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SUSTAINABILITY AND PRODUCTIVITY OF DIFFERENT CROP SEQUENCES UNDER TWO TECHNOLOGICAL MANAGEMENT PRACTICES IN THE PAMPEAN REGION OF ARGENTINA

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ABSTRACT

According to FAO estimates, global food production needs to increase by 60% to feed the world's population in 2050. This increasing demand for food has led to agricultural intensification, which has strongly affected the structure and function of agroecosystems. The objective of this study was to evaluate productivity and sustainability of different crop sequences based on different indicators under two technological management practices (medium and high levels) in the Pampean Region, Argentina. The following indicators were evaluated: balances of nitrogen (N), phosphorous (P), carbon (C), and water use efficiency (WUE). Canola/ soybean (late-sown)–corn–sorghum–wheat was the sequence with the highest annual mean values of productivity (234 GJ ha^{-1}), C balance (923 kg ha^{-1}), and water use efficiency (9.60 kg ha^{-1} mm^{-1}). However, it recorded the lowest negative annual balances of N (-138 kg ha^{-1}) and P (-20 kg ha^{-1}). Oat/soybean (late-sown)-corn-sunflower sequence had the lowest annual nutrient extractions, and thus the least negative annual nutrient balances of N (-81.75 kg ha^{-1}) and P (-8.67 kg ha^{-1}), also recording the lowest annual productivity (172 GJ ha^{-1}) and WUE (7.99 kg ha^{-1} mm-^{1}). Barley/soybean (late-sown)-corn-soybean- wheat and wheat/soybean (late-sown)-corn-soybean-wheat sequences had high productivity and contributed C to the soil, but they also caused high nutrient extraction. High technological level resulted in higher levels of productivity (194 GJ ha^{-1}), balance of C (602 kg ha^{-1}), N (-97.5 kg ha^{-1}) and P (13.7 kg ha^{-1}), as well as increased

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water use efficiency (8.95 kg ha^{-1} mm^{-1}) compared to the medium technological level. The increasing demand for food and the search for resilient agricultural practices that combine productive and ecological aspects highlight the importance of diversified production based on indicators, allowing for sustainable food production systems.

Keywords: Carbon balance, nutrients balance, water use efficiency.

INTRODUCTION

According to FAO estimates, world food production should increase by 60 % in 2050 to meet the needs of a population that could exceed 9,000 million inhabitants (FAO, 2009). This inevitably entails greater production per unit of input, leading to the intensification of agriculture in many areas of the world, which has significantly modified the structure and function of agroecosystems (Cruzate and Casas, 2017). Agriculture intensification (driven among other factors by a better profitability of crops with respect to livestock), the permanent improvement of genetic materials, the availability of biotechnological proposals (mainly glyphosate resistant soybean (*Glycine max* (L.) Merr.)) and the significant increase in no-till sowing, have caused various degrees problems in the agricultural soils (Andrade et al., 2017). At present, there is great concern about the long-term sustainability of food production systems. In fact, there is evidence that when intensive agricultural systems are extremely productive and competitive, they also result in economic, social, and environmental problems (Andrade et al., 2017).

In Argentina, soybean is the most important crop with an average sown area of nearly 19 million hectares in the last ten years (MAGyP, 2020). This oilseed occupies more than 50 % of the sown area, accounting for almost 50 % of the agricultural production of the country. However, crop rotations or crop sequences, which allow both short- and long-term profitability, are not common. From a technical point of view, crop rotations have numerous advantages. Sequences that include cereals, such as wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.), have important production benefits as they maintain soil fertility and allow stable productivity over time. The root architecture of these grasses is one of the main factors contributing to regenerate soil structure (Corbin et al., 2010). In fact, their fibrous rooting system, which is mainly found in the first 40-60 cm of depth, and their uniform distribution in the soil profile form cracks and channels that increase water infiltration speed and facilitate root development of other crops, improving soil surface porosity (Forján and Manso, 2016). On the other hand, the amount and quality of the stubble that returns to the soil is related to the type of crop used in the sequence and biomass production, which is highly influenced by fertilization levels. The carbon:nitrogen ratio (C:N) of stubble determines decomposition rate, which directly affects humification and subsequent levels of soil organic matter (Menéndez and Hilbert, 2013; Turmel et al., 2015; Sarkar et al., 2020; Fu et al., 2021). Carbono (C) is the main component of organic matter in the soil (56 %), and it is mostly generated by stubble (Alvarez and Steinbach, 2010). The C generated by each crop can be estimated from the stubble it produces, while the C that can be potentially humified can be determined by using humification factors available in the literature (Richmond and Rillo, 2009; Alvarez and Steinbach, 2010). Another aspect to consider is the rate of C mineralization that the soil may have (Alvarez and Steinbach, 2010; Forján and Manso, 2016).

Cultivating more than one crop per year is one of the practices with the greatest impact on farmer´s profitability because it allows a more efficient use of resources (radiation, temperature and rainfall), with positive effects on soil productivity. Double annual crops do not only improve agricultural productivity, but also preserve the soil because there is an increased contribution of crop residues to the soil compared to individual crops (Caviglia and Andrade, 2010). According to Álvarez et al. (2015), the replacement of rotations by monoculture has a negative impact on soil functions and the sustainability of the agroecosystem. Only about a quarter of the total nutrients extracted by soybean grains are restored (Cruzate and Casas, 2017). Apart from the economic risk that a single crop implies, the low nutrient contribution of soybean stubble does not only have a negative impact on the C balance of the soil, but it also makes the soil more susceptible to degradation. Increasing diversity by crop rotation has been related to many benefits. In fact, crop diversity is recognized for its field-level benefits such as improved crop yields, soil health, and input use efficiency (Pretty, 2018). At a higher scale, alternating crops has resulted in higher agricultural resilience to adverse growing conditions (Bowles et al., 2020), and even an increased stability of food production at the national scale (Renard and Tilman, 2019).

Agronomic practices also affect water consumption and water use efficiency (WUE)

(Videla Mensegue et al., 2020), being water one of the main constraints in agricultural production. WUE can be defined at different scales. In general, under rainfed conditions, it is defined as the biomass, yield or production per unit of water consumed (Videla Mensegue et al., 2020).

It is necessary to generate information, through trials, that allow soybean to be included in a more rational way production scheme. Therefore, the objectives of the present study were to evaluate productivity and sustainability of different crop sequences based on different indicators under two technological management practices in the Pampean Region, Argentina.

