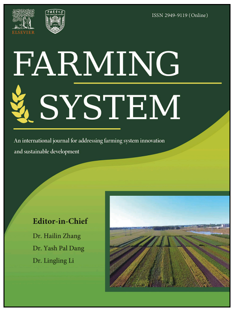
Journal Pre-proof



Changes in productive, socio-economic, and environmental performance of field crop farming in the Argentine Pampas, 2007-2018

M. Victoria Bitar, Silvina M. Cabrini, Hernán A. Urcola

PII: S2949-9119(24)00031-5

DOI: https://doi.org/10.1016/j.farsys.2024.100101

Reference: FARSYS 100101

To appear in: *Farming System*

Received Date: 17 October 2023

Revised Date: 3 May 2024

Accepted Date: 20 May 2024

Changes in productive, socio-economic, and environmental performance of field crop farming in the Argentine Pampas, 2007-2018

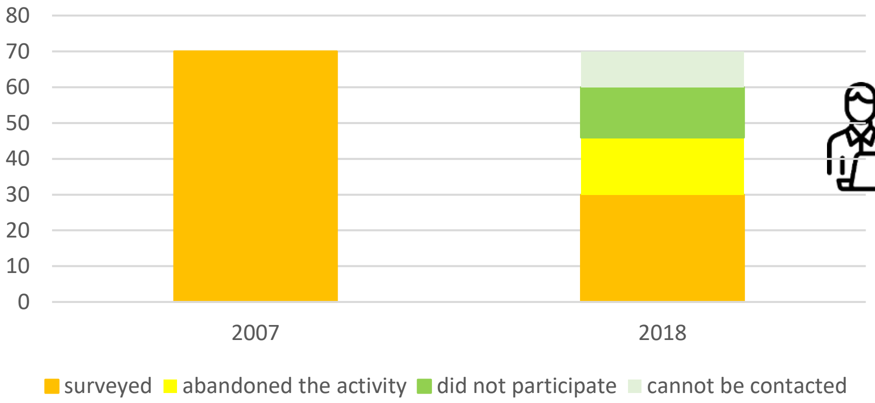
M. Victoria Bitar [a], Silvina M. Cabrini [b], Hernán A. Urcola [c]

My name is M. Victoria Bitar, I am an agricultural engineer graduated from the National University of the Northwest of the Province of Buenos Aires (UNNOBA) Argentina. Through research scholarships awarded by UNNOBA, I completed my postgraduate training and participated in different research projects at the university and the Institute of Agricultural Technology (INTA). I am currently completing my doctorate in agricultural sciences at the Faculty of Agricultural Sciences at the National University of Mar del Plata. This work presented in part of the doctoral thesis, during the course of the doctoral career I take various training courses related to the subject and interact with professionals, teachers and producers, enriching my training.

Changes in productive, socio-economic, and environmental performance of field crop farming in the Argentine Pampas, 2007 - 2018

Data collection

Interview with the same 30 farmers in two moments



Characterization of farms structure and performance

Productive

Economic

Environment

Data Analysis

Test of differences and canonical correlation

Farm size & tenure

farm scale, tenure, and workforce do not show significant changes

Management

the age of managers increased

optimism about the growth expectations decreased

Productive & Economic

16% increase in expected yields

Production cost increased, margins threatened

Environmental

Higher yields determined higher organic carbon inputs to soils

Nutrient balance for most crops continue to be negative

The risk of contamination by pesticides increased for 1st and 2nd soybean and was reduced for corn and wheat

The approach used allows evaluating interactions between the performance and the structure of the farms

Changes in productive, socio-economic, and environmental performance of field crop farming in the Argentine Pampas, 2007-2018

M. Victoria Bitar [1*] Silvina M. Cabrini [2], Hernán A. Urcola [3]

[1]National University of the Northwest of the Province of Buenos Aires, Monteagudo 2772, Pergamino, Argentina, Agricultural Sciences Department, National University of Mar del Plata, RN 226 Km 73,5, Balcarce, Buenos Aires, Argentina mvbitar@unnoba.edu.ar

[2]Economics and Sociology, INTA, EEA Pergamino Av Fondizi km 4.5, Pergamino, Argentina, Department of Economic and Legal Sciences. School of Agricultural Sciences. National University of the Northwest of the Province of Buenos Aires, Monteagudo 2772, Pergamino, Argentina. cabrini.silvina@inta.gob.ar

[3]Institute of Innovation for Agricultural Production and Sustainable Development (IPADS) Balcarce (INTA-CONICET), RN 226 km 73.5, Balcarce, Buenos Aires, Argentina. urcola.hernan@inta.gob.ar

Abstract

This study fills important gaps in research by analyzing the evolution over time of productive, environmental, and socio-economic aspects of agricultural production in the Argentine Pampas, utilizing farm-level data. A longitudinal study was conducted to examine the changes that occurred in farming systems during the period 2007-2018. The study evaluated the changes in 30 farms, examining modifications in the structure and management of each farm, as well as in productive, economic, and environmental performance. Canonical correlation analysis was used to relate the changes that occurred in performance to farms' characteristics at the beginning of the study period. The results indicated that, among the farms that stayed in business, there were no significant changes in land tenure and the amount of labor employed. There was a significant increase in the average age of farmers by 7 years, along with a decrease in the percentage of farmers expecting growth, dropping from 70% to 42% over the period. Canonical correlation analysis revealed that smaller farms, with a higher number of workers at the beginning of the period, were more likely to expand their farming area during the analysis period. The findings also indicate a substantial turnover of producers, with leaving farms being succeeded by larger-scale operations. The yields of the main crops and the direct production costs increased by 16% and 48% respectively, during the period. The environmental indicators for the main crops present a mixed picture: soil organic carbon input increased by 12%, while environmental impact quotient decreased on average, by 6% for cereals but increased by 40% for soybeans, and nutrient imbalances rose. The significance of

this study resides in its application of a comprehensive approach to analyze the transformation of farming systems over time.

Keys word: Farming systems, sustainable intensification, changes in performance, farm-level data, multidimension assessment.

1. Introduction

There is global interest in transforming current farming systems to produce higher-quality and more accessible food with a lower environmental impact (Pretty et al., 2018). Achieving food security through sustainable agricultural farming systems is a central challenge for humanity. Agriculture serves as a major driver of negative environmental impacts while remaining heavily dependent on natural resources for its development (Gerten et al., 2020).

The Argentine Humid Pampa is one of the main regions for food production worldwide. Current production levels of soybeans, corn, wheat, and meat have positioned Argentina among the major producers and exporters of these commodities (WASDE, 2023), and agricultural exports are crucial to the country's economy (INDEC, 2023). The professionalization of the sector and the high technological level, combined with the availability of natural resources, make crop production competitive in the Argentine Pampas, even when the tax burden on the agro-export sector is higher compared to other sectors of the economy and other exporting countries. Transformations that have occurred in recent decades have allowed Argentina to consolidate as a key participant in commodity markets, but they have also raised concerns about potential environmental effects (Cabrini et al., 2018).

In the Argentine humid Pampas, the area dedicated to soybean production has significantly increased over the last few decades, along with total grain production (SAGyP, 2022). Nationally, yield values for some major crops have also undergone significant positive changes in the past 15 years (Satorre and Andrade, 2020)

Concerning crop management, several adverse changes have been reported in recent years. Herbicide levels indicate increases in application doses and frequencies in response to the emergence of resistant/tolerant weeds (Principiano and Acciaresi, 2017； Ferraro et al., 2020;). Additionally, multiple studies indicate a steady decline in soil organic carbon (SOC) stocks over time (Cabrini et al., 2019; Sainz Rozas et al., 2019).

Concerning nutrient balances, recent reports indicate a persistent negative trend associated with diminishing chemical fertility caused by nutrient exports in harvested grains surpassing inputs. This, in turn, is anticipated to incur higher economic costs for sustaining fertility in upcoming growing seasons (de Astarloa and Pengue, 2018; Sainz Rozas et al., 2019). Also, the latest national agricultural censuses demonstrate a sustained decrease in the number of farms within the Pampas region.

