. Proceedings XXIV Congreso Argentino de la Ciencia del Suelo 1–6.

Alvarez, R., Steinbach, H.S., De Paepe, J.L., 2014d. A regional audit of nitrogen fluxes in pampean agroecosystems. Agric. Ecosys. Environ. 184, 1–8.

Alvarez, R., Steinbach, H.S., Alvarez, C.R., De Paepe, J.L., 2015. Fertilizer use in pampean agroecosystems: impact on productivity and nutrient balance. In: Sinha, K.K., Bajrai, S., Govil, J.N. (Eds.), Chemical Engineering Series (ISBN 1-62699-041-7), Fertilizer Technology Vol. 2: Biofertilizers (ISBN 1-62699-047-9). Studdium Press LLC, USA, pp. 352–368 Cap. 15.

Alvarez, C.R., Steinbach, H.S., Alvarez, R., 2016a. El rol de los fertilizantes en la agricultura. In: Alvarez, R. (Ed.), Fertilidad de suelos y fertilización en la Región Pampeana. Editorial Facultad de Agronomía-Universidad de Buenos Aires, Buenos Aires, Argentina, pp. 219–227 (Chapter 10).

Alvarez, R., Steinbach, H.S., De Paepe, J.L., 2016b. Carbono orgánico. In: Alvarez, R. (Ed.), Fertilidad de suelos y fertilización en la Región Pampeana. Editorial Facultad de Agronomía-Universidad de Buenos Aires, Buenos Aires, Argentina, pp. 47–91 (Chapter 3).

Alvarez, C., Barraco, M., Cazorla, C., Colazo, J.C., De Dioz Herrero, J., Lardone, A., Girón, P., Restovich, A., Rillo, S., 2016c. Mejora de propiedades edáficas con inclusión de cultivos de cobertura en agroecosistemas pampeanos. Proceedings of XXV Congreso Argentino de la Ciencia del Suelo 10.

Arshad, M.A., Lowery, B., Grossman, B., 1996. Physical tests for monitoring soil quality. In: Doran, J.W., Jones, J. (Eds.), Methods for Assessing Soil Quality. SSSA, Madison, WI, pp. 123–142 Soil Sci. Soc. Am. Spec. Publ. 49.

Baigorria, T., Cazorla, C., Belluccini, P., Aimeta, B., Pegoraro, V., Boccolini, M., Alvarez, C., 2014. Efecto del rolado de cultivos de cobertura sobre la dinámica de agua y malezas. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 5.

Barraco, M., Lardone, A., Girón, P., Miranda, W., Diaz-Zorita, M., 2016. Secuencias agrícolas y su efecto en la productividad de soja y propiedades edáficas. Proceedings of XXV Congreso Argentino de la Ciencia del Suelo 10.

Basanta, M., Alvarez, C., Giubergia, J.P., Lovera, E., 2013. Cultivos de cobertura en sistemas de agricultura continua en la región central de Córdoba. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 50–57.

Beltrán, M.J., Galantini, J., Brevedan, R., Estrada, E., 2014. Efecto del centeno sobre los niveles de carbono y nitrógeno del suelo. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 5.

Berhongaray, G., Alvarez, R., De Paepe, J., Caride, C., Cantet, R., 2013. Land use effects on soil carbon in the Argentine Pampas. Geoderma 192, 97–110.

Bertolla, A., Baigorria, T., Goméz, D., Cazorla, C., Cagliero, M., Lardone, A., Bojanich, M., Aimetta, B., 2013. Efecto de la Fertilización sobre la eficiencia del uso del agua de especies invernales utilizadas como cultivos de cobertura. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 138–147.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods. Am. Soc. Agron.-Soil Sci. Soc. Am., Madison, USA, pp. 363–375.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert, G.W., 2015. Cover crops and ecosystems services: insights from studies in temperate soils. Agron. J. 107, 2449–2474.

Boeiro, J.P., Romagnoli, J., Lorenzatti, S., Peruzzi, D., Muñoz, S., Sánchez, M., Bianchini, A., Romagnoli, G., 2013. Cultivos de cobertura y fertilización nitrogenada en maíz. Proceedings of Simposio Fertilidad 2013: Nutrición de cultivos para la intensificación productiva sustentable 156–159.

Bono, A., Alvarez, R., 2016. Estimación del uso consuntivo de trigo, maíz y girasol en la Región Semiárida-Subhúmeda Pampeana. Actas XXV Congreso Argentino de la Ciencia del Suelo (5 p.).