MATERIALS AND METHODS

Field trials and experimental design

Two field trials were conducted between 2011 and 2015 at the J. Hirschhorn Experimental Station, Facultad de Ciencias Agrarias y Forestales, Universidad Nacional de La Plata (34° 52′ LS; 57° 58′ LO), Argentina, with the same four crop sequences. Trial 1 included crop sequences from 2011 to 2014, whereas Trial 2 comprised sequences from 2012 to 2015. Crop sequences (seq) are indicated as follow: seq1) wheat/soybean (late-sown)-corn (*Zea mays* L.)-soybean-wheat (W/S-C-S-W); seq2) barley/soybean (late-sown)-corn-soybean- wheat (B/S-C-S-W); seq3) oat/soybean (late-sown)-corn-sunflower (*Helianthus annuus* L.)-wheat (O/S-C-Su-W); seq4) canola (*Brassica napus* L.) /soybean (late-sown)-corn-sorghum (*Sorghum bicolor* L. (Moench))-wheat (Ca/S-C-So-W). Late-sown soybean was sown immediately after harvest of the preceding winter crop. These sequences were managed under two on-farm technological management practices: medium technological level (MTL), which corresponds to the one used by the average farmer in the area, and high technological level (HTL), which is used by farmers who usually obtain higher yields on their crops. Crops were sown under no-till. Fertilizer applications differed between technological levels and are indicated in Table 1. Sowing and harvest dates, sowing rates and cultivar names per crop in each crop sequence are provided in Table 2. The two

Table 1. Fertilizers applied to the different crops in the 4-year rotations under two technological management practices (Seq: sequence).

Year	Crop	Medium technological level	High technological level
Year 1	Seq1: Wheat Seq2: Oat Seq3: Barley	Diammonium phosphate (18-46-0) 50 kg ha^{-1} Urea (46-0-0) 100 kg ha^{-1}	Diammonium phosphate (18-46-0) 50 kg ha^{-1} Urea (46-0-0) 140 kg ha^{-1}
	Seq4: Canola	Diammonium phosphate (18-46-0) 50 kg ha^{-1} Urea (46-0-0) 100 kg ha^{-1}	Diammonium phosphate (18-46-0) 50 kg ha^{-1} Monoammonium phosphate enriched with sulfur (11-34-0-9S) 100 kg ha^{-1} Urea (46-0-0) 120 kg ha^{-1}
	Soybean (late-sown)	None	Niebla NPS® (foliar)** 6 kg ha^{-1}
Year 2	Corn	Triple superphosphate (0-46-0) 80 kg ha^{-1} Urea (46-0-0) 140 kg ha^{-1}	Triple superphosphate (0-46-0) 80 kg ha^{-1} Urea (46-0-0) 100 kg ha^{-1}
Year 3	Seq1 and Seq2: Soybean	None	Starfert® (foliar)*** 1 L ha^{-1}
	Seq3: Sunflower	None	Diammonium phosphate (18-46-0) 60 kg ha^{-1} Urea (46-0-0) 50 kg ha^{-1}
	Seq4: Sorghum	None	Urea (46-0-0) 50 kg ha^{-1}
Year 4	Wheat	Diammonium phosphate (18-46-0) 50 kg ha^{-1} Urea (46-0-0) 100 kg ha^{-1}	Diammonium phosphate (18-46-0) 50 kg ha^{-1} Urea (46-0-0) 140 kg ha^{-1}

** Composition: 09-2.6-00, 5.5 % sulfur.

*** Composition: Total N: 8.9 %, Assimilable P: 1.6 %, K soluble in water: 3.7 %, Ca: 0.3 %, Mg: 0.3 %, Fe: 0.8 %, Mn: 0.2 %, Zn: 0.2 %, Cu: 0.2 %, SO_4^{-2}: 1.1 %, B: 0.2 %, Mo: 0.06 %, Total humic extract: 15.7 %, Humic acids: 0.8 %, Fulvic acids: 14.9 %

Table 2. Sowing and harvest dates, sowing rate and cultivar name for each crop included in each sequence for the two trials (2011-14 and 2012-15).

Trial 1	Sequence 1	Sequence 2	Sequence 3	Sequence 4
		Year 2011		
Crop	**Wheat**	**Barley**	**Oat**	**Canola**
Sowing date	8/Jul/2011	8/Jul/2011	8/Jul/2011	24/May/2011
Sowing rate	144 kg ha^{-1}	153 kg ha^{-1}	110 kg ha^{-1}	6 kg ha^{-1}
Cultivar name	Meteoro	Scarlett	Bonaerense INTA Calén	Hyola 571
Harvest date	10/Dec/2011	25/Nov/2011	5/Dec/2011	7/Nov/2011
Crop	**Soybean (late-sown)**	**Soybean (late-sown)**	**Soybean (late-sown)**	**Soybean (late-sown)**
Sowing date	16/Dec/2011	2/Dec/2011	13/Dec/2011	14/Nov/2011
Sowing rate	107 kg ha^{-1}	103 kg ha^{-1}	107 kg ha^{-1}	94 kg ha^{-1}
Cultivar	DM4970	DM4210	DM4970	DM4210 (NTM)
Harvest date	13/Apr/2012	8/Apr/2012	13/Apr/2012	1/Apr/2012
		Year 2012		
Crop	**Corn**	**Corn**	**Corn**	**Corn**
Sowing date	27/Oct/2012	27/Oct/2012	27/Oct/2012	27/Oct/2012
Sowing rate	32 kg ha^{-1}	32 kg ha^{-1}	32 kg ha^{-1}	32 kg ha^{-1}
Cultivar	DM2741 MG RR2 32	DM2741 MG RR2 32	DM2741 MG RR2 32	DM2741 MG RR2 32
Harvest date	18/Mar/2013	18/Mar/2013	18/Mar/2013	18/Mar/2013
		Year 2013		
Crop	**Soybean**	**Soybean**	**Sunflower**	**Sorghum**
Sowing date	18/Nov/2013	18/Nov/2013	4/Nov/2013	13/Nov/13
Sowing rate	78 kg ha^{-1}	78 kg ha^{-1}	3.5 kg ha^{-1}	6.75 kg ha^{-1}
Cultivar	DM5.1	DM5.1	Paraíso 22	AD64
Harvest date	6/Apr/2014	6/Apr/2014	5/Mar/2014	1/Apr/2014
		Year 2014		
Crop	**Wheat**	**Wheat**	**Wheat**	**Wheat**
Sowing date	5/Jul/2014	5/Jul/2014	5/Jul/2014	5/Jul/2014
Sowing rate	144 kg ha^{-1}	144 kg ha^{-1}	144 kg ha^{-1}	144 kg ha^{-1}
Cultivar	Meteoro	Meteoro	Meteoro	Meteoro
Harvest date	2/Dec/2014	2/Dec/2014	2/Dec/2014	2/Dec/2014
Trial 2	Sequence 1	Sequence 2	Sequence 3	Sequence 4
		Year 2012		
Crop	**Wheat**	**Barley**	**Oat**	**Canola**
Sowing date	8/Jul/2012	8/Jul/2012	10/Jul/2012	24/May/2012
Sowing rate	119 kg ha^{-1}	120 kg ha^{-1}	110 kg ha^{-1}	6 kg ha^{-1}
Cultivar	Meteoro	Scarlett	Bonaerense INTA Calén	Hyola 571
Harvest date	13/Dec/2012	4/Dec/2012	9/Dec/2012	7/Nov/2012
Crop	**Soybean (late-sown)**	**Soybean (late-sown)**	**Soybean (late-sown)**	**Soybean (late-sown)**
Sowing date	13/Dec/2012	13/Dec/2012	13/Dec/2012	13/Dec/2012
Sowing rate	114 kg ha^{-1}	114 kg ha^{-1}	114 kg ha^{-1}	114 kg ha^{-1}
Cultivar	DM4970	DM4970	DM4970	DM4970
Harvest date	22/Apr/2013	22/Apr/2013	22/Apr/2013	22/Apr/2013
		Year 2013		
Crop	**Corn**	**Corn**	**Corn**	**Corn**
Sowing date	19/Oct/2013	19/Oct/2013	19/Oct/2013	19/Oct/2013
Sowing rate	DM2741 MG RR2	DM2741 MG RR2	DM2741 MG RR2	DM2741 MG RR2
Cultivar	32 kg ha^{-1}	32 kg ha^{-1}	32 kg ha^{-1}	32 kg ha^{-1}
Harvest date	27/Mar/2014	27/Mar/2014	27/Mar/2014	27/Mar/2014