The sustainable intensification (SI) concept has been employed to describe changes occurring at the regional level in Argentine Pampas (Ferraro et al., 2020; Satorre and Andrade, 2020; Martinez et al., 2022). This concept was first coined in the 1990 (Pretty 1997) and has since been endorsed by various research and development institutions like the Royal Society and FAO, among others. SI refers to farming systems and crop management technologies that enhance productivity while reducing adverse effects on natural resources, improving resilience to climate change, and creating an environment for farmers to competitively engage in markets (FAO, 2014)

Given its multifunctional nature, the study of SI requires a more comprehensive perspective of production systems (Mahon et al., 2018). In the literature, several robust criteria are presented for evaluating the economic, productive, and environmental impacts of production systems; however, the same does not hold true for social and human criteria (Smith et al., 2017). The introduction of the Sustainable Intensification (SI) concept has sparked debates regarding the desired outcomes, methods of performance evaluation, and priorities for agriculture (Struik et al., 2014). According to Mahon (2017), these debates are not surprising, given that both words describing the concept mean different things to different people. As asserted by Struik (2017), society needs an agriculture that demonstrates resilience to future changes, an agronomy capable of addressing diverse trade-offs among different stakeholders, and sustainability perceived as a dynamic process based on agreed-upon values and shared knowledge, insight, and wisdom.

While numerous studies have assessed the performance of agricultural production in the Pampas, only a few have examined the progression of sustainable intensification using farm-level data. Limited research has addressed productive, environmental, and economic changes through data gathered from farms over time.

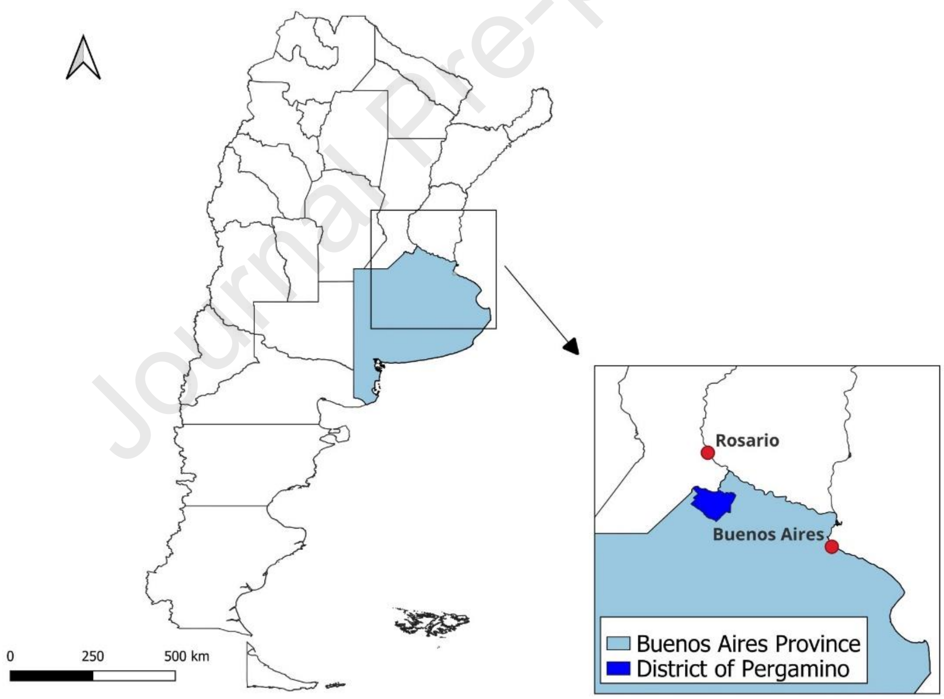
In Argentina, Calvi et al. (2019) studied the evolution of three dimensions of sustainability through time, but exclusively for cattle systems in the Province of Corrientes. Additionally, Pacín and Oesterheld (2014) integrated productive, environmental, and economic dimensions to study the effects of diversification on the level and stability of economic returns for farms in the Buenos Aires Province. Finally, Hara et al. (2022) explored the main drivers that promoted the sustainable intensification of farms in Northern Patagonia. Nevertheless, except for the work of Pacín and Oesterheld (2014), the studies mentioned above involve extra-Pampean systems

Furthermore, existing research has yet to identify the characteristics of productive systems that may encourage transformations aligned with Sustainable Intensification (SI). There are no longitudinal sustainability studies that integrate environmental and socio-productive variables applied to real farming systems in the Pampas region. This literature gap not only impedes the comprehension of transformation processes but also hinders the formulation of strategies to promote SI. The objective of this study is to examine the changes that occurred in the productive systems of the Central Pampean Region from 2007 to 2018, considering social, economic, and environmental aspects, to assess whether these changes are consistent with a trajectory toward the sustainable intensification of agriculture.

2. Data and methods

2.1. Data collection

A survey was developed using a longitudinal design to collect the data needed for this study. Within this design, a panel data method was employed, where the same subjects were surveyed more than once (Alaminos and Castejón, 2006). The research focused on analyzing changes in the same subjects between 2007 and 2018 (first and second sampling times). The study was conducted in the northern part of the province of Buenos Aires, specifically in the district of Pergamino (Fig. 1). This district is one of the most productive and dynamic regions in the country.



Source: GIS INTA EEA Pergamino

Fig 1. Study Area. District of Pergamino map, Buenos Aires, Argentina.

In 2007, the survey was first administered by researchers from INTA EEA Pergamino (Cabrini and Calcaterra, 2008) to 70 farmers in the Pergamino district, Buenos Aires. The same questionnaire used in 2007, which had already been validated, served as the foundation, with the addition of some questions and minor modifications.

The questionnaire comprises both closed and open-ended questions to gather information about farms, farmers, farm management, and technical approach to crop cultivation. It consists of 22 questions covering various topics of the farming systems as well as characteristics of the farmer managing the farm operation. The surveys were conducted in person with the farmers by the group of researchers participating in this research.

Between June 2017 and January 2018, several communication attempts were made through different channels to reach all the farmers from the initial sample. Out of the initial number of respondents, 60 could be contacted, and the remaining 10 could not be located.

Out of the 60 farmers contacted in 2017/2018, 30 were willing and able to respond to the survey again, 16 had discontinued their agricultural activities. This means that approximately 1 in every 4 farmers surveyed in 2007 had ceased agricultural activities by 2018. There were various reasons for leaving agriculture, including death or advanced age, economic constraints, land leasing, or sale. The remaining 14 farmers were contacted in 2017/2018 but were not surveyed a second time because they were unwilling to participate in the survey. Therefore, the current study analyzes the changes in the 30 cases that were willing and able to respond to the survey at both sampling times.

In cases where the surveyed farmer in 2007 was leasing part of the land, the contact information of the new person in charge of the plots was requested. Descriptive statistics for the cases that left farming and those who took over farming the same land are presented in Table 1 of the supplementary material. A detailed characterization of rainfall patterns, land use changes, and price evolution for the study period is also provided in the supplementary material.

2.2. Selected variables

A set of variables was chosen to assess changes in each farm under study. These variables were selected to characterize the farm structure and their managers, as well as the productive, economic, and environmental performance of each farm. The characteristics of farms and their managers were evaluated through indicators describing farm scale and land tenure (farming area, area rented, length of leasing arrangements), workers (family and hired labor), and management (manager's minimum age and maximum education, legal structure of the firm, record-keeping practices, use of technical advice, short-term debt level, provision of custom operation service, farm business growth expectation), and farming systems (productive diversity index and the proportion of first-season soybean) (Table 1). The performance of each individual farm was characterized through indicators such as yield (productive dimension), gross margin, and direct costs (economic dimension), as well as the risk of pesticide contamination, organic carbon input to soil, and nutrient balances (environmental dimension). Detailed methods for computing each indicator are provided in Table 2.

Table 1 Variables selected for the analysis of changes in farms and farmers' characteristics between 2007 and 2018.