Bouwer, H., 1986. Intake rate: cylinder infiltrometer. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods. Am. Soc. Agron.-Soil Sci. Soc. Am., Madison, USA, pp. 825–844.

Bradford, J.M., 1986. Penetrability. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods. Am. Soc. Agron.-Soil Sci. Soc. Am., Madison, USA, pp. 463–478.

Brambilla, E.C., Eiza, M.J., Carfagno, P., Quiroga, A., 2012. Cultivos de cobertura: impacto sobre la materia orgánica del suelo. Proceedings of XXIII Congreso Argentino de la Ciencia del Suelo 6.

Capurro, J., Dickie, M.J., Ninfi, D., Surjack, J., Monti, J., Ninfi, D., Zazzarini, A., Tosi, E., Adriani, J., Gonzalez, M.C., 2013. Cultivos de cobertura en el Sur de la provincia de Santa Fe. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 92–104.

Carfagno, P.F., Eiza, M.J., Quiroga, A., Babinec, F., 2014a. Recarga del perfil hídrico en barbechos de distinta duración con diferentes niveles de cobertura. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 6.

Carfagno, P.F., Eiza, M.J., Rivera Vázquez, J.M., Quiroga, A., Babinec, F., 2014b. Cultivos de cobertura: efecto sobre la porosidad y el rendimiento de soja. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 6.

Cazorla, C., Galarza, C., Cisneros, J., Moreno, I., 2010. Balance de carbono en sistemas agrícolas continuos de la región sudeste de la Provincia de Córdoba. Proceedings of XXII Congreso Argentino de la Ciencia del Suelo 4.

Chen, G., Weil, R.R., Hill, R.L., 2014. Effects of compaction and cover crops on soil least limiting water range and air permeability. Soil till. Res. 136, 61–69.

Cherr, C.M., Scholberg, J.M.S., McSorley, R., 2006. Green manure approaches to crop production: a synthesis. Agron. J. 98, 302–319.

Constantin, J., Le Bas, C., Justes, E., 2015. Large-scale assessment of optimal emergence and destruction dates for cover crops to reduce leaching in temperate conditions using STICS soil-crop model. Eur. J. Agron. 69, 75–87.

Corral, R.A., Studdert, G.A., Domínguez, G.F., Agostini, M.A., 2014. Rendimiento de maíz: Efecto de cultivos de cobertura/abonos verdes en el sudeste bonaerense. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 6.

Costa, M.C., Bonvecchi, V.E., Irigoin, J., Dettler, A., Rutti, S., Bulos, L., 2014. Cultivos de cobertura: Longitud de barbecho y disponibilidad hídrica. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo (4 p.).

Dardanelli, J., Collino, D., Otegui, M.E., Sadras, V.O., et al., 2003. Bases funcionales para el manejo del agua en los sistemas de producción de los cultivos de granos. In: Satorre, H. (Ed.), Producción de granos. Bases funcionales para su manejo. Editoral FAUBA, Buenos Aires, Argentina, pp. 375–440.

De Boodt, M.L., De Leenheer, M.L., Kirkham, D., 1961. Soil aggregate stability indexes and crop yields. Soil Sci. 91, 138–146.

De Paepe, J.L., Alvarez, R., 2013. Developments of a soil productivity index using an artificial neural network approach. Agron. J. 105, 1803–1813.

De Paepe, J.L., Alvarez, R., 2016. Wheat yield gap in the pampas: modeling the impact of environmental factors. Agron. J. 108, 1367–1378.

Diez, S.N., Dominguez, G.F., Studdert, G.A., Cendoya, G., Sainz Rozas, H.R., 2016. Producción sustentable de maíz: el rol de los cultivos puente en el sistema de cultivo. Proceedings of XXV Congreso Argentino de la Ciencia del Suelo 17 p.

Eiza, M.J., Carfagno, P.F., Irurtia, C., 2014. Cultivos de cobertura y descompactación: dos practicas complementarias. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 6.

Fageria, N.K., Baligar, V.C., Bailey, B.A., 2005. Role of cover crops in improving soil and row crop productivity. Commun. Soil Sci. Plant Anal. 36, 2733–2757.