		Year 2014		
Crop	**Soybean**	**Soybean**	**Sunflower**	**Sorghum**
Sowing date	28/Nov/2014	28/Nov/2014	16/Oct/2014	13/Nov/13
Sowing rate	117 kg ha^{-1}	117 kg ha^{-1}	3.2 kg ha^{-1}	6.75 kg ha^{-1}
Cultivar	DM4913	DM4913	Paraíso 22	AD64
Harvest date	8/May/2015	8/May/2015	6/Mar/2015	1/Apr/2015
		Year 2015		
Crop	**Wheat**	**Wheat**	**Wheat**	**Wheat**
Sowing date	16/Jul/2015	16/Jul/2015	16/Jul/2015	16/Jul/2015
Sowing rate	144 kg ha^{-1}	144 kg ha^{-1}	144 kg ha^{-1}	144 kg ha^{-1}
Cultivar	Buck SY300	Buck SY300	Buck SY300	Buck SY300
Harvest date	21/Dec/2015	21/Dec/2015	21/Dec/2015	21/Dec/2015

trials were maintained free of weeds, pests and diseases.

The experiment was established in randomized block design with four replications and in subdivided plots. The main plot corresponded to the trials: Trial 1 (2011-14) and Trial 2 (2012-15); while the subplot and sub-subplot corresponded to crop sequence and technological management practice, respectively. The area of each sub-subplot was 22 m^2. The soil was a Typic Argiudoll. Monthly precipitation and mean temperatures were recorded at a Davis® Meteorological Station located 100 m from the experimental site within the experimental station (Fig. 1).

Evaluations of grain yield, aerial biomass, aerial plus root stubble, humified C of aerial plus root stubble and C balance

To determine the aerial biomass production (kg ha^{-1}) and yield (kg ha^{-1}) of each crop, plants were cut at ground level on a surface of 0.6 m^2 for wheat, oat, barley and canola; 1 m^2 for soybean and late-sown soybean; 7 m^2 for corn and sorghum; and 1.5 m^2 for sunflower. Total aerial biomass and grain yield were calculated for each complete sequence. In order to compare yields between sequences, yields were transformed into productivity values in JG ha^{-1}, by multiplying the yields of each crop by the corresponding energy coefficient.

The amount of C humified by each 4-year crop sequence was quantified based on the contributions of stubble from each crop. A 20 % was added to this value, usually described in the literature as the contribution of organic matter from the decomposing root system (Richmond and Rillo, 2009). Humified C was obtained through the multiplication of the C contribution of aerial plus root stubbles (considered in 45% of the total stubble) by the mean humification coefficient corresponding to each crop for different edaphoclimatic situations: 0.36 % for wheat, oat, barley, maize and sorghum and 0.38 for canola, soybean and sunflower (Richmond and Rillo, 2009; Álvarez and Steinbach, 2010; Menéndez and Hilbert, 2013).

Soil samples were collected up to 15 cm deep. Organic matter (OM) was determined by the Walkley-Black method (IRAM-SAGyP 29571 -3: 2016), while bulk density was measured by the cylinder method (Blake and Hartge,1986). Organic matter was 2.85 % and apparent density was 1.18 g cm^{-3}. As OM contains 56 % of the C (Richmond and Rillo, 2009; Álvarez and Steinbach, 2010), C content was approximately 28,224 kg ha^{-1}. Several studies have reported between 3 and 5 % of mineralization on an annually basis under no-till systems (Richmond and Rillo, 2009; Alvarez and Steinbach, 2010). Hence, if we consider a value of 4 %, then 1,128 kg ha^{-1} of C would be annual mineralized.

Evaluations of N, P, K and S extractions, N and P balance and water use efficiency

N, P, K, and S extractions were calculated by multiplying each nutrient percentage by the grain yield.

N concentration was determined by Kjeldahl, while P, K, and S concentrations were determined through inductively coupled Ar plasma spectrometry (AOAC International, 2000).

Nutrient inputs are those coming from fertilizers and biological N fixation in soybean. Fertilizer inputs were calculated from fertilizer doses and their composition for each crop and sequence. For soybean, the biological N fixation was estimated at 40%. For each crop sequence, N and P balances were calculated as the difference between nutrient inputs and nutrient extraction.

Water use efficiency per year (WUE) was calculated according to the following formula:

$$\text{WUE [kg ha}^{-1}\text{.mm}^{-1}\text{]} = Y / R$$

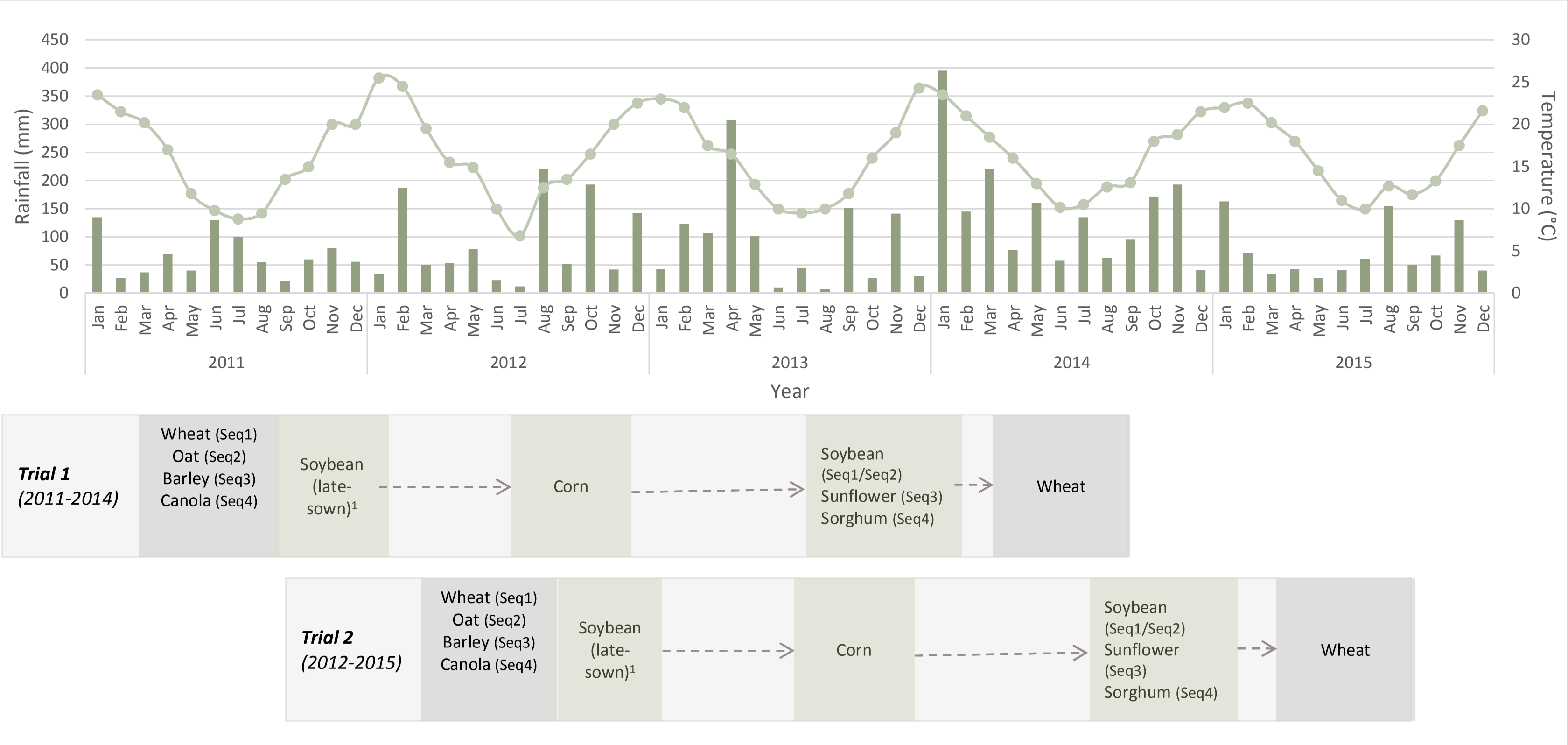

Fig. 1. Monthly mean temperatures and rainfall during the crop cycles comprising from Jan 2011 to Dec 2015. An approximate indication of the crop is also provided (Seq: crop sequence). [1] Understood as soybean immediately sown after the crop that comes from winter without fallowing.

where Y corresponds to grain yield and R is rainfall. The latter corresponds to the rainfall events recorded during the crop cycle and the two months prior to sowing.

Statistical analysis

Data were analyzed by analysis of variance (ANOVA) for a subdivided plot design using InfoStat® statistical program (Di Rienzo et al., 2016). Mean values were compared using the LSD test ($p<0.05$). Treatment variances were homogeneous, and residuals fitted normal distributions.

RESULTS

Productivity, aerial biomass, aerial plus root stubble, humified C of stubble plus roots and C balance

Significant differences were found in *Trial*, *Sequence*, *Management* main factors and the *Sequence* × *Trial* interaction for productivity, aerial biomass, aerial plus root stubble, humified C of aerial plus root stubble and C balance (Table 3, Fig. 2a, 2b, 2c and 2d). All the variables were significantly higher in Trial 2 than Trial 1. Productivity was 21% higher in Trial 2 compared to Trial 1, and 3.5% higher in HTL compared to MTL. Regarding sequences, productivity presented the following decreasing order: Ca/S-C-So-W > B/S-C-S-W > W/S-C-S-W > O/S-C-Su-W, but these last three sequences did not differ statistically (Table 3). For the *Sequence* × *Trial* interaction, sequences W/S-C-S-W, B/S-C-S-W and O/S-C-Su-W showed similar productivity in both trials, while Ca/S-C-So-W recorded a larger increase in Trial 2, achieving the highest yield value (Fig. 2a).

The aerial biomass was 17% higher in Trial 2 compared to Trial 1, and 5% higher for HTL with respect to MTL. Aerial biomass for sequences presented the following decreasing order: Ca/S-C-So-W > B/S-C-S-W > W/S-C-S-W > O/S-C-Su-W (Table 3). For the *Sequence* × *Trial* interaction, Ca/S-C-So-W was the sequence that presented the greatest increase in Trial 2, while the other sequences had a similar behavior, with a slight increase in the amount of aerial biomass (Fig. 2b).

Aerial plus root stubble was 20% higher in Trial 2 than Trial 1, and 6% higher for HTL compared to MTL. In addition, the Ca/S-C-So-W sequence was statistically different from B/S-C-S-W, W/S-C-S-W, and O/S-C-Su-W sequences (Table 3). The humified C of aerial plus root stubble was 25% higher in Trial 2 with respect to Trial 1, being 6% higher for HTL compared to MTL. Again, the Ca/S-C-So-W sequence differed statistically from the B/S-C-S-W, W/S-C-S-W and O/S-C-Su-W sequences (Table 3). Carbon balance was positive for all the parameters analyzed, being 60

Table 3. Mean values of yield, aerial biomass, aerial plus root stubble, C of aerial plus root stubble, humified C of aerial plus root stubble and C balance for the two trials (2011-14 and 2012-15) with different crop sequences and technological management practices.

Source of variation	Productivity (GJ ha^{-1})	Aerial biomass (kg ha^{-1})	Aerial + root stubble (kg ha^{-1})	Humified C aerial + root stubble (kg ha^{-1})	C Balance (kg ha^{-1})
Trial					
Trial 1 (2011-14)	673.13 a	69,963 a	54,762 a	8,872 a	1,238 a
Trial 2 (2012-15)	849.51 b	84,471 b	68,227 b	11,053 b	3,096 b
Sequence					
W/S-C-S-W	694.58 a	74,015 ab	58,717 a	8,103 a	1,558 a
B/S-C-S-W	727.18 a	74,500 b	57,637 a	7,954 a	1,635 a
O/S-C-Su-W	688.09 a	70,317 a	57,081 a	7,877 a	1,784 a
Ca/S-C-So-W	935.42 b	89,536 c	72,545 b	10,011 b	3,692 b
Management					
MTL	747.61 a	75,069 a	59,743 a	8,244 a	1,926 a
HTL	775.03 b	79,364 b	63,247 b	8,728 b	2,409 b

Means with different letters between columns (within each treatment) indicate significant differences ($p<0.05$). Crop sequences: wheat/soybean-corn-soybean-wheat (W/S-C-S-W), barley/soybean (late-sown)-corn-soybean–wheat (B/S-C-S-W), oat/soybean (late-sown)-corn-sunflower–wheat (O/S-C-Su-W), canola/soybean (late-sown)-corn-sorghum-wheat (Ca/S-C-So-W). Management: medium technological level (MTL) and high technological level (HTL).