Group	Variable	Unit	Definition
Scale	Farming area	ha	Total operated land
Land tenure	Area rented in	%	Percentage of the operated area that is rented in
	Length of leasing arrangements	crop years	Length of leasing arrangements
Workers	Family labor	full-time equivalent	Family labor expressed in numbers of full-time workers
	Hired labor	full-time equivalent	Salaried labor expressed in numbers of full-time workers
Management	Managers' minimum age	years	Age of the youngest manager
	Managers' maximum education	years	Highest educational level reached by those responsible for the farm
	Legal type	binary	Indicates whether sole proprietorship is the legal type of the farm (=1), or other (=0)
	Number of records kept	quantity of records	Number of records kept in the farm taking into account (eight categories:(inputs, nutrients, costs, taxes, gross margin, budgets and economic benefit)
	Technical advice	binary	Indicates if the farmer receives technical advice (=1) or not (=0)
	Medium or high short-term debt level	binary	Indicates if the level of debt in the short term is medium or high (=1) or low (=0)
	Provision of custom farming service	ha	Total area for which custom operation service is provided. The different tasks are expressed in equivalent harvested area, taking into account the price relationship between each task and the custom harvest's price.
	Future projection-grow	binary	It indicates growth expectations in the next 10 years, (=1) when planning to increase operated land, either through the purchase or rental of a larger area, (=0) otherwise.
Production system	Productive diversity index		1/HH x10000. The Herfindahl-Hirschman (HH) coefficient is calculated for each farm as the sum of the squared percentages of land allocated to each activity. The indicator takes a value of 1 for monoculture and higher values for higher levels of productive diversification.
	First season soybeans proportion	%	Proportion of land assigned to first season soybean

Table 2 Variables selected for the analysis of productive, economic and environmental performance of the farming systems analyzed between 2007 and 2018.

Group	Name	Unit	Definition
Productive performance	Yields	kg ha^{-1}	Productive performance was determined based on crop yields.
Economic performance	Gross margin	US$ ha^{-1}	Calculated as the difference between income and direct costs.
	Direct costs	US$ ha^{-1}	Calculated for each activity as the sum of labor and input costs
Environmental performance	Risk of pesticide contamination		Measured by the Environmental Impact Quotient (EIQ [1]) The EIQ considers three components, related to the impacts on consumers, farmworkers and the environment. (ecological)
	Organic carbon input to soil	Mg C ha^{-1}	Humifiable carbon (m x k1) calculated as m content (annual C input to soil of crop residues) times the humification rate of crop residues coefficient k1 [2]
	Nitrogen balance	kg ha^{-1}	Inputs: N fertilizers + N biological fixation (Di Ciocco et al., 2011) + N rainfall (Carnelos and Long, 2014) – output: N in harvested grain
	Phosphorous balance	kg ha^{-1}	Inputs: P fertilizers – output: P in harvested grain

Note: [1] EIQ (Kovach et al., 1992) [2] AMG model (Andriulo et al., 1999)

Using indicators that enable the evaluation of each farm's performance, it becomes possible to assess their trajectory and observe how these changes are consistent with a path towards SI. Positive changes in productivity, economic performance, and carbon input to the soil would indicate an evolution in line with the principles of SI. Similarly, reductions in risks associated with pesticide contamination and the achievement of nutrient balances close to neutrality would also align with SI strategies.

2.3. Data analysis

Various tests were employed to analyze the statistical significance of changes occurring from 2007 to 2018 in mean values of selected variables describing farms and farmers' characteristics. For quantitative variables, the differences between sampling times were calculated for each farm. The Shapiro-Wilks normality test was conducted on the differences. When the normality hypothesis was rejected ($\alpha = 0.05$), the Kolmogorov-Smirnov non-parametric test was used to determine the statistical significance of changes. Otherwise, a t-test for mean difference was employed. For binomial variables, the test of differences in proportions was applied.

The changes in yield, gross margin, direct costs, risk of pesticide contamination, organic carbon input to soil, and nutrient balances were evaluated for the three main crops—soybean, corn, and wheat—that collectively occupy 95% of the planted area in the district of Pergamino. Expected yields and prices at each sampling time were used to analyze changes in indicators. Expected yields at the beginning and end of the period were calculated for individual farms by multiplying actual yields (reported by farmers for each crop year) by the ratio between the historical yield trend and the yield for the Pergamino district in each crop year (Please refer to the supplementary material for the computations of yield trends). Expected prices were computed as the average prices in the period 2007-2018. The aim of this calculation is to correct for climatic and specific market effects of each growing season. To assess the changes in performance indicators, spider graphs were generated for each crop. To facilitate comparison between growing seasons, changes in each variable were expressed as percentages relative to 2007 values.

Finally, a canonical correlation analysis was conducted (Sherry and Henson, 2005; Cuadras, 2007) to establish the relationship between changes in performance and the structural characteristics of farms at the beginning of the period. Canonical correlation is a multivariate analysis employed to identify and measure the association between two sets of variables. This technique is theoretically consistent with complex processes that have multiple causes and effects (Sherry and Henson, 2005). Canonical correlation estimates several canonical functions that maximize the correlation between linear combinations of the original variables X and Y (Badii et al., 2007). These canonical functions are specified in a manner that ensures each new function is orthogonal to the previous functions and represents the best possible explanation for group Y that has not been obtained from the previous combinations of group X. The selected explanatory variables for the year 2007 were farming area, the maximum education level of managers, the minimum age of managers, and labor. Dependent variables were the differences between the second and the first sampling time for scale and performance: farming area, gross margin, organic carbon input to soil, and N and P balances. All statistical analyses were conducted using R software with the factorextra and CCA packages.

3. Results

3.1 Changes in scale, land tenure, labor management and production system

Table 3 displays mean values as well as differences in farm size, land tenure, labor, and management practices between sampling times. The average farming area and length of leasing arrangements show slight increases, but they are not statistically significant. Similarly, family labor and hired labor exhibit a decrease for the last period under analysis, but this decline is not statistically significant.

Regarding variables that characterize farm management, no differences were found in the managers' maximum education achieved. However, statistically significant differences were observed both in the managers' minimum age and in the future projection-growth of each farm. The average minimum age of managers indicates that a smaller proportion of young managers were present in the second sampling period. In terms of future growth projections, during the initial surveying moment, a greater proportion of farmers expressed optimistic growth expectations for the forthcoming decade compared to what was found during the second surveying moment.

Increases were observed in the number of records kept, medium or high short-term debt level, and a decrease was found in the provision of custom farming service, but these changes were not statistically significant. Similarly, no significant differences were observed in the productive diversity index or the proportion of first-season soybeans throughout the period.

The comparison of farming operations that ceased during the study period with those that replaced them indicates that farmers who left farming were mostly landowners of small-scale production farms. On the other hand, farmer businesses that replace those of quitting farmers, on average, manage more land, with a higher proportion of rented land, exhibit a higher degree of professionalization, have a lower minimum age for managers, and had a higher maximum educational level (see Table 1 in the supplementary material).

Table 3 Changes in the farm size, land tenure, labor, management and production system of sampled farms in 2007 and 2018 in Pergamino district.

Variables		**N**	**Mean 2007**	**Mean 2018**	**Mean difference**	**p-value**	
Scale							
Farming area	ha	30	393	443	50	0.799	(2)
Land tenure							
Area rented in	%	30	38	42	4	0.953	(2)

Length of leasing arrangements	year	12	4.35	11.77	7.42	0.075	(1)
Workers							
Family labor	full-time equivalent	27	1.13	1.07	-0.06	0.999	(2)
Hired labor	full-time equivalent	27	1.48	1.37	-0.11	0.997	(2)
Management							
Managers' minimum age	year	27	46.67	53.25	6.58	0.035*	(2)
Managers' maximum education	year	20	12.89	13.30	0.41	0.693	(2)
Legal type - sole proprietorship	%	30	60	60	0		
Number of records kept	unit	30	4.16	4.46	0.30	0.634	(1)
Technical advice	%	30	93	83	-10	0.421	(3)
Medium or high short-term debt level	%	30	6	20	14	0.255	(3)
Provision of custom farming service	ha	29	489	320	-169	0.782	(2)
Future projection-grow	%	29	70	42	-28	0.037*	(3)
Production system							
Productive diversity index		30	1.91	1.82	-0.09	0.952	(2)
First season soybeans proportion	%	30	55.95	58.78	2.83	0.531	(1)

Note: For continuous variables, the Shapiro-Wilks normality test was performed on the differences. When normality was not rejected, the *t* test (1) was performed, otherwise the Kolmogorov-Smirnov (2) test was performed. For binomial variables, the test of differences in proportions was performed (3). (*) indicates P < 0.05

3.2 Productive performance

Performance indicators for soybean as a first or as a second crop, wheat, and corn are presented in Table 4. In this initial step of the analysis, information is presented based on the yields reported by farmers at both sampling times and market prices for each crop year. Therefore, this analysis captures the effects of prevailing weather and market conditions in each year.