Fargioni, M., Vega, C., Baigorria, T., Pietrantoni, J., Cazorla, C., 2012. Efecto de los cultivos de cobertura sobre la disponibilidad hídrica y nitrogenada a la siembra y rendimiento de maíz. Technical Bulletin N° 24. Estación Experimental Agropecuaria, http://inta.gob.ar/documentos/efecto-de-los-cultivos-de-cobertura-sobre-la-disponibilidad-hidrica-y-nitrogenada-a-la-siembra-y-el-rendimiento-de-maiz/ (Accessed 29 April 2016).

Fernández, R., Quiroga, A., Noellemeyer, E., 2012. Cultivos de cobertura, ¿Una alternativa viable para la Región Semiárida Pampeana? Ciencia del Suelo 30, 137–150.

Fernández, R., Quiroga, A., Noellemeyer, E., 2013. Cultivo de cobertura como antecesor del cultivo de maíz en la Región Semiárida Pampeana. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 117–127.

Folorunso, O.A., Rolston, D.E., Prichard, T., Louie, D.T., 1992. Soil surface strength and infiltration rate as affected by winter cover crops. Soil Technol. 5, 189–197.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Filesbach, A., Buchman, N., Mäder, P., Stolze, M., Smith, P., El-Hage Scialabba, N., Niggli, U., 2012. Enhance top soil carbon stocks under organic farming. PNAS 30, 18226–18231.

Giron, P., Scianca, C., Barranco, M., Lardone, A., Miranda, W., 2014. Cambios en el carbono orgánico por la inclusión de cultivos de cobertura. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 5.

Gudelf, O.E., Pochettino, P.A., Galarza, C.M., 2016. Efecto del cultivo de cobertura y la fertilización sobre propiedades físicas de un Argiudol. Proceedings of XXV Congreso Argentino de la Ciencia del Suelo 12.

Gurevitch, J., Hedges, L.V., 1999. Statistical issues in ecological meta-analysis. Ecology 80, 1142–1149.

Gurevitch, J., Hedges, L.V., 2001. Meta-analysis. Combining the results of independent experiments. In: Scheiner, S.M., Gurevitch, J. (Eds.), Design and Analysis of Ecological Experiments. Oxford University Press, pp. 347–369.

Gutierrez Boehm, F., 2016. Dosificación de la fertilización en soja. In: Alvarez, R. (Ed.), Fertilidad de suelos y fertilización en la Región Pampeana. Editorial FAUBA, Buenos Aires Argentina, pp. 333–348 (Chapter 16).

Hakansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Till. Res. 53, 71–85.

Hall, A.J., Rebella, C., Guersa, C., Culot, J., 1992. Field-crop system of the Pampas. In: Pearson, C.J. (Ed.), Field Crop Ecosystems. Elsevier, Amsterdam.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems. A review of the nature: causes and possible solutions. Soil Till. Res 82, 121–145.

Harrwing, N.L., Ulrich Ammon, H., 2002. Cover crops and living mulches. Weed Sci. 50, 688–699.

Hedges, L.V., Olkin, I., 1985. Statistical Methods for Meta-Analysis. Academic Press, London (369 p.).

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.

Hermawan, B., Bomke, A.A., 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Till. Res. 44, 109–120.

Hubbard, R.K., Strickland, T.C., Phatak, S., 2013. Effects of cover crop systems on soil physical properties and carbon/nitrogen relationships in the plain of southeastern USA. Soil till. Res. 126, 276–283.

Hungate, B.A., van Groenigen, K.J., Six, J., Jastrow, J.D., Luo, Y., de Graaff, M.A., van Kessel, C., Osenberg, C.W., 2009. Assesing the effect of elevated carbon dioxide on soil carbon: a comparison of four meta-analysis. Global Change Biol. 15, 2020–2034.

INDEC, 2002. Censo Nacional De Población, Hogares Y Viviendas. Available at: http://www.indec.gov.ar/agropecuario/cna.asp (10/12/1912).

Kabir, Z., Koide, R.T., 2002. Effect of autumn and winter mycorrhizal cover crops on soil properties nutrient uptake and yield of sweet corn in Pennsylvania, USA. Plant and Soil 238, 205–2115.

Kallenbach, C., Grandy, A.S., 2011. Controls over soil microbial biomass responses to carbon amendments in agricultural systems: a meta-analysis. Agric. Ecosys. Environ. 144, 241–252.

Kemper, W.D., Rosenau, R.C., 1986. Agregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods.. Am. Soc. Agron.-Soil Sci. Soc. Am., Madison, USA, pp. 425–442.