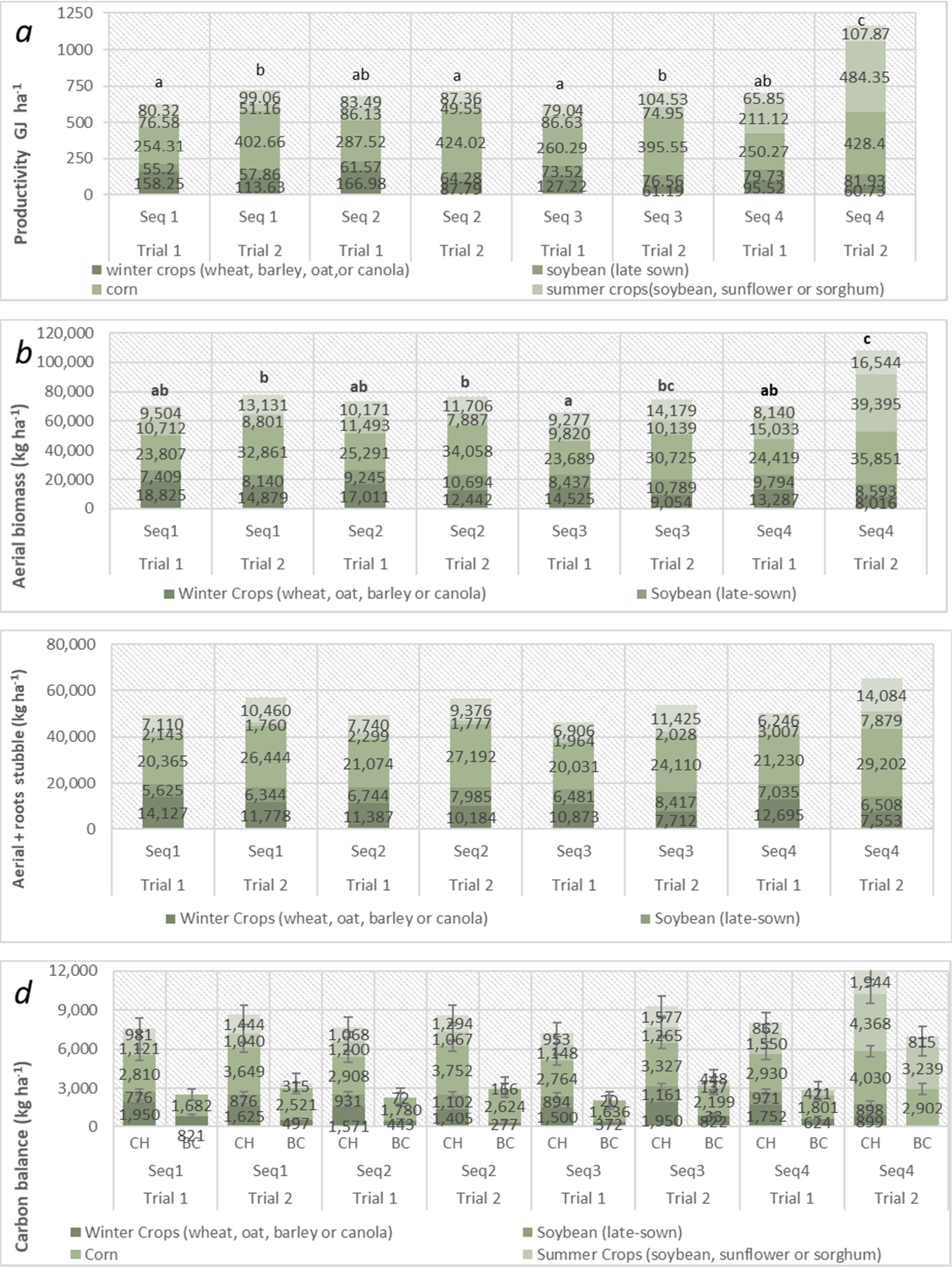

Fig. 2. Mean values of (a) productivity, (b) aerial biomass, (c) aerial plus root stubble and (d) humified C of aerial plus root stubble (CH), and carbon balance (BC) for the Sequence × Trial Interaction. Different letters between columns indicate significant differences, considering the total crops of each crop sequence (p<0.05). The bars indicate the standard error.

% higher in Trial 2 compared to Trial 1, and 20% higher for HTL than MTL. Among sequences, the Ca/S-C-So-W sequence showed the highest C balance, being 55% higher than the average values of the other sequences that did not differ statistically (Table 3).

For the *Sequence* × *Trial* interaction, Ca/S-C-So-W in Trial 2 had the highest values for all these variables: aerial biomass, aerial plus root stubble, humified C of stubble plus roots and C balance, whereas the O/S-C-Su-W sequence in Trial 1 had the lowest value (Fig. 2b, 2c, 2d). The annual mineralized C of the soil, calculated from the organic matter percentage, soil density and at a depth of 15 cm was 1,128 kg ha^{-1}.

When analyzing trials, winter cereals (wheat, barley and oats) and canola recorded higher productivity, aerial biomass, aerial plus root stubble, and humidified C of aerial and root stubble in Trial 1. Late-sown soybean had the highest values of all these parameters in Trial 2 in the W/S-C-S-W, B/S-C-S-W and O/S-C-Su-W sequences. Corn and summer crops had the highest productivity in Trial 2. Wheat showed similar productivity, biomass and stubble production in the four sequences in both trials (Fig. 2a, 2b, 2c, 2d). Likewise, corn behaved similarly in all the sequences in the two trials, while the highest C balance was recorded by sorghum in Trial 2 (Fig. 2d). In addition, barley always presented positive balances, although to a lesser degree than corn and sorghum. Oat only had a negative C balance in the O/S-C-Su-W sequence in Trial 2 (-64 kg ha^{-1}), and wheat in all the sequences of Trial 1 (W/S-C-S-W: -147 kg ha^{-1}, B/S-C-S-W: -60 kg ha^{-1}, O/S-C-Su-W: -176 kg ha^{-1}, Ca/S-C-So-W: -166 kg ha^{-1}). Late-sown soybean without fallow presented a negative balance for all the sequences in Trial 1 (W/S-C-S-W: -352 kg ha^{-1}, B/S-C-S-W: -198 kg ha^{-1}, O/S-C-Su-W: -234 kg ha^{-1}, Ca/S-C-So-W: -158 kg ha^{-1}) and for three sequences in Trial 2 (W/S-C-S-W: -253 kg ha^{-1}, B/S-C-S-W: -20 kg ha^{-1}, Ca/S-C-So-W: -230 kg ha^{-1}). Soybean (sown after fallow) also caused a negative balance in the W/S-C-S-W sequence in both trials (Trial 1: -8 kg ha^{-1} and Trial 2: -89 kg ha^{-1}) and in the B/S-C-S-W sequence for Trial 2 (-61 kg ha^{1}) (data not shown).