Significant changes were observed in the yields of summer crops (first-season soybean, second-season soybean, and corn) between both sampling periods, with reductions possibly resulting from lower rainfall during the 2017/2018 growing season (additional information in the supplementary material). Differences in wheat yield between both growing seasons do not show statistical significance.

Direct costs were significantly higher for all crops in 2018, even when considering the correction for inflation in dollars during that period (21%). Gross margin (GM) values are higher for first-season soybean, second-season soybean, and wheat in 2018 than in 2007.

Regarding nutrient inputs, there has been an increase in the amounts of fertilizers used for most crops, but the values are not statistically different. Nitrogen input is slightly lower in the first-season soybean. Nutrient balances for N and P show more positive values in 2018 than in 2007 for all crops, with differences being statistically significant for the second-season soybean and corn.

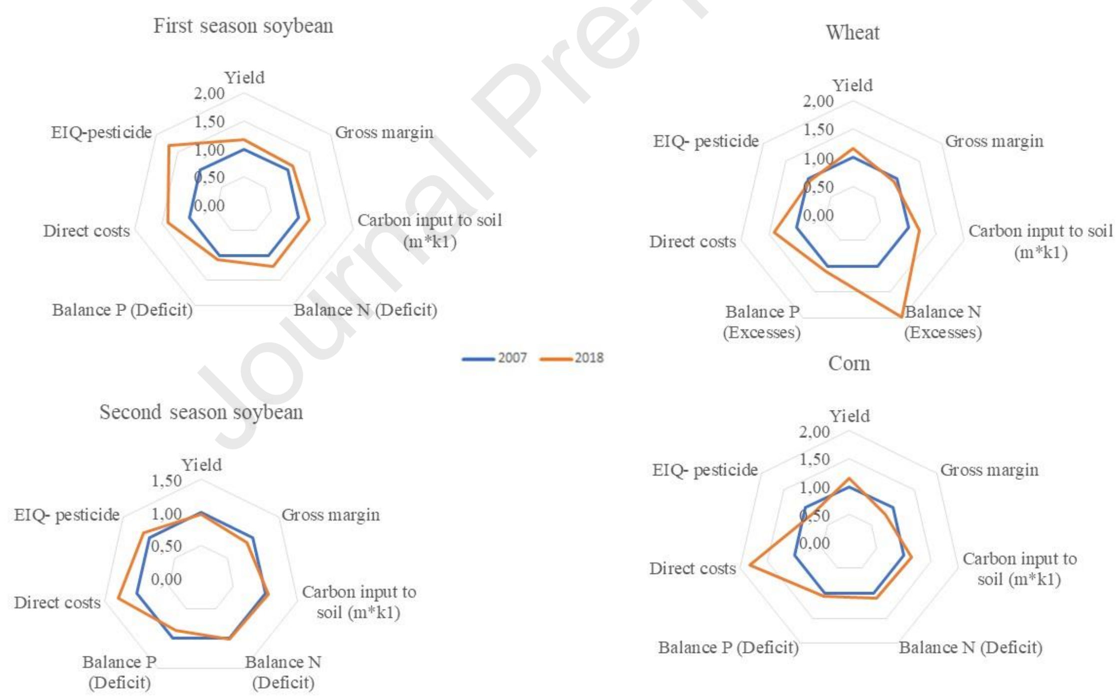
Concerning the risk of contamination by pesticides, measured by the EIQ, an increase was observed in the number of active ingredients for all crops. For the first and second seasons of soybean, EIQ was higher in 2018 for all three components. Throughout the period under study, pesticide use was notably intensified, from the application of a single herbicide, most of the time, to the combination of five different products (data not published, but available upon request). In wheat, the overall EIQ has slightly decreased with the use of new pesticides; although the toxicity risk for consumers and the environment has been reduced, the risk for workers has increased. For corn, EIQ values have been reduced; even with more pesticides being used, these have lower EIQ values.

Table 4 Productive, environmental, and economic performance variables for the main crops in 2007 and 2018

		First season soybean				Wheat				Second season soybean				Corn			
		2007	**2018**	**p-value**		**2007**	**2018**	**p-value**		**2007**	**2018**	**p-value**		**2007**	**2018**	**p-value**	
Yield	kg ha^{-1}	3700	3300	<0.01*	1	3900	4400	0.11	1	3100	2100	<0.01*	1	9700	8000	<0.01*	1
Direct costs	US$ ha^{-1}	188.50	263.21	<0.01*	1	221.00	312.00	<0.01*	1	159.00	203.00	<0.01*	2	291.00	531.00	<0.01*	1
Gross margin	US$ ha^{-1}	453.58	661.62	0.04*	2	205.63	272.14	0.03*		373.43	377.77	0.95	1	676.18	639.22	0.55	1
Input of N in fertilizer	kg ha^{-1}	2.88	2.85	0.54	2	74.77	90.73	0.24	1	0.88	0.00	0.33	1	75.98	88.75	0.21	1
Biological N fixation	kg ha^{-1}	141.27	127.79	0.03*	1					117.07	80.48	<0.01*	1				
N exports in harvested grain	kg ha^{-1}	164.27	148.60	0.03*	1	70.80	75.93	0.41	1	136.14	93.58	<0.01*	1	124.51	102.42	<0.01*	1
N fertilizer / N harvested grain		0.02	0.02	0.35	2	1.02	1.18	0.19	1	0.00	0.00			0.60	0.89	<0.01*	1
N balance	kg ha^{-1}	-47.36	-45.39	0.06	2	2.85	11.27	0.39	2	-20.09	-14.42	<0.01*	1	-75.80	-41.34	<0.01*	1
P fertilizer input	kg ha^{-1}	10.13	12.86	0.35	2	21.99	24.97	0.37	1	3.51	4.62	0.93	2	20.54	23.79	0.33	1
P crop removal	kg ha^{-1}	19.84	17.68	0.01*	1	13.48	15.18	0.11	1	16.44	11.28	<0.01*	1	25.24	20.81	<0.01*	1
P fertilization/ extraction ratio		0.51	0.74	0.35	2	1.63	1.61	0.39	2	0.21	0.33	0.93	2	0.80	1.18	0.03*	1
P balance	kg ha^{-1}	-9.51	-4.82	0.11	2	8.51	9.78	0.13	2	-12.94	-6.66	0.03*	2	-4.69	2.95	0.04*	1
Carbon input to soil (m)	Mg C ha^{-1}	3.11	2.78	0.01*	1	3.03	3.40	0.13	1	2.60	1.75	<0.01*	1	5.31	4.40	<0.01*	1
Carbon input x humification coefficient (m x k1)	Mg C ha^{-1}	0.59	0.54	0.06	2	0.39	0.46	0.06	1	0.43	0.31	<0.01*	1	0.76	0.62	0.03*	1
Environmental Impact Quotient (EIQ)		46.98	79.56			26.45	25.66			33.78	37.34			74.90	62.42		
EIQ – consumer component		9.23	19.08			8.26	6.71			6.63	8.50			19.60	17.26		
EIQ – farmworker component		24	51.41			13.30	17.62			17.30	19.89			36.10	34.09		
EIQ – ecological component		107	168.29			57.49	52.83			76.91	83.94			169.45	136.32		

Note: Direct costs include labor and crop inputs without marketing costs. The Shapiro-Wilks normality test was performed on the differences. When normality was not rejected, the *t* test (1) was performed, otherwise the Kolmogorov-Smirnov (2) test was performed. (*) indicates $P < 0.05$. The p-values for the Environmental Impact Quotient (EIQ) are not provided since only average values were accessible for the year 2007.