Ketterings, Q.M., Swink, S.N., Duiker, S.W., Czymmek, K.J., Beegle, D.B., Cox, W.J., 2015. Integrating cover crops for nitrogen management in corn systems on Northeastern U.S. dairies. Agron. J. 107, 1365–1376.

Klein, R.F., 2013. Cultivos de cobertura: Un puente para el nitrógeno. Informaciones Agronómicas de Hispanoamérica 11, 20–26.

LaRue, T.A., Patterson, T.G., 1981. How much nitrógeno do legumes fix? Adv Agron 34, 15–38.

Lal, R., Wilson, G.F., Okigbo, B.N., 1978. No-till framing alter various grasses and leguminous cover crops in tropical Alfisol. I: Crop performance. Field Crops Res. 1, 71–84.

Langdale, G.W., Blevins, R.L., Karlen, D.L., McCool, D.K., Nearing, M.A., Skidmore, E.L., Thomas, A.W., Tyler, D.D., Williams, J.R., 1991. Cover crops effects on soil erosion by wind and water. In: Hargrove, W.L. (Ed.), Cover Crops for Clean Water. Soil and Water Conservation Society, 7515 N.E. Iowa, USA, pp. 15–22.

Lardone, A.V., Barraco, M., Scianca, C., Álvarez, C., Díaz-Zorita, M., 2012. Cultivos de cobertura en sistemas con soja bajo siembra directa. Proceedings of XXIII Congreso Argentino de la Ciencia del Suelo 5.

Lardone, A.V., Barraco, M., Justo, C., Girón, P., 2014. Dinámica hídrica en un sistema de monocultivo de soja con y sin cultivos de cobertura. Memoria técnica 2013–2014. INTA EEA General Villegas, pp. 80–83.

Li, X., Sorensen, P., Li, F., Petersen, S.O., Olensen, J.E., 2015. Quantifying biological nitrogen fixation of different catch crops, and residual effects of roots and tops on nitrogen uptake in barley using in-situ ^{15}N labelling. Plant Soil 395, 273–287.

Liu, A., Ma, B.L., Bomke, A.A., 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil Sci. Soc. Am. J. 69, 2041–2048.

Luo, Y., Hui, D., Zhang, D., 2006. Elevated CO_2 stimulates net accumulation of carbon and nitrogen in land ecosystems: a meta-analysis. Ecology 87, 53–63.

Agropecuarios, Márgenes, 2016. Editorial Márgenes Agropecuarios S.R.L. Año 32, N° 374. Balbi S.A., Buenos Aires, Argentina.

Müller, D.G., Saluzzio, M.F., De Battista, J.J., 2008. Comparación de distintos cultivos de cobertura en un suelo vertisol. Proceedings of XXI Congreso Argentino de la Ciencia del Suelo 6.

Magrin, G.O., Travasso, M.I., Rodríguez, G.R., 2005. Changes in climate and crop production during the 20TH Century in Argentina. Clim. Change 72, 229–249.

Mandrini, E., Barraco, M., Scianca, C., Costa, C., 2012. Trigo como cultivo de cobertura: Efecto de la fecha de siembra. Proceedings of XXIII Congreso Argentino de la Ciencia del Suelo 6.

Martínez, J.P., Barbieri, P.A., Saínz Rozas, H.S., Echeverría, H.E., 2012. Alternativas de manejo al monocultivo de soja en un Molisol de Balcarce. Proceedings of XXIII Congreso Argentino de la Ciencia del Suelo 3.

Martínez, J.P., Barbieri, P.A., Saínz Rozas, H.S., Echeverría, H.E., 2013. Incorporación de cultivos de cobertura previos a soja en el sudeste bonaerense. Informaciones Agronómicas de Hispanoamérica 10, 21–25.

Mendes, I.C., Bandick, A.K., Dick, R.P., Bottombey, P.J., 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63, 873–881.

Miguez, F.E., Bollero, A., 2005. Review of corn yield response under winter cover cropping systems using meta-analysis methods. Crop Sci. 45, 2318–2329.

MinAgri 2016. Available online: www.minagri.gob.ar (acceded 20/6/2016).

Miranda, W., Scianca, C., Barraco, M., Alvarez, C., Lardone, A., 2012. Cultivo de cobertura: Dinámica de agua luego de dos momentos de secado. Memoria técnica. Instituto Nacional de Tecnología Agropecuaria, EEA General Villegas, pp. 60–65.

Miranda, W., Scianca, C., Lardone, A., Barraco, M., Abadie, G., 2014. Cultivo de cobertura-maíz tardío en dos ambientes representativos del Noroeste Bonaerense. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 6.

Miranda, W., Girón, P., Pérez, M., Barraco, M., 2015. Cultivo de cobertura: espaciamiento entre hileras de siembra y manejo de malezas. Memoria técnica. Instituto Nacional de Tecnología Agropecuaria, EEA General Villegas, pp. 11–14.

Miranda, W., Girón, P., Barraco, M., 2016. Densidad de siembra de Vicia villosa Roth. Como cultivo de cobertura en el Noroeste Bonaerense. Proceedings of XXV Congreso Argentino de la Ciencia del Suelo 10.

Mulvaney, R.L., 1986. Nitrogen-inorganic forms. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3, Chemical Methods.. Am. Soc. Agron.-Soil Sci. Soc. Am., Madison, USA, pp. 1123–1184.

Nave, L.E., Vance, E.D., Swanson, C.W., Curtis, P.S., 2010. Harvest impacts on soil carbon storage in temperate forest. For. Ecol. Manag. 259, 857–866.

Nelson, D.W., Sommers, L.E., 1986. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3, Chemical Methods. Am. Soc. Agron.-Soil Sci. Soc. Am., Madison, USA, pp. 961–1010.

O'Connell, S.O., Shi, W., Grossman, J.M., Hoyt, G.D., Fager, K.L., Creamer, N.G., 2015. Short-term nitrogen mineralization from warm-season cover crops in organic farming systems. Plant Soil 396, 353–367.

Ortiz, J., Bojanich, M., Ferreyra, L., Cazorla, C., Baigorria, T., Canale, A., Pegoraro, V., 2012. Evaluación de cultivos de cobertura antecesores de soja en suelos de texturas contrastantes. Proceedings of XXIII Congreso Argentino de la Ciencia del Suelo 6.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops-A meta-analysis. Agric. Ecosys. Environ. 200, 33–41.

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemaels, B., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone-carbon response functions as a model approach. Glob. Change Biol. 17, 2415–2427.

Post, W.M., Kwon, C., 2000. Soil carbon sequestration and land-use change: processes and potencial. Glob. Change Biol. 6, 317–327.

Reeves, D.W., 1994. Cover crops and rotations. In: Hatfield, J.L., Stewart, B.A. (Eds.), Crops Residue Management. Advances in Soil Science. Lewis Publishers, Boca Raton, FL, pp. 125–172.

Restovich, S., Andriulo, A., 2013. Cultivos de cobertura en la rotación soja-maíz: biomasa aérea, captura de nitrógeno, consumo de agua y efecto sobre el rendimiento en grano. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 29–35.

Restovich, S.B., Andriulo, A.E., Améndola, C., 2011. Introducción de cultivos de cobertura en la rotación soja-maíz: efecto sobre algunas propiedades del suelo. Ciencia del Suelo 29, 61–73.

Ridley, N., 2013. Cultivos de cobertura en el sur de Santa Fe: Efectos sobre la eficiencia de barbecho y la porosidad del suelo. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 7–15.

Rillo, S., Álvarez, C., Bagnato, R., Noellemeyer, E., 2013. Cultivos de cobertura: gramíneas y leguminosas en el centro oeste de la provincia de Buenos Aires. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 58–68.

Rimski-Korsakov, H., Zubillaga, M.S., Landrisini, M.R., Lavado, R.S., 2013. Utilización de un cultivo de cobertura luego de maíz, para recuperar nitratos residuales susceptibles de lixiviarse. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 69–75.

Rimski-Korsakov, H., Alvarez, C.R., Lavado, R.S., 2015. Cover crops in the agricultural systems of the Argentine Pampas. J. Soil Water. Cons. 70, 112A–118A.

Rinaudo, D., Baigorria, T., Cazorla, C.R., Boccolini, M.F., 2012. Efecto de Vicia villosa (Roth) en el desarrollo y rendimiento de maíz. Proceedings of XXIII Congreso Argentino de la Ciencia del Suelo 5.

Romano, N.F., Álvarez, R., Bono, A., 2014. Mineralización de nitrógeno en suelos de la Región Semiárida Pampeana. XXIV Congreso Argentino de la Ciencia del Suelo actas 6 pág.

Ronconi, A.P., Silvestre, P.S., Saluzzio, M.F., De Battista, J., 2008. Efectos de los cultivos de cobertura con distinta duración de barbecho químico. Proceedings of XXI Congreso Argentino de la Ciencia del Suelo 6.

Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. MetaWin. Statistical Software for Meta-analysis, Version 2.0. 133 p..

Sá Pereira, E., Galantini, A.J., Quiroga, A.R., 2013. Sistemas de cultivos de cobertura de suelo de otoño-invierno: sus efectos sobre la disponibilidad de agua. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 76–82.

Sá Pereira, E., Galantini, A.J., Quiroga, A.R., Landriscini, M.R., 2014. Efecto de los cultivos de cobertura otoño invernales sobre el rendimiento y acumulación de N en maíz en el sudoeste bonaerense. Ciencia del Suelo 32, 219–231.

Saénz, C., Colazo, 2013. Costo hídrico de cultivos de cobertura invernales en San Luis. Primeras experiencias. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 16–20.

Sainju, U.M., Singh, B.P., 1997. Winter cover crops for sustainable agricultural systems: influence on soil properties, water quality, and crop yields. HortScience 32, 21–28.

Salvagiotti, F., Vernizzi, A., Bodrero, M., Bacigaluppo, S., 2013. Cambios en el corto plazo en distintas fracciones de la materia orgánica en respuesta a la inclusión de cultivos de cobertura en secuencias basadas en soja. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 88–91.

Sardiña, C.L., Guerrero, L., Orelia, M., Quiroga, A., 2008. Cultivo de cobertura efectos de la fertilización sobre la producción de biomasa, eficiencia de uso del agua y el cultivo sucesor. Proceedings of VII Congreso Nacional de trigo, Santa Rosa, Argentina, pp. 2.

Satorre, E., Slafer, G., 1999. Wheat production systems of the Pampas. In: Satorre, E., Slafer, G. (Eds.), Wheat. Ecology and physiology of yield determination. Food Products Press, NY, USA, pp. 333–348.

Scianca, C., Alvarez, C., Barraco, M., Quiroga, A., Zalba, P., 2006. Cultivos de cobertura. Aporte de carbono e influencia sobre propiedades edáficas. Proceedings XX Congreso Argentino de la Ciencia del Suelo 5.

Scianca, C., Alvarez, C., Barraco, M., Quiroga, A., Zalba, P., 2008. Cultivos de cobertura en un Argiudol Típico del Noroeste Bonaerense. Proceedings of XXI Congreso Argentino de la Ciencia del Suelo 5.

Scianca, C., Alvarez, C., Barraco, M., Quiroga, A., 2010. Centeno utilizado como cultivo de cobertura en la Región de la Pampa Arenosa. Proceedings of XXII Congreso Argentino de la Ciencia del Suelo 4.

Scianca, C., Miranda, W., Lardone, A., Barraco, M., abandie, G., Quiroga, A., 2012. Cultivo de cobertura ?maíz tardío en dos ambientes representativos del noroeste bonaerense. Memoria Técnica 2011–2012. Instituto Nacional de Tecnología Agropecuaria, EEA General Villegas, pp. 77–82.

Scianca, C., Varela, M., Barraco, M., Álvarez, C., Quiroga, A., 2013. Cultivos de cobertura en un Hapludol Thapto Árgico de La Pampa Arenosa: análisis de cinco campañas. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 105–116.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J., O'Neil, K., 2005. Evaluating cover crops for benefits, cost and performance within cropping systems niches. Agron. J. 97, 322–332.

Steele, M.K., Coale, F.J., Hill, R.L., 2012. Winter annual cover crop impacts on no-till soil physical properties and organic matter. Soil Sci. Soc. Am. J. 76, 2164–2173.

Teixeira, E.I., Johnstone, P., Chakwizira, E., de Ruiter, J., Malcoln, B., Shaw, N., Zyskowski, E., Khaembah, E., Sharp, J., Meenken, E., Fraser, P., Thomas, S., Brown, H., Curtis, D., 2016. Sources of variability in the effectiveness of winter cover crops for mitigating N leaching. Agric. Ecosys. Environ. 220, 226–235.

Teruggi, M.E., 1957. The nature and origin of argentine loess. J Sed. Petrol. 27, 322–332.

Thorup-Kristensen, K., Magid, J., Stoumann Jensen, L., 2003. Catch crops and green manure as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–302.