N, P, K and S extractions, N and P balances, and WUE

Nutrient extractions and balances evidenced significant differences between trials, sequences, management and *Sequence* × *Trial* interaction for all the variables under study (Table 4). Nutrient extractions were greater in Trial 2 compared to Trial 1 (N 13%, P 8%, K 19% and S 8%), also recording the most negative N and P balances. Among the sequences, the most extractive sequence with the most negative nutrient balances was Ca/S-C-So-W, followed by the B/S-C-S-W and W/S-C-S-W sequences. O/S-C-Su-W was the least extractive sequence with the least negative balances. Considering technological management, HTL resulted in higher extraction values, but with higher nutrient balances (Table 4).

Overall, for the *Sequence* × *Trial* interaction, the W/S-C-S-W sequence did not show differences between trials for the extractions nor for the balances of the different nutrients (Fig. 3, 4a and 4b). The B/S-C-S-W sequence presented high nutrient extractions and, therefore, balances were more negative in Trial 1. Nutrient extractions and balances for the O/S-C-Su-W sequence were very similar between trials, except for K extraction that was higher in Trial 2. Moreover, this was the least extractive sequence with the best nutrient balances. Significant differences between trials were found in the Ca/S-C-So-W sequence in terms of extraction and nutrient balances. For this

Table 4. Mean values of N, P, K and S extractions, N and P balances, and WUE for the two trials (2011-14 and 2012-15) with different crop sequences and management.

Source of variation	N Extraction (kg ha^{-1})	P Extraction (kg ha^{-1})	K Extraction (kg ha^{-1})	S Extraction (kg ha^{-1})	N Balance (kg ha^{-1})	P Balance (kgha^{-1})	WUE (kgha^{-1} mm^{-1})
Trial							
Trial 1	563 a	113 a	211 a	56.0 a	-372 b	-55.6 b	8.58 a
Trial 2	651 b	122 b	261 b	60.8 b	-460 a	-64.8 a	8.99 b
Sequences							
W/S-C-S-W	568 b	111 b	202 b	51.8 b	-383 b	-61.6 b	8.46 b
B/S-C-S-W	587 b	114 b	235 c	58.8 c	-403 b	-64.4 b	9.10 c
O/S-C-Su-W	529 a	97.8 a	169 a	46.3 a	-327 c	-34.7 c	7.99 a
Ca/S-C-So-W	746 c	146 c	338 d	76.8 d	-552 a	-80.1 a	9.60 d
Management							
MTL	597 a	114 a	231 a	57.0 a	-442 a	-65.1 a	8.63 a
HTL	618 b	120 b	241 b	59.7 b	-390 b	-55.3 b	8.95 b

Means with different letters between columns (within each treatment) indicate significant differences ($p<0.05$). Crop sequences: wheat/soybean-corn-soybean-wheat (W/S-C-S-W), barley/soybean (late-sown)-corn-soybean–wheat (B/S-C-S-W), oat/soybean (late-sown)-corn-sunflower–wheat (O/S-C-Su-W), canola/soybean (late-sown)-corn-sorghum-wheat (Ca/S-C-So-W). Management: medium technological level (MTL) and high technological level (HTL).

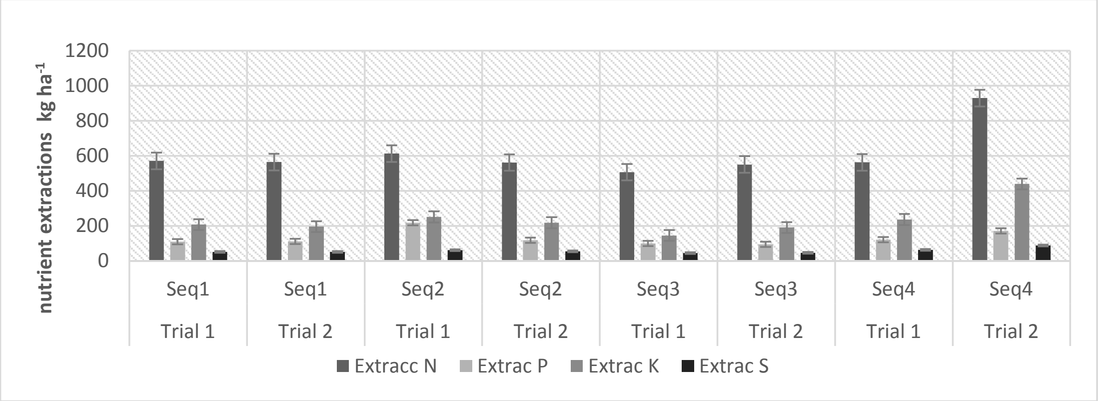

Fig. 3. Mean values of N, P, K, and S extractions for the *Sequence* × *Trial* interaction. The bars indicate the standard error. Crop sequences: wheat/soybean-corn-soybean-wheat (Seq 1), barley/soybean (late-sown)-corn-soybean–wheat (Seq 2), oat/soybean (late-sown)-corn-sunflower–wheat (Seq 3), canola/soybean (late-sown)-corn-sorghum-wheat (Seq 4).

sequence, nutrient extractions were higher and nutrient balances were more negative in Trial 2, which was associated with the higher levels of biomass and productivity recorded in the 2012-15 rotation (Fig. 4a and 4b).

Regarding crops, the most negative balances were recorded by late-sown soybean in all the sequences, soybean in W/S-C-S-W and B/S-C-S-W, corn in all the sequences and sorghum in Trial 2 (Fig. 4a and 4b). WUE showed significant differences between trials, sequences, management practices and the *Sequence* × *Trial* interaction (Table 4). WUE was 5% higher in Trial 2 compared to Trial 1, and 4% higher in HTL compared to MTL (Table 4). The highest and lowest water use efficiency was observed in Ca/S-C-So-W and O/S-C-Su-W, respectively. For the *Sequence* × *Trial* interaction, WUE was lower for the B/S-C-S-W sequence in Trial 2 and for the Ca/S-C-So-W sequence in Trial 1, with no statistical differences between trials for W/S-C-S-W and O/S-C-Su-W (Fig. 4c).

DISCUSSION

Productivity, aerial biomass and stubble

In both trials, non-quantitative differences were found in rainfall distribution patterns, affecting biomass accumulation and productivity of all the crops. Wheat, oat, barley, and canola presented higher biomass and productivity in Trial 1 due to higher water availability during sowing establishment compared to Trial 2. Late-sown soybean (sown immediately after harvest of winter cereals and canola) had higher water availability in Trial 2, allowing for better seedling establishment, and resulting in higher establishment efficiency. Water availability constitutes one of the most frequent constraints for the survival of plants in late-sown soybean preceding other crops without fallow. This did not apply for the Ca/S-C-So-W sequence because the predecessor crop was canola, and then soybean was sown with greater availability of moisture in the soil. For corn, the highest productivity was achieved in Trial 2, mainly associated with higher water availability during the critical period where the number of grains is determined (mid-January to mid-February in our trial). Soybean productivity increased in Trial 1 because sowing date (November 18) was earlier than in Trial 2 (Table 2), and rainfall recorded that month allowed for a good seedling establishment. On the contrary, sowing in Trial 2 took place at the end of November and it was followed by a dry December with very little rainfall, which evidently affected the stand of plants. Sunflower had a similar response. In Trial 2, sorghum had an increased grain productivity and aerial biomass production, which can be explained by an earlier sowing during this trial compared to the other summer crops (soybean and corn), which allowed for more water availability in November. Although rainfall was lower during the crop cycle in Trial 1, sorghum had high water availability during the critical period. Wheat behaved similarly in both trials (Fig.1, Table 2), and variations in yield were associated with good water availability in key periods of the growing season as well as with sowing and harvest dates. This agrees with previous studies on crop rotations in various regions of the world (Van Duinen et al., 2015; Silva et al., 2020).