Fig. 2 summarizes changes in productive, economic, and environmental indicators for all crops, calculated using expected yields and prices for both seasons (See supplementary material for expected yields and prices computations). The use of expected yields and prices has allowed for the evaluation of results regardless of the climate conditions in the crop years analyzed. An overall average increase of about 16% in expected yields was observed between 2007 and 2018, except for the second season soybean, which presented a slight yield reduction. Direct costs have increased (by 48% on average) for all the crops under study, and GM values show an increase only for the first-season soybean. Among environmental variables, soil organic carbon (m xk1) contribution has notably increased in the first-season soybean (20%), wheat (20%), and corn (14%). For the first-season soybean, nutrient balance shows greater deficits in nitrogen and phosphorus as a result of higher yields and, therefore, higher nutrient extraction by the crop. The risk of contamination by pesticides has increased considerably for the first soybean and to a lesser extent in the second soybean. On the other hand, the risk of contamination with pesticides was reduced in corn and wheat, with the reduction being greater in the former.



Note: The definitions of the indicators used in the figure are presented in Table 2

Fig.2 Changes in the productive, economic and environmental indicators for the four crops analyzed in the 2007 and 2018 crop years, considering the expected yields and prices. All changes expressed in proportional terms relative to 2007.

3.3 Changes in farm performance

The canonical correlation model explored the relationship between vector X (by farm.area.07 (farming area in 2007), max.edu.07 (managers' maximum education level in 2007), min.age.07 (managers' minimum age in 2007), and labor07 (labor hired anf family in 2007)), corresponding to selected farms' and farmers' characteristics at the beginning of the period, and vector Y (d.farm.area (change in the farming area), d.GM (gross margin change), d.mxk1 (organic carbon input to soil change), d.N.bal (nitrogen balance change), and d.Pbal (phosphorus balance change), corresponding to the changes in scale and performance that occurred throughout the study period.

Fig. 3 shows the correlations within each vector. As observed in Fig. 3A, the only significant and negative correlation found was that between labor and the minimum age of managers. The positive correlation coefficient identified for the maximum education level and cultivated area is not statistically significant, although considerable.

Regarding changes in farm performance (Fig. 3B), the average gross margin has been positively correlated with an increase in organic carbon input to soil and negatively correlated with the nitrogen balance. A further significant and negative correlation was found between changes in the nitrogen balance and organic carbon input.

As a second step, a canonical correlation model was run relating the characteristics of each farm and their managers to the changes in the productive, economic, and environmental performance (Table 5 and 6). For each dimension analyzed, eigenvalues, canonical correlation coefficients (Rc), explained and accumulated variability, approximate F, degrees of freedom, p-values, and the Lambda statistics are presented.

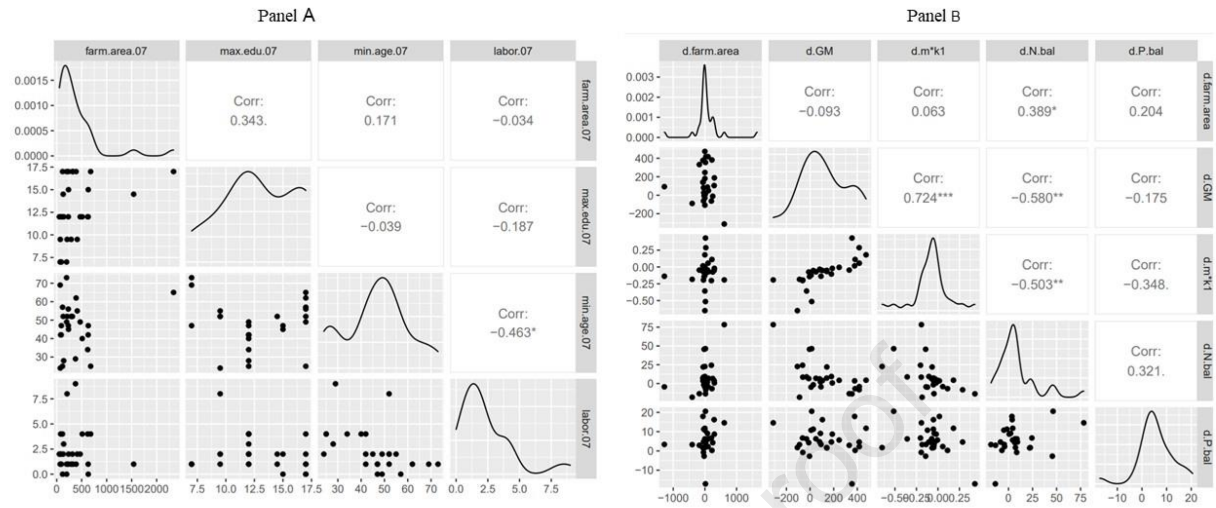


Fig. 3 Correlations for farm structure and performance change variables for the 2007 – 2018 period. Note: Panel A: farm.area.07 (farming area in 2007); max.edu.07 (managers' maximum education level in 2007); min.age.07 (managers minimum age in 2007); labor.07 (labor hired and familiar in 2007). Panel B: d.farm.area (change in the farming area); d.GM (gross margin change); d.mk1 (Organic carbon input to soil change); d.N.bal. (nitrogen balance change); d.Pbal.(phosphorus balance change).

Table 5 Canonical functions for structure and performance of the studied farms.

Dimensions	Eigenvalue	Canonical Correlation	Explained variability	Cumulative explained variability	Approximate F	Degrees of freedom	p-value	Lambda statistic
1	0.458	0.676	47.982	47.982	1.503	20	0.10	0.308
2	0.288	0.537	30.233	78.216	1.158	12	0.33	0.569
3	0.158	0.397	16.576	94.792	0.905	6	0.50	0.799
4	0.049	0.223	5.207	100	0.627	2	0.54	0.950

Canonical correlation between the first and second dimension was 0.68 and 0.54, respectively. Together, such correlations accounted for 78.22% of the variability observed in the data set. However, only the first dimension is statistically significant with a p-value of 0.1. The presented model explains a significant proportion of the variability shared by both data sets. Given the effects of explained variability for each canonical function, only the first dimension is considered in the following analysis.

Table 6. Standardized canonical correlation coefficient, structure coefficient and structure coefficient squared for the first canonical function

	Standardized canonical correlation coefficient	r_s structure coefficient	r_s^2 structure coefficient squared
Vector X. Farms' and farmers' characteristics in 2007			
farm.area.07	0.001	0.373	0.139
max.edu.07	-0.013	0.273	0.074
min.age.07	-0.036	0.069	0.005
labor.07	-0.441	-0.473	0.224
Vector Y. Changes in farm scale, economic and environmental performance 2007-2018			
d.farm.area	-0.002	-0.456	0.208
d.GM	-0.004	-0.181	0.003
d.mk1	4.862	0.204	0.041
d.N.bal	-0.009	-0.216	0.046
d.P.bal	0.062	0.054	0.003

Note: farm.area.07 (farming area in 2007); max.edu.07 (managers' maximum education level in 2007); min.age.07 (managers minimum age in 2007); labor.07 (labor in 2007). d.farm.area (change in the farming area); d.GM (gross margin change); d.mk1 (Organic carbon input to soil change); d.N.bal. (nitrogen balance change); d.Pbal.(phosphorus balance change).

Table 6 presents the standardized canonical correlation coefficient, the structure coefficient (rs), and the squared structure coefficient (rs^2). The absolute values of the structure coefficient and squared structure coefficient indicate each variable's contribution to the synthetic variable. Therefore, according to the structure coefficients, labor (labor.07) and cultivated area (farm.area.07) were the most relevant explanatory variables. Changes in cultivated area (d.farm.area), nitrogen balances (d.N.bal), and soil organic carbon content (d.mk1) were the most relevant dependent variables in the model.

The correlation between independent and dependent variables is indicated by rs (same signs indicate a positive correlation, and different signs indicate a negative correlation) (Sherry and Henson, 2005). Consequently, changes in cultivated area (d.farm.area) are negatively related to cultivated area (farm.area.07), maximum education (max.edu.07), and minimum age (min.age.07) and positively related to the number of workers in 2007 (labor.07). Maximum education level and minimum age of managers show very low explanatory power. In other words, the strongest relationship found is that smaller farms with a greater number of workers in 2007 increased the cultivated area along the study period.

4. Discussion

This study focuses on assessing the changes that occurred in 30 farm businesses that remained active between 2007 and 2018 in Pergamino County. The farms that exited agricultural activity and those that began production in the study area during this period are also characterized.