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallow with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agric. Ecosys. Environm. 112, 58–72.

Tourn, S.N., Studdert, G.A., Platz, P., Dominguez, G.F., Agostini, M.A., Diez, S.N., Capurro, J.A., 2012. Efecto de paraplow y de cultivos de cobertura en planteos agrícolas bajo siembra directa continua. Proceedings XIX Congreso Argentino de la Ciencia del Suelos 5.

Tourn, S.N., Domínguez, G.F., Agostini, M.A., Studdert, G.A., 2014. Paraplow y cultivos de cobertura: Efecto sobre algunas propiedades físicas bajo siembra directa. Proceedings of XXIV Congreso Argentino de la Ciencia del Suelo 6.

Tranter, G., Minasmy, B., Mcbratney, A.B., Murphy, B., Mckenzie, N.J., Grundy, M., Brough, D., 2007. Building and testing conceptual and empirial models for predicting soil bulk density. Soil Use Manag. 23, 437–443.

USDA, 2014. Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No. 51. Version 2. , pp. 457.

Valkama, E., Lemola, R., Känkänen, R., Turtola, E., 2015. Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. Agric. Ecosys. Environm. 203, 93–101.

Vanzolini, J.I., Galantini, J., Agamennoni, R., 2013. Cultivos de cobertura de *Vicia villosa* Roth. en el valle bonaerense del Río Colorado. In: Alvarez, C., Quiroga, A., Santos, D., Bodrero, M. (Eds.), Contribuciones de los cultivos de cobertura a la sostenibilidad de los sistemas de producción. Ediciones INTA, La Pampa, Argentina, pp. 21–28.

Varela, M.F., Fernández, P.L., Alvarez, C., Scianca, C., Rubio, G., Taboada, M.A., 2010. Propiedades físicas que varian por incorporación de cultivos de cobertura en Hapludoles franco arenosos. Proceedings XXII Congreso Argentino de la Ciencia del Suelo 5.

Varillas, G., Pedraz, F., Kruck, B., Barraco, M., 2014. Cultivos de cobertura en ambientes limitantes del O este de Buenos Aires. Proceedings XXIV Congreso Argentino de la Ciencia del Suelo 5.

Viglizzo, E.F., Roberto, Z.E., Lértora, Z.E., López Gay, E., Bernardos, J., 1997. Climate and land-use change in field-crop ecosystems of Argentina. Agric. Ecosys. Environm. 66, 61–70.

Viglizzo, E.F., Létora, F., Pordomingo, A.J., Bernardos, J.N., Roberto, Z.E., Del Valle, H., 2001. Ecological lessons and applications from one Century of low external-input farming in the Pampas of Argentina. Agric. Ecosys. Environ. 83, 64–81.

Viglizzo, E.F., Frank, F.C., Carreño, L.V., Jobbágy, E.G., Pereyra, H., Clatt, J., Pincén, D., Ricard, F., 2011. Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. Global Change Biol. 17, 959–973.

Vilches, D., Baigorria, T., Cazorla, C., Aimetta, B., Santos, D., Bojanich, M., Ortiz, J., Pegoraro, V., 2012. Efecto de vicia villosa como cultivo antecesor y la fertilización nitrogenada sobre la producción del cultivo de maíz. Marcos Juárez. Argentina, Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Agropecuaria, pp. 4.

Wiebe, N., Vandermeer, B., Platt, R.W., Klassen, T.P., Moher, D., Barrowman, N.J., 2006. A systematic review identifies a lack of standardization in methods for handling Messing variance data. J. Clin. Edidem. 59, 342–353.

Zhao, X., Zhang, R., Xue, J., Pu, C., Zhang, X., Liu, S., Chen, F., Lal, R., Zhang, H., 2015. Management-induced changes to soil organic carbon in China: a meta-analysis. Adv. Agron. 134, 1–50.

Zhu, B., Yi, L., Gou, L., Chen, G., Hu, Y., Tang, H., Xiao, C., Xiao, X., Yang, G., Acharya, S. A., Zeng, Z., 2012. Performance of two winter cover crops and their impacts on soil properties and two subsequent rice crops in Dongting Lake Plain Hunan. China. Soil Till. Res. 124, 95–101.

van Groenigen, K.j., vOsenberg, C.W., Hungate, B.A., 2011. Increased soil emissions of potent greenhouse gases under increased atmospheric CO_2. Nature 475, 214–216.