Productivity and aerial biomass were higher in Trial 2 for the following sequences (in decreasing

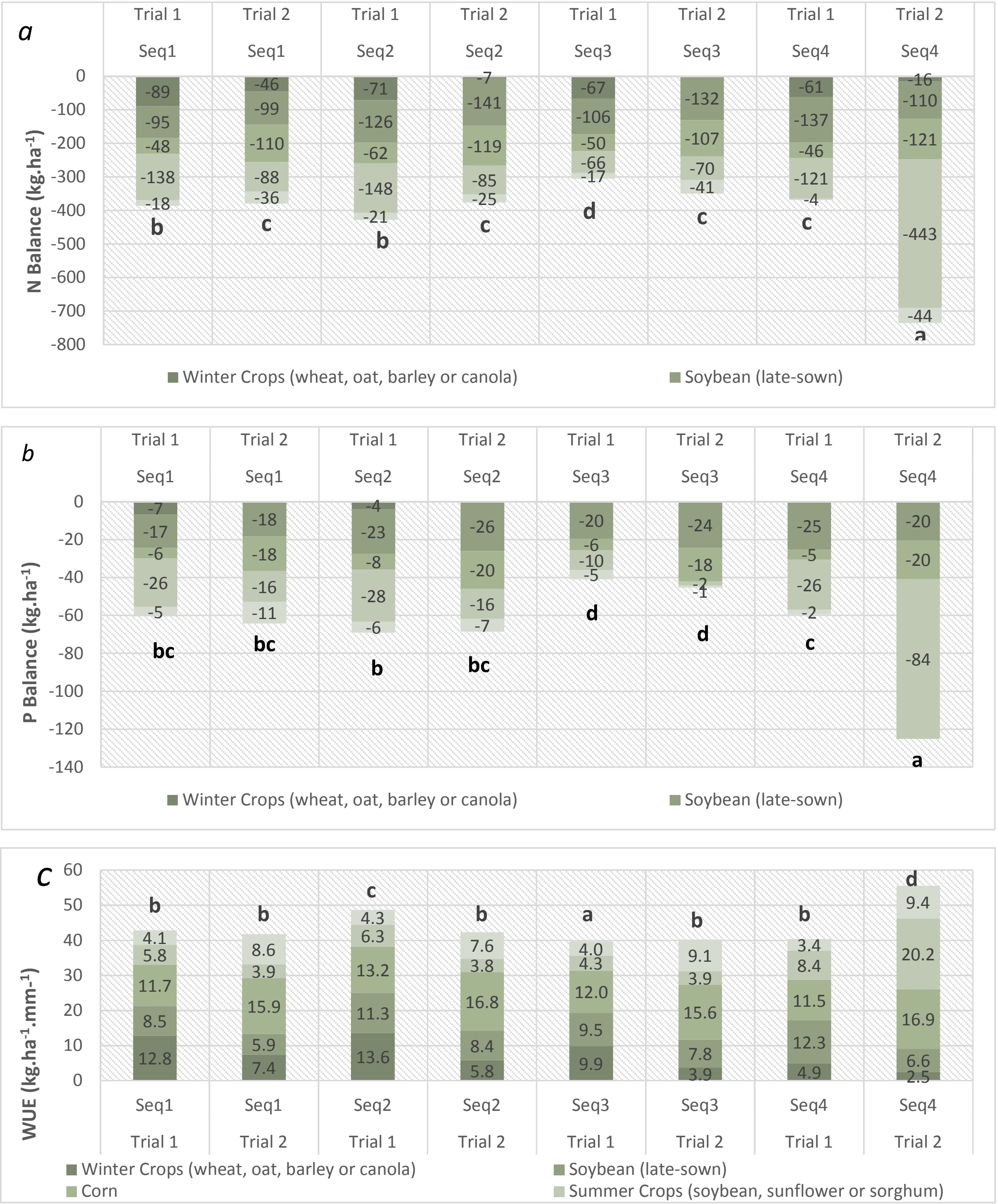

Fig. 4. Mean values of (a) N Balance, (b) P Balance and (c) WUE for the *Sequence* × *Trial* interaction. Different letters between columns indicate significant differences (*p<0.05*).

order): Ca/S-C-So-W > B/S-C-S-W > W/S-C-S-W > O/S-C-Su-W, which was associated with the components of each sequence. In this sense, corn had an important role in soil carbon recovery in all the sequences and sorghum in the Ca/S-C-So-W sequence in Trial 2. These results agree with those found by Menéndez and Hilbert (2013), Turmel et al. (2015), Sarkar et al. (2020), and Fu et al. (2021), who reported that the amount and quality of stubble differ depending on the crop selected for the sequence. Soybean presented a negative balance in the contribution of total C, even for the HTL. Menéndez and Hilbert (2013) evaluated the contribution of dry matter of stubble produced by different agricultural crops in Argentina. In general, sorghum, corn and wheat are the crops produce the largest amounts of crop residues, frequently reaching 10 t ha^{-1} of dry matter. For sunflower, contributions of 6-7 t ha^{-1} have been reported, followed by soybean (4-6 t ha^{-1}), and then late-sown soybean (3 to 3.5 t ha^{-1}) (Menéndez and Hilbert, 2013). The amount of stubble can be characterized by the C:N ratio, which allows predicting how fast residues decompose in the soil. In this sense, high C:N values indicate a slow decomposition rate and, in turn, longer durability of the stubble; whereas low C:N ratios indicate a rapid decomposition and, consequently, an early loss of coverage on the ground surface. In many cases, the amount and/or quality of the stubble left by the predecessor influences the behavior of the successor crop. Pellegrini et al. (2014) reported that the amount of stubble produced by the predecessor crops for corn were similar for the different sequences. However, the authors found statistical differences in particulate organic carbon, which corresponds to the weakest fraction of organic matter, where the O/S-C-Su-W and B/S-C-S-W sequences recorded the highest values of 1.29 g kg^{-1} and 1.17 g kg^{-1} respectively, followed by W/S-C-S-W (1.11 g kg^{-1}) and Ca/S-C-So-W (1.0 g kg^{-1}).

Chahal et al. (2021) have recently found a positive relationship between soil organic carbon and crop productivity, which indicates a direct association between soil carbon status and agroecosystem resilience. The authors have also reported that crop rotation increases surface soil organic carbon sequestration and crop productivity in the long term, indicating that crop diversity is a key component for developing sustainable agroecosystems. In this sense, alternating crops with different productions and amounts of residues is necessary, particularly in some environments. Flower et al. (2021) conducted a study in Mediterranean-type environments of Australia and found that retaining all the residues in a cereal-dominant rotation resulted in the highest amounts of residues, but it also reduced crop establishment and herbicide efficacy. The amount of residues was reduced to optimal levels by including legume crops or canola in the crop rotation as these residues were more rapidly broken down than cereal residues, whilst maintaining residue retention practices.

In the Argentine Pampas, soil carbon loss is mainly attributed to the high frequency of soybean in crop rotations (Caride et al., 2012; Milesi Delaye et al., 2013). In this regard, several studies have demonstrated that soybean monoculture decreases soil carbon stocks (Caride et al., 2012). Soil organic carbon is associated with land productivity since an adequate level of soil organic matter is related to higher air and water circulation, and nutrient availability. Moreover, carbon sequestration contributes to climate change mitigation (Stockmann et al., 2013). In the present study, all the sequences showed a positive C balance between the C mineralized in the soil and the C humified by the crops. This constitutes a factor of fundamental importance for the contribution of organic matter to the soil. This balance was higher in the Ca/S-C-So-W sequence than in the others, highlighting the importance of including crops such as sorghum in rotations. In Argentina, sorghum has often been displaced by corn and soybean due to their greater short-term economic profitability. When selecting crops, important aspects such as the non-degradation and improved soil health achieved with sorghum have been disregarded by farmers despite the fact that such aspects are equally or more important than productive parameters because they directly contribute to soil conservation.

Nutrient extractions and balances and water use efficiency

Nutrient balances are also indicators of the environmental effect of agricultural systems, mainly due to concerns about soil and water contamination associated with nutrient excess (Ten Berge et al., 2000; Austin et al., 2013). However, extraction of soil N and P is creating deficits rather than excesses in some regions of Latin America (Díaz de Astarloa and Pengue, 2018). In Argentina, there is an increasing concern about the negative nutrient balances and the importance of considering these deficits in land management and fertilization decision making. Nutrient deficits decrease land productivity and increase fertilization requirements (Cabrini et al., 2013; Alvarez et al., 2014). In the present study, the highest nutrient extractions were found in Trial 2 and were associated with higher biomass yields and productivity in this experiment. Regarding sequences, the highest extractions were recorded with the Ca/S-C-So-W sequence, mainly due to canola and sorghum crops. Sorghum had a lower nutrient harvest index than soybean and corn, but its high productivity resulted in higher nutrient extraction. B/S-C-S-W and W/S-C-S-W were sequences with high yields and high frequency of soybean, which resulted in high extraction of nutrients per ton of grain. The O/S-C-Su-W sequence was the least extractive, being in turn the one with the lowest productivity, amount of biomass and stubble contribution.

N balances were deficient in the four sequences.

Given the higher fertilization in the HTL, aerial biomass and productivity increased, consequently increasing nutrient extraction compared to values observed in the MTL. Although HTL ensured a higher level of restitution (especially N), N balance was negative. P balance was also negative in the four sequences. W/S-C-S-W and B/S-C-S-W, which included soybean twice within the 4-year rotation, and Ca/S-C-So-W were the sequences with the highest negative balances. According to García and. Correndo (2016), canola requires twice P per ton of grain compared to soybean, 1.5 times more P than sunflower, and between 3 and 4 times more than grasses. Many authors argue that the high frequency of soybean in crop rotations is responsible for more negative balances of N and P in the Argentine Pampas (Díaz de Astarloa and Pengue, 2018). Even though a large proportion of N in soybean grains comes from biological fixation, there are big N exports in harvested grains associated with this crop (Collino et al., 2015). Only about a quarter of the total nutrients extracted by soybean grains are replenished (Cruzate and Casas, 2017). The negative nutrient balances obtained here are in agreement with those found by Flores and Sarandón (2002) for wheat, corn and soybean in the Pampean Region of Argentina during the 1990s. Unfortunately, the cost-benefit analysis (commonly used by producers) does not include the cost of soil degradation, overestimating the benefits of agricultural activity. At a national scale, Cruzate and Casas (2017) found that the percentage of total nutrient replacement is 24.5 % of that extracted, with 31% replacement of N, 39% of P, 3% of K, 46% of Ca and 31% of S. Therefore, this cost should be included to allow for sustainable agricultural systems.

WUE was higher in Trial 2, which can be explained by different factors. For crop sequences, the order of efficiency was as follows: Ca/S-C-So-W > B/S-C-S-W > W/S-C-S-W > O/S-C-Su-W. The crops included in each sequence accounted for the differences in hydric behavior. Crop selection has been described as a good technique to improve WUE (Sadras and McDonald, 2012; Fontaine et al., 2020; Malobane et al., 2020). Sorghum is well-recognized as one of the most efficient crops in terms of water use. This greater efficiency could be due to its higher residue production and root system. Crop residues can increase soil water by increasing water infiltration and reducing evaporation (Hulugalle et al., 2017), while crops have different effects on macroaggregation and hydro-physical properties of the soil (Nouria et al., 2019). According to Chen et al. (2021), poor soil hydraulic properties were mainly improved by crops with high root length density, and influenced by root diameter distribution, suggesting that fine roots played a key role in forming aeration and active capillary pores, which could be applicable to sorghum. The higher fertilization levels in the HTL resulted in higher biomass and greater WUE comparted to values observed in the MTL. In fact, HTL did not only improve crop biomass production and yield, but also different processes of agroecosystem functioning related to water use and C cycle. Additionally, N and P balances improved in the soil. In this sense, some authors have indicated that practices that combine economic and ecological benefits highlight the importance of diversified production (Ponisio and Ehrlich, 2016) and inclusion of cover crops and/or composts during fallows (Golik et al., 2020).

CONCLUSIONS

Non-quantitative differences were found between the environmental conditions during the two trials of 4-year rotation (2011-14 and 2012-15). However, differences in distribution patterns were recorded in each year of the two trials. The sequences showed significant differences for all the parameters analyzed. Ca/S-C-So-W was the sequence with the highest productivity, C balance and WUE, but it recorded more negative balances of N and P than the other sequences. The O/S-C-Su-W sequence had the lowest nutrient extractions and hence the least negative nutrient balances, also being the sequence with the lowest productivity and WUE. The B/S-C-S-W and W/S-C-S-W sequences had high productivity and contributed C to the soil, but also caused high nutrient extraction. The indicators analyzed differed significantly between technological management practices. HTL resulted in increased biomass, yield, stubble and balance of humidified C compared to the MTL. In addition, even though nutrient extraction was higher under HTL, N and P balances were less negative, and WUE improved. The search for cropping practices that combine productive as well as indirect economic and ecological objectives highlights the importance of diversified production and the use of indicators that contribute to achieving sustainable food systems.

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