When examining repeated cases in the sample, this study reveals limited significant changes in the average farm size, type of land tenure, amount of labor employed, and management practices during the study period. The results show that the increase on the average operated land is not statistically significant for the 30 farmers that stayed in business, however, there is significant negative relation between initial farm size and the growth in operated land. This implies that small farmers who remained had to expand their operations. Additionally, new entrants to the region tend to be large-scale farmers, and management is predominantly handled by tenants.

This information is consistent with the data from the CNA 2018, that indicates a reduced number of farms and an increase in their scale. The results also agree with the findings of Bert et al. (2011), who posited that smaller farmers may struggle to offset years of low income, leading to a gradual loss of capital and an elevated likelihood of leasing their land to larger farm operations. Building on census data (CNA, 1988, 2002) and proprietary data, Urcola et al. (2015) observed growth in both production scale and the area of farmland being leased in the Balcarce district. These authors underscored the risk of small-scale farmers exiting agricultural activities and eventually selling their land.

In contrast, Calvi et al. (2019) found no significant changes in terms of farm size, land tenure, and management practices among cattle farms in the Province of Corrientes. Other authors have similarly argued that the scale of production and land tenure are extensively influenced by economic, political, and technological factors (Bert et al., 2011; Deininger & Byerlee, 2012).

Our results revealed differences in the economic performance of farms between the two sampling periods. When considering expected yield and expected prices, yields and costs were higher in 2017. As a consequence, the gross margin increased only for soybeans as a first crop. Increases in the production costs of extensive crops and their reducing effect on economic margins have been documented both in Argentina and in Europe (Aparicio et al., 2018; van der Ploeg et al., 2019).

Our findings revealed disparities in the economic performance of crop production between the two sampling periods. A positive trend in crop yields, coupled with a stable output price, led to an overall increase in farm income during this timeframe. However, the boost in productivity per unit of land was counterbalanced by a rise in farm inputs, resulting in a slight decrease in gross margin for most crops during the analyzed period. The escalation in cost per unit of land can be attributed to declining soil fertility and the emergence of resistant weeds over the studied period.

In terms of environmental performance, we observed a higher contribution to soil organic carbon from crop residues, likely due to increased crop yields. However, nitrogen and phosphorus balances remain negative for most crops, suggesting potential higher costs for fertility maintenance in subsequent growing seasons (Cabrini et al., 2019; Sainz Rozas et al., 2019). Recent findings from Leguizamón et al., (2023) indicate that Argentine farming systems deplete key nutrients, irrespective of the environmental potential of the field or the land tenure system.

Concerning pesticide use, notable changes include variations in the typical active ingredients used, along with the application of higher doses and increased frequencies, aligning with previous research findings (Ferraro et al., 2020; Principiano and Acciaresi, 2017). The risk of pesticide contamination significantly increased for first-season soybeans (over a 50% increment in the EIQ value), a matter of particular concern given that soybeans constitute the primary annual crop, occupying 54% of the cultivated area in the district of Pergamino

5. Conclusion

The objective of this study was to analyze the transformations in the farming systems of the Central Pampean Region from 2007 to 2018, encompassing social, economic, and environmental dimensions. The complexity of this process arises from the challenges associated with locating the same producers at different time points and their willingness to participate in surveys. Over the study period, some farmers exited the agricultural sector, while others took their place in cultivating the same land. This turnover presents a challenge in data analysis but provides valuable insights into the context and characteristics of farms entering or leaving the activity. Despite these challenges, this approach facilitated the examination of changes in farm businesses over time.

This study reveals a significant turnover of producers, wherein departing farmers are followed by larger-scale operations. This transition has led to a concentration of production, as larger areas are managed by a reduced number of producers who, on average, are younger and have a higher level of education.

The study employed a comprehensive approach to data collection and analysis to examine sustainability changes in 30 farms in the Pergamino district. Due to the limited sample size, the findings may not be readily generalizable to other regions or contexts. Future research endeavors should aim to explore the broader applicability of these insights. Nonetheless, this work addresses a notable information gap by applying comprehensive methods to assess the sustainability evolution in the Argentine Pampas through the examination of actual farm practices.

The primary contribution of this work lies in its ability to assess the interactions between the structure and performance of farms over a specific period, thereby surpassing partial evaluations of sustainability that focus on the evolution of individual dimensions or evaluations conducted at specific moments.

Regarding the environmental dimension, the findings are less clear, as some variables evolved negatively (e.g., the risk of pesticide contamination for first-season soybeans) while others evolved favorably (e.g., contributions of organic carbon to the soil). This trade-off between environmental variables can be explained by increases in crop yields that generate improvements in organic carbon input indicators but negative impacts on pesticide contamination risks and nutrient balances. These changes suggest that the agricultural systems under study are advancing partially towards a path of sustainable intensification.

Acknowledgements

We are grateful to the farmers who participated in this work, without their collaboration it would not have been possible. This project was financed by the Universidad Nacional del Noroeste de la Provincia de Buenos Aires through research projects, research grants and postgraduate fellowships program. Additional financial support was provided by INTA Projects, PD I065 and PE I218. This work is a Partial requirement to qualify for the academic degree of Doctor in Agricultural Sciences, Faculty of Agricultural Sciences, National University of Mar del Plata.

References

Alaminos, C. and Castejón, C. 2006. Elaboración, análisis e interpretación de encuestas,cuestionarios y escalas de opinión. In *Universidad de Alicante* 42. https://doi.org/10.1097/01.ccm.0000457813.83878.83

de Astarloa, D. D., and Pengue, W. A., 2018. Nutrients metabolism of agricultural production in Argentina: NPK input and output flows from 1961 to 2015. *Ecol. Econ. 147*, 74-83. https://doi.org/10.1016/j.ecolecon.2018.01.001

Aparicio, V. C., Zamora, M., Barbera, A., Castro-Franco, M., Domenech, M., De Gerónimo, E., and Costa, J. L.,2018. Industrial agriculture and agroecological transition systems: A comparative analysis of productivity results, organic matter and glyphosate in soil. *Agric. Syst. 167* 103–112. https://doi.org/10.1016/j.agsy.2018.09.005

Badii, M., Castillo, J., Cortez, K., Wong, A., and Villalpando, P., 2007. Analisis de correlacion canonica (ACC) e investigacion cientifica (Canonical correlation analysis and scientific research). *Innovaciones de Negocios 4*(8), 405–422. http://www.web.facpya.uanl.mx/rev_in/Revistas/4.2/A9.pdf https://doi.org/10.29105/rinn4.8-9

Bert, F. E., Podestá, G. P., Rovere, S. L., Menéndez, Á. N., North, M., Tatara, E., Laciana, C. E., Weber, E., oranzo, F. R., 2011 An agent based model to simulate structural and land use changes in farming systems of the argentine pampas. *Ecol. Modell. 222*(19), 3486–3499. https://doi.org/10.1016/j.ecolmodel.2011.08.007

Cabrini, S. M., Calcaterra, C. P.,2008. *Los Sistemas de Producción en la Cuenca del Arroyo Pergamino. Proyecto AEES 1732*,38.

Cabrini, S. M., Portela, S. I., Cano, P. B., and López, D. A., 2019 Heterogeneity in agricultural land use decisions in Argentine Rolling Pampas: The effects on environmental and economic indicators. Cogent Environ. Sci. 5(1), 1667709. https://doi.org/10.1080/23311843.2019.1667709

Cabrini, S. M., Cristeche, E. R., De Prada, J. D., Dupleich, J., Engler, P. L., Esposito, M. E., … and Vicente, G., 2018. Percepción sobre el impacto ambiental de la producción agropecuaria de la región pampeana argentina.

Calvi, M., Urcola, H. A., Cabrini, S., andChavez, M. D., 2019. Cambios Estructurales Y Tecnológicos De La Ganadería Del Centro Sur De Corrientes, Argentina, En El Período 2005-2015. Chil. J. Agric. Anim. Sci. https://doi.org/10.4067/s0719-38902019005000307

Carnelos, D. A., and Long, M. E. F., 2014. *Índice De Satisfacción Hídrica Como Estimador De*. *34*, 1–16.

Cuadras, C. M. (2007). Nuevos Metodos de Analisis Multivariante. *Revista Española de Quimioterapia : Publicación Oficial de La Sociedad Española de Quimioterapia*, *20*(3), 249. http://www.ncbi.nlm.nih.gov/pubmed/19406528

Deininger, K., and Byerlee, D.,2012. The rise of large farms in land abundant countries: Do they have a future? World Dev. *40*(4), 701–714. https://doi.org/10.1016/j.worlddev.2011.04.030

Di Ciocco, C., Penón, E., Coviella, C., López, S., Díaz-Zorita, M., Momo, F., and Álvarez, R.,2011. Nitrogen fixation by soybean in the Pampas: Relationship between yield and soil nitrogen balance. *Agrochimica*, *55*(6), 305–313.

FAO. (2014). *Sustainability Pathways: Evaluaciónes de la sostenibilidad (SAFA*. http://www.fao.org/nr/sustainability/evaluaciones-de-la-sostenibilidad-safa/es/

Ferraro, D. O., Ghersa, F., de Paula, R., Vera, A. C. D., and Pessah, S., 2020. Historical trends of the ecotoxicological pesticide risk from the main grain crops in Rolling Pampa (Argentina). *PLoS ONE*, *15*(11), 1–16. https://doi.org/10.1371/journal.pone.0238676

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., ...and Schellnhuber, H. J., 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sustainability*, *3*(3), 200-208.

Hara, S. M., Faverín, C., Villagra, E. S., Easdale, M. H., and Tittonell, P., 2022. Exploring drivers and levels of technology adoption for ecological intensification of pastoral systems in north Patagonia drylands. Agric., Ecosyst. Environ. *324*. https://doi.org/10.1016/j.agee.2021.107704

INDEC (2023). *Argentine foreign trade statistics: Preliminary Data for 2021*. Retrieved from: Instituto Nacional de Estadística y Censos - Informes Técnicos Vol. 6 Núm. 17 - Comercio Exterior Vol. 6 Núm. 2: https://www.indec.gob.ar/uploads/informesdeprensa/i_argent_02_22911A4A9AB1.pdf

Leguizamón, Y., Goldenberg, M. G., Jobbágy, E., Seppelt, R., and Garibaldi, L. A., 2023. Environmental potential for crop production and tenure regime influence fertilizer application and soil nutrient mining in soybean and maize crops. *Agric. Syst. 210* (May). https://doi.org/10.1016/j.agsy.2023.103690

Mahon, N., Crute, I., Simmons, E., and Islam, M. M., 2017. Sustainable intensification–“oxymoron” or “third-way”? A systematic review. *Ecol. Indic. 74*, 73-97. https://doi.org/10.1016/j.ecolind.2016.11.001

Mahon, N., Crute, I., Di Bonito, M., Simmons, E. A., and Islam, M. M., 2018. Towards a broad-based and holistic framework of Sustainable Intensification indicators. *Land Use Policy*, *77*. https://doi.org/10.1016/j.landusepol.2018.06.009

Martínez, J. P., Crespo, C., Cuervo, M., Echeverría, H., Martínez, F., Cordone, G., and Barbieri, P., 2022. Sustainable intensification of agriculture improves soil nitrogen in the Argentinean Humid Pampas. Agron. J. 114(4), 2200-2212. https://doi.org/10.1002/agj2.21063

Pacín, F., and Oesterheld, M., 2014. In-farm diversity stabilizes return on capital in Argentine agro-ecosystems. *Agric. Syst. 124*, 51–59. https://doi.org/10.1016/j.agsy.2013.10.008

Pretty, J. N. (1997, November). The sustainable intensification of agriculture. In Natural resources forum (Vol. 21, No. 4, pp. 247-256). Oxford, UK: Blackwell Publishing Ltd. https://doi.org/10.1111/j.1477-8947.1997.tb00699.x

Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P. V. V., Reganold, J…andWratten, S., 2018. Global assessment of agricultural system redesign for sustainable intensification. *Nat. Sustain. 1*(8), 441-446.

Sainz Rozas, H. R., Eyherabide, M., Larrea, G., Martínez Cuesta, Nicolás Angelini, H., and Reussi Calvo, Nahuel Wyngaard, N.,2019. Relevamiento y determinación de propiedades químicas en suelos de aptitud agrícola de la región pampeana. *Simposio Fertilidad 2019*, 141–158.

Satorre, E. H., and Andrade, F. H., 2020. *Cambios productivos y tecnológicos de la agricultura extensiva argentina en los últimos quince años*.vol 29, n 173.

Secreatria de agricultura, ganaderia y Pesca (2022). Presidencia de la Nacion. Argentina. Estimaciones agricolas. Estimaciones Agrícolas (magyp.gob.ar) (accessed 15 march of 2022)

Sherry, A., and Henson, R. K., 2005. Conducting and interpreting canonical correlation analysis in personality research: A user-friendly primer. *J. Pers. Assess. 84*(1), 37–48. https://doi.org/10.1207/s15327752jpa8401_09

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., and Glover, J., 2017. Measuring sustainable intensification in smallholder agroecosystems: A review. *Glob. Food Secur. 12*, 127-138. https://doi.org/10.1016/j.gfs.2016.11.002

Struik, P. C., Kuyper, T. W., Brussaard, L., and Leeuwis, C. ,2014. Deconstructing and unpacking scientific controversies in intensification and sustainability: why the tensions in concepts and values? Curr. Opin. Environ. Sustain. *8*, 80-88. https://doi.org/10.1016/j.cosust.2014.10.002

Struik, P. C., and Kuyper, T. W.,2017. Sustainable intensification in agriculture: the richer shade of green. A review. Agron. Sustain. Dev. 37, 1-15.

Urcola, H. A., de Sartre, X. A., Veiga, I., Elverdin, J., and Albaladejo, C., 2015. Land tenancy, soybean, actors and transformations in the pampas: A district balance. J. Rural Stud. *39*, 32–40. https://doi.org/10.1016/j.jrurstud.2015.03.001

van der Ploeg, J. D., Barjolle, D., Bruil, J., Brunori, G., Costa Madureira, L. M., Dessein, J., Drąg, Z., Fink-Kessler, A., Gasselin, P., Gonzalez de Molina, M., Gorlach, K., Jürgens, K., Kinsella, J., Kirwan, J., Knickel, K., Lucas, V., Marsden, T., Maye, D., Migliorini, P., … Wezel, A.,2019. The economic potential of agroecology: Empirical evidence from Europe. J. Rural Stud. *71*, 46–61. https://doi.org/10.1016/j.jrurstud.2019.09.003

World Agricultural Supply and Demand Estimates (WASDE) (2024) United States.
WASDE Report | USDA (accessed 2 of september 2023)

Table 1: Variables selected for the analysis of changes in farms and farmers' characteristics between 2007 and 2018.

Group	Variable	Unit	Definition
Scale	Farming area	ha	Total operated land
Land tenure	Area rented in	%	Percentage of the operated area that is rented in
	Length of leasing arrangements	crop years	Length of leasing arrangements
Workers	Family labor	full-time equivalent	Family labor expressed in numbers of full-time workers
	Hired labor	full-time equivalent	Salaried labor expressed in numbers of full-time workers
Management	Managers' mínimum age	years	Age of the youngest manager
	Managers' máximum education	years	Highest educational level reached by those responsible for the farm
	Legal type	binary	Indicates whether sole proprietorship is the legal type of the farm (=1), or other (=0)
	Number of records kept	quantity of records	Number of records kept in the farm taking into account (eight categories:(inputs, nutrients, costs, taxes, gross margin, budgets and economic benefit)
	Technical advice	binary	Indicates if the farmer receives technical advice (=1) or not (=0)
	Medium or high short-term debt level	binary	Indicates if the level of debt in the short term is medium or high (=1) or low (=0)
	Provision of custom farming service	ha	Total area for which custom operation service is provided. The different tasks are expressed in equivalent harvested area, taking into account the price relationship between each task and the custom harvest's price.
	Future projection-grow	binary	It indicates growth expectations in the next 10 years, (=1) when planning to increase operated land, either through the purchase or rental of a larger area, (=0) otherwise.
Production system	Productive diversity index		1/HH x 10000. The Herfindahl-Hirschman (HH) coefficient is calculated for each farm as the sum of the squared percentages of land allocated to each activity. The indicator takes a value of 1 for monoculture and higher values for higher levels of productive diversification.
	First season soybeans proportion	%	Proportion of land assigned to first season soybean

Table 2: Variables selected for the analysis of productive, economic and environmental performance of the farming systems analyzed between 2007 and 2018.

Group	Name	Unit	Definition
Productive performance	Yields	kg ha^{-1}	Productive performance was determined based on crop yields.
Economic performance	Gross margin	US$ ha^{-1}	Calculated as the difference between income and direct costs.
	Direct costs	US$ ha^{-1}	Calculated for each activity as the sum of labor and input costs
Environmental performance	Risk of pesticide contamination		Measured by the Environmental Impact Quotient (EIQ [1]) The EIQ considers three components, related to the impacts on consumers, farmworkers and the environment. (ecological)
	Organic carbon input to soil	Mg C ha^{-}	Humifiable carbon (m x k1) calculated as m content (annual C input to soil of crop residues) times the humification rate of crop residues coefficient k1 [2]
	Nitrogen balance	kg ha^{-1}	Inputs: N fertilizers + N biological fixation (Di Ciocco et al., 2011) + N rainfall (Carnelos and Long, 2014) – output: N in harvested grain
	Phosphorous balance	kg ha^{-1}	Inputs: P fertilizers – output: P in harvested grain

Table 3: Changes in the farm size, land tenure, labor, management and production system of sampled farms in 2007 and 2018 in Pergamino district.

Variables		N	Mean 2007	Mean 2018	Mean difference	p-value	
Scale							
Farming area	ha	30	393	443	50	0.799	(2)
Land tenure							
Area rented in	%	30	38	42	4	0.953	(2)
Length of leasing arrangements	year	12	4.35	11.77	7.42	0.075	(1)
Workers							
Family labor	full-time equivalent	27	1.13	1.07	-0.06	0.999	(2)
Hired labor	full-time equivalent	27	1.48	1.37	-0.11	0.997	(2)

Management							
Managers' mínimum age	year	27	46.67	53.25	6.58	0.035*	(2)
Managers' máximum education	year	20	12.89	13.30	0.41	0.693	(2)
Legal type - sole proprietorship	%	30	60	60	0		
Number of records kept	unit	30	4.16	4.46	0.30	0.634	(1)
Technical advice	%	30	93	83	-10	0.421	(3)
Medium or high short-term debt level	%	30	6	20	14	0.255	(3)
Provision of custom farming service	ha	29	489	320	-169	0.782	(2)
Future projection-grow	%	29	70	42	-28	0.037*	(3)
Production system							
Productive diversity index		30	1.91	1.82	-0.09	0.952	(2)
First season soybeans proportion	%	30	55.95	58.78	2.83	0.531	(1)

Table 4: Productive, environmental and economic performance variables for the main crops in 2007 and 2018

		First season soybean			Wheat			Second season soybean			Corn		
		2007	2018	p-value	2007	2018	p-value	2007	2018	p-value	2007	2018	p-value
Yield	$kg\ ha^{-1}$	3700	3300	<0.01* [1]	3900	4400	0.11 [1]	3100	2100	<0.01* [1]	9700	8000	<0.01* [1]
Direct costs	$US\$\ ha^{-1}$	188.50	263.21	<0.01* [1]	221.00	312.00	<0.01* [1]	159.00	203.00	<0.01* [2]	291.00	531.00	<0.01* [1]
Gross margin	$US\$\ ha^{-1}$	453.58	661.62	0.04* [2]	205.63	272.14	0.03*	373.43	377.77	0.95 [1]	676.18	639.22	0.55 [1]
Input of N in fertilizer	$kg\ ha^{-1}$	2.88	2.85	0.54 [2]	74.77	90.73	0.24 [1]	0.88	0.00	0.33 [1]	75.98	88.75	0.21 [1]
Biological N fixation	$kg\ ha^{-1}$	141.27	127.79	0.03* [1]				117.07	80.48	<0.01* [1]			
N exports in harvested grain	$kg\ ha^{-1}$	164.27	148.60	0.03* [1]	70.80	75.93	0.41 [1]	136.14	93.58	<0.01* [1]	124.51	102.42	<0.01* [1]
N fertilizer / N harvested grain		0.02	0.02	0.35 [2]	1.02	1.18	0.19 [1]	0.00	0.00		0.60	0.89	<0.01* [1]
N balance	$kg\ ha^{-1}$	-47.36	-45.39	0.06 [2]	2.85	11.27	0.39 [2]	-20.09	-14.42	<0.01* [1]	-75.80	-41.34	<0.01* [1]
P fertilizer input	$kg\ ha^{-1}$	10.13	12.86	0.35 [2]	21.99	24.97	0.37 [1]	3.51	4.62	0.93 [2]	20.54	23.79	0.33 [1]
P crop removal	$kg\ ha^{-1}$	19.84	17.68	0.01* [1]	13.48	15.18	0.11 [1]	16.44	11.28	<0.01* [1]	25.24	20.81	<0.01* [1]
P fertilization/ extraction ratio		0.51	0.74	0.35 [2]	1.63	1.61	0.39 [2]	0.21	0.33	0.93 [2]	0.80	1.18	0.03* [1]
P balance	$kg\ ha^{-1}$	-9.51	-4.82	0.11 [2]	8.51	9.78	0.13 [2]	-12.94	-6.66	0.03* [2]	-4.69	2.95	0.04* [1]
Carbon input to soil (m)	$Mg\ C\ ha^{-1}$	3.11	2.78	0.01* [1]	3.03	3.40	0.13 [1]	2.60	1.75	<0.01* [1]	5.31	4.40	<0.01* [1]
Carbon input x humification coefficient (mxk1)	$Mg\ C\ ha^{-1}$	0.59	0.54	0.06 [2]	0.39	0.46	0.06 [1]	0.43	0.31	<0.01* [1]	0.76	0.62	0.03* [1]
Environmental Impact Quotient (EIQ)		46.98	79.56		26.45	25.66		33.78	37.34		74.90	62.42	
EIQ – consumer component		9.23	19.08		8.26	6.71		6.63	8.50		19.60	17.26	
EIQ – farmworker component		24	51.41		13.30	17.62		17.30	19.89		36.10	34.09	
EIQ – ecological component		107	168.29		57.49	52.83		76.91	83.94		169.45	136.32	

Table 5: Canonical functions for structure and performance of the studied farms.

Dimensions	Eigenvalue	Canonical Correlation	Explained variability	Cumulative explained variability	Approximate F	Degrees of freedom	p-value	Lambda statistic
1	0.458	0.676	47.982	47.982	1.503	20	0.10	0.308
2	0.288	0.537	30.233	78.216	1.158	12	0.33	0.569
3	0.158	0.397	16.576	94.792	0.905	6	0.50	0.799
4	0.049	0.223	5.207	100	0.627	2	0.54	0.950

Table 6: Standardized canonical correlation coefficient, structure coefficient and structure coefficient squared for the first canonical function

	Standardized canonical correlation coefficient	r_s structure coefficient	r_s^2 structure coefficient squared
Vector X. Farms' and farmers' characteristics in 2007			
farm.area.07	0.001	0.373	0.139
max.edu.07	-0.013	0.273	0.074
min.age.07	-0.036	0.069	0.005
labor.07	-0.441	-0.473	0.224
Vector Y. Changes in farm scale, economic and environmental performance 2007-2018			
d.farm.area	-0.002	-0.456	0.208
d.GM	-0.004	-0.181	0.003
d.mk1	4.862	0.204	0.041
d.N.bal	-0.009	-0.216	0.046
d.P.bal	0.062	0.054	0.003

Highlights

- Transformations were evaluated by analyzing mean value changes in farm structure and performance indicators and conducting canonical correlation analysis.
- Findings show significant producer turnover, with smaller farms replaced by larger ones.
- Among the farms that stayed in business, smaller farms with more workers expanded cultivation.
- Crops yields and the direct production costs increased during the period.
- Soil organic carbon input increased; pesticide contamination risk decreased for cereals but increased for soybeans; nutrient imbalances rose.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: