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Trayectoria reciente de los sistemas de cultivo del litoral oeste de Uruguay: Impacto en la calidad del suelo y la brecha de rendimiento de soja

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Le dedico este trabajo a aquellos que,
de manera voluntaria,
ofrecen su tiempo para contribuir a una mejora de la sociedad.

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TABLA DE CONTENIDO

RESUMEN

El cambio en el uso del suelo ocurrido en la región generó diferencias en la calidad del suelo, que responden a los años de agricultura continua y diversidad de cultivos que integran la secuencia; y que esta pérdida de calidad del suelo generada por el sistema de cultivo (CS, sigla en inglés) se manifiesta como incremento en la brecha de rendimiento explotable de soja (Yg^{Exp}) aún bajo sistemas sin labranza, que puede ser explicada por factores que determinan cambios en la disponibilidad de recursos y en la eficiencia de uso de estos. Los objetivos fueron: i) identificar CS implementados actualmente en el litoral oeste de Uruguay; ii) asociar estos CSs con indicadores de calidad del suelo; iii) cuantificar Yg^{Exp} que impone el CS y sus componentes, brecha de rendimiento generada por eficiencia de uso de recursos (Yg^{Ef}) y brecha de rendimiento atribuible a diferencias en la disponibilidad de recursos (Yg^{Re}); iv) identificar factores asociados a la calidad del suelo y mejoras tecnológicas determinantes del rendimiento actual (Ya). A partir de una base de datos de 45 predios, se identificaron los CSs dominantes en la actualidad. Se seleccionaron 65 sitios representativos de los CSs identificados y se evaluaron 46 propiedades del suelo sensibles a cambios a mediano plazo. Se determinó que una menor diversificación del CS (rotación cultivo-pastura > incorporación de maíz > alta frecuencia de soja) se relaciona con una pérdida en la fertilidad del suelo. Sobre cada sitio se sembró un cultivo de soja de primera y se instaló un experimento donde se manejaron dos estrategias de fertilización: limitado y no limitado por nutrientes. Mediante un análisis de frontera estocástica de producción (SFPF, sigla en inglés) se calculó el rendimiento alcanzable (Yatt, sigla en inglés; 4,4 Mg ha^{-1}) y el rendimiento máximo alcanzable (Ymax; 6,2 Mg ha^{-1}). Con la diferencia entre Ymax e Ya se calculó la Yg^{Exp} en 3,1 Mg ha^{-1}. Se desagregó la Yg^{Exp} en Yg^{Ef} (Yatt – Ya = 1,3 Mg ha^{-1}), estando relacionada con la diversidad del CS y el riego suplementario, y Yg^{Re} (Ymax – Ya = 1,8 Mg ha^{-1}), con pérdida de calidad de suelo y mejoras tecnológicas como el riego y la fertilización en entornos altamente productivos.

Palabras clave: intensificación sostenible, diversificación, frontera de producción, rendimiento máximo alcanzable, uso del suelo

CROPPING SYSTEMS TRAJECTORY IN THE EASTERN PAMPAS OF SOUTH AMERICA: IMPACT ON SOIL QUALITY AND SOYBEAN YIELD GAP

SUMMARY

The study is based on the hypothesis that i) the agricultural intensification process, that has occurred in the region since the beginning of the century, can be characterized at a commercial level measuring soil properties that capture medium term changes in cropping systems trajectory (CSs), and ii) CS design influences the exploitable yield gap of soybean (YgExp) by striking soil quality losses tied to resource availability and efficiency. The objectives were: i) to identify CSs currently implemented eastern Pampas of South America; ii) to associate these CSs with soil quality indicators that describe their trajectory over time; iii) to quantify the Yg^{Exp} imposed by the CS, and disaggregate it into an efficiency yield gap (Yg^{Ef}) and a resource-based yield gap (Yg^{Re}), and iv) to identify factors associated with soil quality and technological improvements determining current yield (Ya). A total of 65 representative management units, from 45 farms, were analyzed to determine the dominant CSs. For each management unit, 46 soil properties sensitive to medium-term changes were evaluated. It was determined that lower CS diversification (crop-pasture rotation > maize incorporation > high soybean frequency) is related to a loss of soil fertility and nutrient availability. A first-year soybean crop was planted at each site and an experiment with two fertilization strategies (limited and non-limited by nutrients) was set up. Using a stochastic production frontier analysis (SFPF), we calculated the average attainable yield (Yatt; 4.4 Mg ha^{-1}) and the maximum attainable yield (Ymax; 6.2 Mg ha^{-1}). The difference between Ymax and Ya yielded Yg^{Exp} of 3.1 Mg ha^{-1}. Yg^{Exp} was broken down into Yg^{Ef} (Yatt - Ya = 1.3 Mg ha^{-1}), linked to CS diversity and supplementary irrigation, and Yg^{Re} (Ymax - Ya = 1.8 Mg ha^{-1}), linked to soil quality loss and technological improvements such as irrigation and fertilization in high-yield environments.

Keywords: sustainable intensification, diversification, production frontier, maximun attainable yield, land use.

1. INTRODUCCIÓN

Satisfacer la demanda futura de alimentos depende de aumentar la producción mundial. El dilema actual consiste en lograrlo mediante un uso inteligente de las capacidades naturales que ofrecen los ecosistemas. El proceso debe resultar de «diseñar agroecosistemas con múltiples funciones que, por ser sostenidos por la naturaleza, son sostenibles en su naturaleza» (Tittonell, 2014). De esta manera, un agroecosistema podrá capitalizar los servicios ecosistémicos que brinda la planificación del uso del paisaje, lo que permitiría aumentar la producción de alimento por unidad de recurso mientras se minimiza el impacto ambiental (Hochman et al., 2013).

En la región de los pastizales del Río de la Plata, la sustitución de las pasturas de la rotación cultivos-pasturas (Ernst y Siri-Prieto, 2009) por sistemas de cultivos (CSs, sigla en inglés) continuos sin labranza, con alta frecuencia de soja (CC_Soybean, sigla en inglés) (Franzluebbers et al., 2014), se sustentó bajo el paradigma de que eliminar la labranza controla el deterioro de las propiedades del suelo asociadas a los CSs continuo. Sin embargo, aumentar la frecuencia de soja ha resultado, en el mediano plazo, en pérdidas asociadas a la reducción de la fertilidad química y física del suelo (Ernst et al., 2018, Novelli et al., 2013), determinando que el proceso de intensificación actual no sea sostenible.

Un CS sostenible debe cumplir con tres premisas que todo ecosistema natural terrestre de alta productividad posee: i) mínimo disturbio del suelo, ii) alta intensificación del uso del suelo (doble cultivo o pasturas) y iii) un alto nivel de complejidad (Ernst et al., 2020, Novelli et al., 2016, 2011). Cuando la diversidad doméstica (planificada) es muy baja (monocultivo), los agroecosistemas tienden a ser más susceptibles a la variabilidad climática y a problemas de malezas, plagas, enfermedades, lo que aumenta la dependencia y necesidad de insumos externos (Nicholls et al., 2022). Su menor eficiencia en el uso de nutrientes (nitrógeno y fósforo), radiación y agua ocasiona impactos ambientales negativos (Foley et al., 2005). En cambio, los CSs diversos se basan en la existencia de un equilibrio dinámico. Por lo tanto, si existe equilibrio, es por un tiempo limitado, lo cual implica que la estabilidad y la resiliencia del sistema dependen de mantener la diversidad en el tiempo (Sanford et al., 2021, Tamburini et al., 2020).

La evidencia es clara sobre la mejora global en la provisión de los servicios ecosistémicos al aumentar el grado de diversificación de los CSs (Tamburini et al., 2020, Nunes et al., 2018, Andrade et al., 2017, Tiemann et al., 2015, Kremen y Miles, 2012). Sin embargo, existe una gran heterogeneidad entre los resultados obtenidos cuando se analiza el efecto de distintas estrategias de diversificación por separado en función de la zona de estudio (Beillouin et al., 2021). Un factor clave, ya que los procesos de intensificación sostenible deben considerar prácticas de manejo que tengan en cuenta el contexto y las limitaciones locales (Reimer et al., 2012, Panell et al., 2006).

En este marco surge la necesidad de identificar estrategias de producción que permitan transitar un proceso de intensificación agrícola sostenible, adaptado a las condiciones locales de producción, que permita mantener las propiedades funcionales del suelo sin disminuir la productividad de los cultivos.

Para ello se propuso: i) identificar CSs contrastantes en el uso del suelo y en la diversidad de cultivos que integran la rotación, ii) relacionar estos CSs con sus propiedades funcionales del suelo y iii) cuantificar su impacto sobre la productividad de soja, el cultivo de mayor importancia en superficie sembrada en la actualidad en la región.

Para relevar la calidad del suelo en función del CS, primero se identificará, a partir de una base de datos de productores de referencia del litoral oeste agrícola de Uruguay, los principales CSs implementados en la actualidad. Sobre estos, se seleccionarán sitios representativos para evaluar la calidad del suelo con un conjunto mínimo de indicadores (Arshad y Martin, 2002, Doran y Parkin, 1996), seleccionados mediante la aplicación de análisis multivariados (Stevenson et al., 2015, Wander y Bollero, 1999). Para la selección entre algunas variables muy correlacionadas se consideró también el juicio de expertos (Sparling y Schipper, 2002).

Para cuantificar la brecha de rendimiento es necesario conocer el rendimiento obtenido a campo por los productores (rendimiento actual; Ya) y disponer de valores de referencia de utilidad para el análisis de la información. En nuestro estudio se evaluó la brecha de rendimiento explotable de soja (Yg^{Exp}), conceptualmente equivalente a la definida por Cassman et al. (2003) como el 80 % de la brecha de rendimiento total.

Para lograrlo se adaptó la propuesta de Silva et al. (2017) para desagregar la Yg^{Exp} en una brecha de rendimiento de eficiencia (Yg^{Ef}), que cuantifica diferencias entre productores en la eficiencia de uso de los recursos disponibles, y una brecha de rendimiento atribuible a la diferencia en la disponibilidad de recursos (Yg^{Re}). Además de determinar el Ya, mediante muestreos *in situ*, se trabajó con dos rendimientos de referencia: i) el rendimiento alcanzable (Yatt), definido como el logrado por los productores si aplicaran las mejores prácticas de manejo actual con la máxima eficiencia (Fischer y Edmeades, 2010), y ii) el rendimiento máximo alcanzable (Ymax), que es el máximo nivel de producción con el mayor y más eficiente uso de los recursos disponibles en la zona. Yatt considera tanto aquellos factores que definen el rendimiento potencial, genotipo, radiación y temperatura, como a los factores que lo limitan, como la disponibilidad hídrica y de nutrientes (van Ittersum y Rabbinge, 1997). Si la base de datos utilizada para el cálculo del Yatt contempla la mayor disponibilidad de recursos y la mejor tecnología disponible para la zona, Ymax es un valor práctico para determinar el margen que tienen los productores para aumentar el rendimiento de los cultivos. La diferencia entre Yatt e Ya para una misma disponibilidad de recursos determina la Yg^{Ef}. La diferencia entre Yatt e Ymax determina Yg^{Re} (Silva et al., 2017).

En el litoral oeste agrícola de Uruguay, gran parte de los CSs han sustituido las pasturas de la rotación por CSs continuo, pero aún quedan productores que se han mantenido en CSs que rotan con pasturas (ROT-PC) en suelos con similar capacidad de uso agrícola. Esto representa una oportunidad para capturar sus posibles efectos, tanto en la calidad del suelo como en el rendimiento actual de soja a nivel de CSs comerciales. La elección de soja como cultivo para evaluar la respuesta a este proceso de intensificación se justifica porque, a pesar de su importancia actual en los CSs de la región, es un fenómeno relativamente reciente, por lo que existen pocos antecedentes que cuantifiquen el impacto de su inclusión en el mediano plazo.

1.1. HIPÓTESIS Y OBJETIVOS

1.1.1. Hipótesis

1. El cambio en el uso del suelo ocurrido en la región genera diferencias en la calidad del suelo, que responden a los años de agricultura continua y diversidad de cultivos que integran la secuencia.
2. La pérdida de calidad del suelo generada por el CS se manifiesta como incremento en la brecha de rendimiento de soja aún bajo sistemas sin labranza.

1.1.2. Objetivos

1. Identificar CS implementados actualmente en el litoral oeste de Uruguay;
2. asociar estos CSs con indicadores de calidad del suelo;
3. cuantificar la Yg^{Exp} que impone el CS y sus componentes, brecha de rendimiento generada por eficiencia de uso de recursos (Yg^{Ef}) y brecha de rendimiento atribuible a diferencias en la disponibilidad de recursos (Yg^{Re});
4. identificar factores asociados a la calidad del suelo y mejoras tecnológicas determinantes del rendimiento actual (Ya).

1.2. ESTRUCTURA DE LA TESIS

El primer capítulo de la tesis consta de la introducción general, donde se presentan los antecedentes, objetivos e hipótesis del trabajo. El segundo capítulo corresponde a un artículo titulado «Impact of Cropping Systems on Soil Quality», redactado según las normas de la revista *European Journal of Agronomy*, y pretende enfocarse en la primera hipótesis y trabajar sobre los dos primeros objetivos. El tercer capítulo se titula «Diversfied Cropping Systems Reduce Soybean Yield Gap», siendo un artículo escrito en el formato *Field Crops Research*, y se enfoca en la segunda hipótesis y en los últimos dos objetivos. En el cuarto capítulo se presenta una discusión y conclusión general del trabajo en su conjunto.

2. IMPACT OF CROPPING SYSTEMS ON SOIL QUALITY

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2.1. RESUMEN

El proceso de intensificación agrícola ocurrido en el litoral oeste de Uruguay en el pasado reciente consistió en sustituir un sistema de rotación cultivo pastura por un sistema de cultivo (CS, sigla en inglés) continuo sin labranza. La hipótesis fue que este proceso puede ser caracterizado a campo por indicadores de propiedades del suelo sensibles a cambios en el uso del suelo en el mediano plazo. Los objetivos fueron: i) identificar CSs en función del uso del suelo de predios representativos de la región; ii) asociar propiedades del suelo a los CSs. Se construyó una base de datos con la descripción del uso del suelo del período 2014-2020 de 45 predios comerciales (699 unidades de manejo y 12.699 ha). Se realizó un análisis de componentes principales (PCA) con 14 descriptores del uso del suelo para seleccionar aquellos que mejor resumen la información. Se seleccionaron la relación pastura/cultivo (PCR), frecuencia de soja durante la fase agrícola de verano (SSbCF), intensidad de la fase agrícola (IAI) e intensidad de uso del suelo (ISI). Con un análisis de conglomerados se identificaron tres CSs: rotación pastura-cultivo (ROT-PC), cultivo continuo con alta frecuencia de especies de fotosíntesis C_4 como maíz (CC_Corn) y cultivo continuo con alta frecuencia de soja (CC_Soybean). Se seleccionaron 64 sitios representativos de estos CSs, ubicados en un rango de 60 km de radio. En cada sitio se relevaron 46 propiedades del suelo. Con un PCA se seleccionaron aquellas que mejor resumieran la información. Con estas y los CSs seleccionados se realizó un análisis discriminante lineal (LDA), el cual permitió concluir que una menor diversificación de los CS (ROT-

PC > CC_Corn > CC_Soybean) redujo a la fertilidad del suelo (carbono orgánico, conductividad eléctrica y disponibilidad de potasio). Sin embargo, solo con las propiedades del suelo del sitio no se pudo identificar a que CS pertenecen.

Palabras clave: intensificación, sostenible, diversificación, rotación, fertilidad

2.2. ABSTRACT

Over the past two decades in the eastern Pampas of South America, there has been a transition in agricultural practices from rotating crops with perennial pastures to adopting a continuous no-till cropping system (CS), resulting in an impact on soil functionality in the medium term. The hypothesis was that this process could be characterized by soil property indicators. The objectives were: i) to identify CSs based on land use and ii) to characterize soil properties associated with different CSs. Based on this, a database was built with the land use description from 2014 to 2020 of 45 commercial farms. A principal component analysis (PCA) was performed with 14 land use indicators to select those that best summarized all the information. The selected indicators were pasture-crop ratio (PCR), soybean frequency during the summer agricultural phase (SSbCF), intensification of agricultural phase index (IAI) and intensity of soil use index (ISI). By performing a cluster analysis with these indicators, the following CSs were identified: pasture-crop rotation (ROT-PC), continuous cropping with high frequency of C_4 photosynthesis species (CC_Corn) and continuous cropping with high frequency of soybean (CC_Soybean). Based on the identified CS, 64 representative sites were selected within a 60 km radius range, assessing 46 soil properties. A PCA was used to select soil properties that best summarized the information. Using these properties and the selected CSs, a Linear Discriminant Analysis (LDA) was conducted, leading to the conclusion that a lower diversification of CSs (ROT-PC > CC_Corn > CC_Soybean) affected soil fertility (organic carbon, electrical conductivity, and potassium availability). However, solely based on soil properties, it was not possible to identify which CS they belonged to.

Keywords: sustainable intensification, diversification, rotation, soil fertility, land use.

2.3. INTRODUCTION

Sustainable intensification underscores the necessity of ensuring cropping systems (CSs) do not lead to a deterioration in soil quality. However, the global imperative to increase food production has led to significant changes in land use. In the eastern Pampas of South America it has been driven by two key factors: i) a shift towards more intensive agricultural land use, where traditional pasture-crop rotation systems (ROT-PC) are being phased out in favour of continuous no-till CSs, centred around soybean (CC_Soybean) (Franzluebbers et al., 2014); and ii) the expansion of these CSs into marginal areas (Baeza and Paruelo, 2020).

Continuous CSs were based on the paradigm that no-till could control the deterioration of soil properties associated with continuous CSs. However, as CC_Soybean carried on over time, annual input of crop residues dwindled, resulting in an unfavourable carbon balance (Novelli et al., 2011) that affected soil functions and ecosystem services relying on it, including food provision (Seifert et al., 2017), nutrient cycling (Ernst et al., 2018) and soil formation (Wingeyer et al., 2015).

Ecosystem services, defined as benefits humans obtain from ecosystems (Millennium Ecosystem Assessment, 2005), highlight the pressing need to address the deterioration of these services as pastures are displaced. This calls for the development of CSs that take into consideration the negative carbon balance that occurs during the soybean cycle (Wingeyer et al., 2015). Achieving it requires an increased focus on resource intensity and efficiency through greater intensification (Novelli et al., 2013; Rubio et al., 2022) and diversification of CSs (Ernst et al., 2020; Tamburini et al., 2020). Land use strategies can be described and compared using indicators, which allow the assessments of changes in soil quality in a specific region. Indicators may include variables such as annual vegetation cover, frequency of a particular crop in a crop sequence (Novelli et al., 2013), or presence of pastures within CSs (Rubio et al., 2022).

Soil quality has been defined as the capacity of the soil to sustain biological productivity, uphold environmental quality and promote vitality of plants and animal life (Doran and Parkin, 1994). The definition brings out the complexity of this environmental quality component and the many connections between its functions and ecosystem services that rely on it. To gauge soil condition, the use of soil quality indicators capable of depicting changes in soil functions tied to short to medium-term processes and properties sensitive to management has been proposed. Assessing soil status is complex because, if it is done with a single indicator or an all-encompassing index, results will be confined to the specific environmental conditions in which they were gathered (Quiroga et al., 2017). An increasing number of indicators may increase collinearity and complexity of relationships between indicators and land use options. A proposed way of dealing with this challenge is to work with a *minimum data set* (Arshad and Martin, 2002; Doran and Parkin, 1996), sorting out the data through a multivariate analysis (Wander and Bollero, 1999; Aparicio and Costa, 2007; Stevenson et al., 2015), sometimes followed by expert judgment (Sparling and Schipper, 2002), thus getting rid of linked properties.

National and regional research has been carried out to quantify CS effect on soil quality. Nonetheless, results came from experiments with contrasting management, such as continuous cropping vs. pasture rotation (García-Préchac et al., 2004; Ernst and Siri-Prieto, 2009; Ernst et al., 2018), tillage vs. no-till (García-Préchac et al., 2004; Ernst and Siri-Prieto, 2009), or were generated by simulation models (Baethgen et al., 2021). The information stemming from these experiments has been applied and adjusted to local CSs, which is essential to quantify how they perform in the current context.

Over the past 50 years, national research, the implementation of public policies (Zurbriggen et al., 2020) and international shifts in pricing (Figueredo et al., 2019) have sparked ongoing transformations in land use. CSs in Uruguay has transitioned over time from conventional tillage, with wheat as the main crop until 1970, to embracing ROT-PC in the 1990s, and to CC_Soybean in the current context. The fact that some CSs have remained in ROT-PC provides an opportunity to capture potential soil quality effects brought on by recent shifts in land use.

The objectives of this study are: i) to pinpoint differing CSs currently in operation in Uruguay's main agricultural region and ii) to link these CSs with soil quality indicators. The hypothesis underpinning this research is that the land use transformation process in the region can be portrayed at field level using sensitive soil property indicators.

2.4. MATERIALS AND METHODS

2.4.1. Study Area and Strategy

The study area encompasses the west and south-central regions of Uruguay, considered prime agricultural land. Soils are classified as Typic Argiudolls & Hapludolls and are considered prime agricultural land. The region has a humid subtropical climate with an average daily temperature of 17.5 °C year-round, subject to significant seasonal fluctuations. Annual precipitation is approximately 1200 mm, with substantial year-to-year variations. Climatic conditions permit double cropping.

The study was carried out in two successive stages. First, a database of 45 fields of members of FUCREA (Uruguayan Federation of CREA Groups) and AUSID (Uruguayan Association for No-Tillage) was employed. This database covered land use history over a six-year period (2014-2020) and included data for all management units, excluding areas left in their natural state, forests, or those where only one crop was sown. Information was available for 699 units, covering an area of 12,699 hectares (1% of agricultural region). Using this data, land use indicators were developed to characterize each field and discern groups of fields implementing different CS.

A second stage was conducted to select sites representative of CSs identified in the first phase, considering units with a land use history of the selected site was completed considering the period 2010-2020. Then, a set of soil properties were surveyed as indicators of soil quality for each selected site.

2.4.2. Stage 1.a: Construction of Land Use Indicators

The characterization of each field was carried out by assessing land use on per-management unit for each semester during the study period (2014-2020) (Table 1). Average land use indicators for each field were calculated considering all management units within the fields weighted by its area (see more in Table 1A of Appendix).

$$\bar{x}_p = \frac{\sum_{i=1}^{N} x_i \ * w_i}{\sum_{i=1}^{N} wi} \tag{1}$$

Where $\bar{x}_p$ is the weighted average of indicator p, x_i is the average of the indicator for each management unit of the field during study period, and W_i is the area of each management unit.

Indicators were defined based on prior research studies, which suggests that crop rotations with perennial pastures (Ernst et al., 2020, 2018; García-Préchac et al., 2004), inclusion of C_4 species into annual crop rotation (Díaz-Zorita et al., 2014; Mazzilli and Ernst, 2019; Novelli et al., 2013) and soil use intensification (Caviglia et al., 2004; Rubio et al., 2022) can either uphold or enhance soil quality and crop yields.

Table 1

Land use indicator	Abbreviation	Description
Total number of cash crops	TC	Total number of cash crops planted during the study period.
Total number of summer cash crops	TSC	Total number of summer cash crops planted.
Winter grass crop percentage	GWC	Proportion of winter grass crops planted during the study period, including cash and cover crops.
Winter legume crop percentage	LWC	Proportion of winter legume crops planted during the study period, including cash and cover crops.
Winter brassica crop percentage	BWC	Proportion of winter brassica (canola) crops planted during the study period, including cash and cover crops.
Summer grass crop percentage	GSC	Proportion of summer grass crops planted during the study period, including cash and cover crops.
Summer legume crop percentage	LSC	Proportion of summer legume crops planted during the study period, including cash and cover crops.
Summer or winter fallow percentage	Fallow	Proportion of time with fallow soil during the study period.
Pasture percentage	PP	Proportion of pastures planted during the study period.
Years of cropping	YC	Duration of the agricultural phase (years).
Pasture/crop ratio	PCR	Ratio of time in the agricultural phase to time in the pasture phase of the rotation.
Summer soybean cropping frequency	SSbCF	Frequency of soybean cultivation in the summer agricultural phase.
Intensification of agricultural phase index	IAI	Number of cash crops planted per year in the agricultural phase.
Intensity of soil use index	ISI	Proportion of time the soil is producing biomass, whether in the pasture or agricultural phase.

Land use indicators for the cropping system implemented in the agricultural area of 45 farms (period 2014-2020).

2.4.3. Stage 1.b: Identifying Cropping Systems Based on Land Use Indicators

We adapted the approach of Peralta and Costa (2013) and Stevenson et al. (2015) to avoid dealing with interrelated land use indicators. A principal component analysis (PCA) was conducted previous standardizing the data, trimming down the data set's dimensions. Unless otherwise specified, data analysis was performed using the statistical package "stats" in R core team (Team, 2000).

The selection process involved: 1) identifying the principal components (PCs); 2) selecting PCs with variance (λ) exceeding 1, depicting at least 5% of data variability; 3) cherry-picking land use indicators with a correlation (Pearson, ρ) exceeding 0.5 with the chosen PCs, and 4) preserving indicators with correlations below 0.6 with one another, opting for one land use indicator for each selected PC. A cluster analysis was performed with the chosen ones. Clusters were generated using hierarchical average linkage clustering based on Euclidean distance. It was directed to cut the tree into 5 clusters. By using selected land use indicators as independent variables and clusters as grouping criterion (Sokal and Michener, 1958), a linear discriminant analysis (LDA) was performed using the MASS statistical package (Team, 2000) to assess predictive capacity and unravel the role of land use indicators in shaping CS groups.

2.4.4. Stage 2.a: Selecting Representative Sampling Sites for Cropping Systems

Sixty-four representative sites were picked out based on the identified CSs (from Stages 1.a and 1.b). Selected sites were within a 60 km radius from the coordinates -33.1722 latitude and -57.7969 longitude, Uruguay's most influential agricultural area. Site selection factored in i) Uruguay's soil recognition map at a 1:1,000,000 scale, mostly identified as Typic and Vertic Argiudolls (42 and 22 sites, respectively), and ii) systems without crop management restrictions. Additional information can be found in Tables A2 and A3 in Appendix.

Eighteen soil properties were assessed to pin down the *minimum data set* to gauge soil quality (Arshad and Martin, 2002). Properties surveyed can be affected by shifts in land use (Morón et al., 2012; Peralta and Costa, 2013; Stevenson et al., 2015; Wander and Bollero, 1999), influencing ecosystem services linked to provision (Aparicio and Costa, 2007; Ernst et al., 2020, 2018), regulation (Janvier et al., 2007; Smith et al., 2020) and support (Novelli et al., 2013; Rubio et al., 2022) (Table 2).

Soil samples were gathered within a 10 m radius of each geo-referenced point between October 15th and November 15th from fallow fields before soybean planting date. Soil chemical properties were determined from a composite sample comprising 15 subsamples per site. These samples were obtained by employing a soil auger to extract soil to a depth of the initial 15 cm. The collected samples were then divided into two sections: 0-7.5 cm and 7.5-15 cm. Apart from PMN (assessed only in the 0-7.5 cm section), the values for the remaining indicators were estimated for the entire 0-15 cm horizon, calculated as the mean of the two sampled strata (0-7.5 cm and 7.5-15 cm). Methodology is provided in Table 2.

Soil penetration resistance (PR) throughout the soil profile was quantified at 2.5 cm intervals down to a depth of 45 cm. Measurements were taken with soil near field capacity at six sampling points per site. Averages PR values were calculated within the intervals of 7.5-15 cm, 15-30 cm, and 30-45 cm depth. Infiltration rate (INF) was determined following the method developed by Soil Quality Institute (1999), with three replicates randomly located within the site. The mean weighted diameter of soil water stable aggregates (CMWD) was measured using the wet sieving method described by Yoder (1936), with modifications as suggested by Kemper and Roseanu (1986, on three samples from the 0-10 cm layer. Apparent electrical conductivity (ECa) was measured in 10 cm layers up to a depth of 30 cm in the soil profile. Available water-holding capacity of the A horizon (SWC_A) was estimated by taking core samples with an auger at each site to quantify the depth (in cm) of the A horizon. Approximately 500 g of sample were collected, sieved through a 2 mm sieve, and laboratory determinations were made for percentage content of sand (Sa), clay (Cl), silt (Si) and organic carbon (SOC), which was converted to organic matter (OM) by multiplying by 1.728. Pedometric functions locally calibrated by Fernández (1979) and Silva et al. (1988) were used to estimate moisture contents at equilibrium at 1/10 atmosphere (field capacity, FC) and at -15 atmospheres (permanent wilting point, PWP), as well as bulk density (BD).

Equations used were as follow:

$$FC = 21.977 - 0.168(Sa\%) + 2.601(O.M\%) + 0.127(Cl\%) \quad (2)$$

$$PWP = -58.1313 + 0.3718(O.M.\%) + 0.5682(Sa\%) + 0.6414(Si\%) + 0.9755(Cl\%) \quad (3)$$

$$BD\ (g/cc) = 3.6725 - 0.0531(O.M.\%) - 0.0210(Sa\%) - 0.0228(Si\%) - 0.0221(Cl\%) \quad (4)$$

Calculation SWC_A involves subtracting PWP from FC. Then, the SWC_A is multiplied by bulk density and horizon thickness to convert the percentage content of available water into water volume (mm). The formula can be expressed as:

$$SWC_A\ (\%) = FC\ (\%) - PWP\ (\%) \quad (5)$$

$$SWC_A\ (mm) = ADH\ (\%) \times BD \times thickness\ /10\ cm \quad (6)$$

Table 2

Soil Property	Layers (cm)	Symbol	Units	Method	Primary Ecosystem Service
Potential nitrogen mineralization	0-7.5	PMN$_{0-7.5}$	kg N ha^{-1}	Waring and Bremner (1964)	Support
Soil organic carbon	0-7.5	SOC$_{0-7.5}$	g 100 g^{-1}	Nelson and Sommers (1996)	Support
	7.5-15	SOC$_{7.5-15}$			
	0-15	SOC$_{0-15}$			
Bray phosphorus	0-7.5	P$_{0-7.5}$	mg P kg^{-1}	Bray and Kurtz (1945)	Support
	7.5-15	P$_{7.5-15}$			
	0-15	P$_{0-15}$			
Soil pH in water	0-7.5	pH $_{0-7.5}$	-	Chapman (1965)	Support
	7.5-15	pH $_{7.5-15}$			
	0-15	pH $_{0-15}$			
Electrical conductivity (1:2.5)	0-7.5	EC$_{0-7.5}$	dS m^{-1}	Chapman (1965)	Support
	7.5-15	EC$_{7.5-15}$			
	0-15	EC$_{0-15}$			
Exchangeable Ca^{+2}	0-7.5	Ca$_{0-7.5}$	meq Ca^{+2} 100 g^{-1}	Extracted with 1 M acetate	Support
	7.5-15	Ca$_{7.5-15}$			
	0-15	Ca$_{0-15}$			
Exchangeable Mg^{+2}	0-7.5	Mg$_{0-7.5}$	meq Mg^{+2} 100 g^{-1}	Extracted with 1 M acetate	Support
	7.5-15	Mg$_{7.5-15}$			
	0-15	Mg$_{0-15}$			
Exchangeable K^{+}	0-7.5	K$_{0-7.5}$	meq K^{+} 100 g^{-1}	Extracted with 1 M acetate	Support
	7.5-15	K$_{7.5-15}$			
	0-15	K$_{0-15}$			
Exchangeable Na^{+}	0-7.5	Na$_{0-7.5}$	meq Na+ 100 g^{-1}	Extracted with 1 M acetate	Support
	7.5-15	Na$_{7.5-15}$			
	0-15	Na$_{0-15}$			
Total bases	0-7.5	TB$_{0-7.5}$	meq 100 g^{-1}	Sum of Ca^{+2}, Mg^{+2}, K^{+}, and Na^{+}	Support
	7.5-15	TB$_{7.5-15}$			
	0-15	TB$_{0-15}$			
Tritable acidity at pH = 7	0-7.5	TA$_{0-7.5}$	meq 100 g^{-1}	Quiaggio and van Raij (2001)	Support
	7.5-15	TA$_{7.5-15}$			
	0-15	TA$_{0-15}$			
Cation exchange capacity at pH = 7	0-7.5	CEC$_{0-7.5}$	meq 100 g^{-1}	Sum of AT, Ca^{+2}, Mg^{+2}, K^{+}, and Na^{+}	Support
	7.5-15	CEC$_{7.5-15}$			
	0-15	CEC$_{0-15}$			
Bases saturated at pH = 7	0-7.5	SB$_{0-7.5}$	-	BT divided by CEC	Support
	7.5-15	SB$_{7.5-15}$			
	0-15	SB$_{0-15}$			
Apparent electrical conductivity	0-10	ECa$_{0-10}$	mS cm^{-1}	Spectrum EC 110	Support and regulation
	10-20	ECa$_{10-20}$			
	20-30	ECa$_{20-30}$			
Penetration resistance	7.5-15	PR$_{7.5-15}$	kPa	FieldScout SC 900	Regulation
	15-30	PR$_{15-30}$			
	30-45	PR$_{30-45}$			

Weighted mean diameter of water-stable aggregates	0-10	CMWD	mm	Kemper and Roseanu, (1986); Yoder (1936)	Regulation
Water infiltration rate	0-8	INF	cm d^{-1}	Soil Quality Institute (1999)	Regulation
Available water-holding capacity of A horizon	Variable	SWC_A	mm	Fernández (1979); Silva et al. (1988)	Regulation

Ecosystem services associated with quantified soil properties: layer, symbol, unit of measurement, quantification method and primary ecosystem service affected.

2.4.5. Stage 2.b: Soil Property Results Analysis

Conforming to concepts and suggestions put forth by Wander and Bollero (1999), Peralta and Costa (2013), and Stevenson et al. (2015), the 46 variables used to describe the soil's physical, chemical and biological properties (Table 2) were grouped by performing a PCA after standardizing the data.

PCs with a variance (λ) greater than 1, representing at least 5% of the collected data's variability, were retained to select the *minimum data set* of soil properties best portraying the data's variability. Subsequently, properties that had a correlation greater than 0.5 with the retained PCs were selected. In cases where two or more properties showed a strong correlation (Pearson) exceeding 0.6, we retained the one that, according to expert judgment (agricultural advisors), was more widely used in productive contexts and easier to quantify (in terms of sampling, sample handling, and availability of labs for analysis).

A Linear Discriminant Analysis (LDA) was performed using the selected soil properties as independent variables and CSs identified in section 2.4.3 as grouping criteria. Analysis was conducted using the MASS statistical package (Team, 2000) to assess whether discrepancies existed between soil properties at each site contingent on the implemented agricultural sequence, and whether chosen properties could predict the CS. Within LDA routine, a univariate analysis of variance was included.

2.5. RESULTS

2.5.1. Land Use Description for the Period 2014-2020

On average in the evaluated fields soils were under agricultural phases 81% of the time, with the remaining 19% in pasture. Approximately 1.4 cash crops were sown annually (Table 3). Considering cash crops, crop sequence was dominated by summer crops (4.8 TSC out of 6.8 TC), with soybean as the primary crop in rotation (SSbCF = 0.83). C4 metabolism species (mainly maize) were seeded approximately once every 6.3 years.

Table 3

Variables	Unit	Mean	Median	Standard deviation	Minimum	Maximum
TC	#	6.8	7.0	1.4	3.8	10.0
TSC	#	4.8	4.9	1.1	2.5	6.0
GWC	%	29	29	9	8	48
LWC	%	1	0	2	0	11
BWC	%	3	1	4	0	17
GSC	%	7	6	7	0	25
LSC	%	33	32	8	19	50
Fallow	%	8	8	6	0	28
PP	%	19	15	18	0	60
PCR	#	0.56	0.40	0.60	0.00	2.29
YC	#	4.8	5.1	1.1	2.4	6.0
IAI	#	1.44	1.41	0.19	1.00	1.93
ISI	#	0.92	0.92	0.06	0.72	1.00
SSbCF	%	0.83	0.86	0.14	0.51	1.00

Summary of land information from the database of 45 farms for the period 2014-2020. TC= Total number of cash crops; TSC= Total number of summer cash crops; GWC= Winter grass crop percentage; LWC= Winter legume crop percentage;BWC= Winter brassica crop percentage; GSC= Summer grass crop percentage; LSC= Summer legume crop percentage; Fallow= Summer or winter fallow percentage; PP= Pasture percentage; PCR= Pasture/crop ratio; YC= Years of cropping; ISI= Intensity of soil use index; IAI= Intensification of agricultural phase index; SSbCF= Summer soybean cropping frequency.

The study period overlapped with the implementation of the Responsible Soil Use and Management Plan (Law No. 15,239) (Zurbriggen et al., 2020), resulting in a high ISI (92%). This is reflected in minimal fallow periods (8%) and a significant presence of winter annual grasses, mainly as cover crops (Table 2A).

2.5.2. Land Use Indicator Selection

Significant correlations were observed between 14 land use indicators in 28 cases (P ≤0.001) and 22 cases (0.001< P ≤0.05) out of 91 possible combinations. Among these, 23 combinations showed strong correlation (P >0.6) (Fig. 2). To define the *minimum data set* [15], land use indicators representative of the first four PCs were selected (highlighted in bold in Table 4).

Tabla 4

Variables	PC 1	PC 2	PC 3	PC 4
TC	0.83	0.28	0.07	0.38
TSC	0.96	0.12	0.10	-0.05
GWC	0.78	0.41	0.06	-0.33
LWC	-0.09	-0.41	0.29	-0.48
BWC	0.11	0.21	0.45	0.71
GSC	0.54	-0.64	0.49	0.07
LSC	0.63	0.67	-0.30	-0.12
Fallow	0.33	-0.63	-0.62	0.29
PP	-0.98	-0.03	0.03	0.00
PCR	**-0.96**	-0.05	0.02	-0.02
YC	0.99	0.02	0.00	-0.01
IAI	-0.53	0.38	0.11	**0.61**
ISI	-0.32	**0.63**	**0.65**	-0.28
SSbCF	-0.42	**0.71**	-0.50	-0.09
Variance (λ)	6.47	2.78	1.70	1.55
Proportion of variance (%)	0.46	0.20	0.12	0.11
Cumulative proportion (%)	0.46	0.66	0.78	0.89

Correlation with principal components (PCs), variances, and percentage of total and cumulative variance explained by the first 5 PCs in the principal component analysis (PCA) of calculated land use variables. Values in bold indicate the selected land use indicator for the corresponding principal component.

PCR was selected for PC 1. It serves as an indicator of crop-pasture rotation or the significance of agriculture in CS. PCR values below 1 indicate a higher proportion of crops, while values above 1 indicate a higher proportion of pastures in the CS.

For PC 2, SSbCF and ISI were selected. SSbCF represents the rotation of the summer crop phase, while ISI indicates the proportion of time the soil remains under active vegetation cover. SSbCF of 0.8 indicates that, for a 10-year agricultural phase, soybeans were planted 8 years. ISI represent the opposite of fallow period.

PC 3 also includes ISI, as it was the primary indicator correlated (above 0.5) with PC 3.

PC 4 is represented by IAI. When IAI = 1, it means one crop was planted per year, with IAI = 2 (double cropping) being the maximum value of the region's CS. Although BWC was strongly correlated with this PC, it also had a weak but significant correlation (p = 0.02) with IAI. Several CS had not yet systematically incorporated rapeseed (primary brassica grown in country), leading to significant variation in BWC (Table 3).

CS level could be described based on indicators related to land use intensity (ISI and IAI) and CS diversification (PCR and SSbCF).

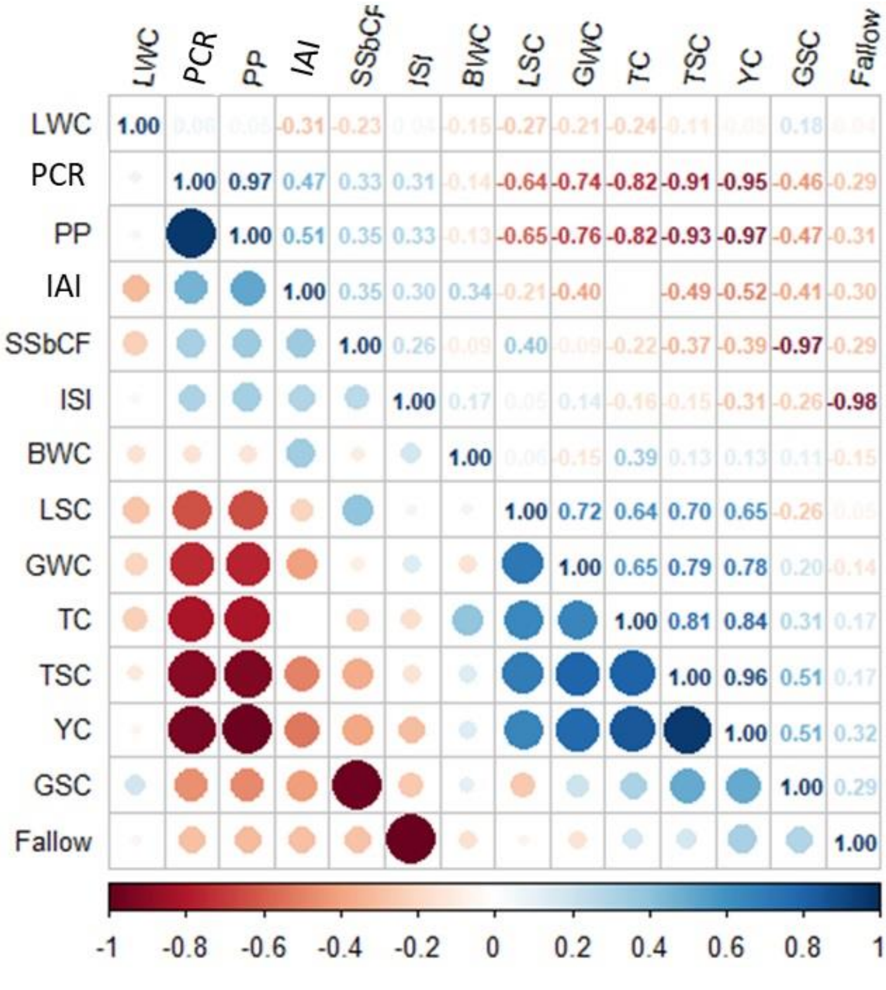

Fig. 2. Pearson correlation matrix estimated for each combination of land use indicators. On the left, the visualization method is in circles, where the area of the circles represents the absolute value of the corresponding coefficients. On the right, the values of the coefficients' are shown. Both visualization methods applied a color gradient for correlation: red (negative), white (neutral) and blue (positive).

2.5.3. Identification of Contrasting Cropping Systems

The cluster analysis formed three major CS groups (clusters 1, 2 and 4 in Table 5). Cluster 2 grouped the largest number of farms (21) and consisted of continuous CS (PCR = 0.24) with a high frequency of soybean (SSbCF = 0.89) (CC_Soybean). Cluster 1 grouped nine fields in continuous CSs (PCR = 0.24) that incorporate C_4 photosynthesis species (SSbCF = 0.62) (CC_Corn). Cluster 4 grouped 12 fields characterized by the inclusion of perennial pastures (PCR = 1.28) (ROT-PC) a high intensification of the agricultural phase (IAI = 1.57), and an average ISI value of 0.96.

Clusters 3 and 5 were not well represented in the data set, with only 1 and 2 fields within each cluster respectively, so they were excluded from further analysis.

Table 5

Cluster	n	PCR	SSbCF	IAI	ISI
1 (CC_Corn)	9	0.24±0.24 c	0.62±0.06 a	1.28±0.15 a	0.92±0.05 b
2 (CC_Soybean)	21	0.24±0.22 c	0.89±0.09 b	1.42±0.13 a	0.91±0.05 b
3	2	0.26±0.37 a	0.72±0.06 a	1.24±0.08 a	0.74±0.03 a
4 (ROT-PC)	12	1.28±0.40 b	0.90±0.08 b	1.57±0.15 b	0.96±0.04 b
5	1	2.29 c	1.00 b	1.93 c	0.99 b

Summary of land use indicators for each cluster. Different letters within columns indicate significant differences ($P \leq 0.05$).

LDA enabled discrimination among CC_Corn, CC_Soybean, and ROT-PC based on land use indicators (intersections in Fig. 3).

Confidence intervals (crosses in Fig. 3) provide a graphical representation of CSs concerning each axis. Axis 1, which accounts for 77% of the data's variability, was determined by two indicators linked to CS diversification (PCR and SSbCF) and IAI. It primarily discriminated continuous CSs (negative values, left) from those involving pasture rotation (positive values, right). Axis 2, which accounts for 23% of the variability, correlated particularly with SSbCF, distinguishing systems with a high frequency of soybean grouped in the CC_Soybean cluster from those that rotate in summer with other crops (CC_Corn).

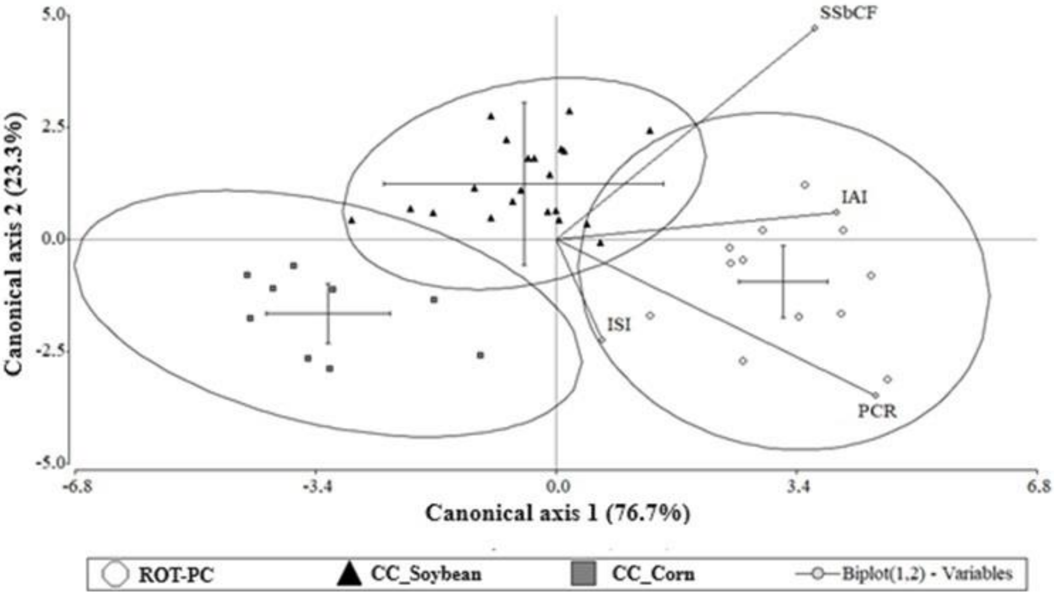

Fig. 3. Biplot with linear discriminant analysis (LDA) for the CC_Soybean (black triangle), ROT-PC (empty circle) and CC_Corn (gray square) groups based on selected land use indicators. Circles represent prediction ellipses (95%) for the clusters of the three groups. Crosses indicate confidence intervals (95%).

The selected land use indicators were useful for predicting characteristics of the CSs (Fig. 3 and Table 6), based solely on the historical semestral land use.

Table 6

Groups	CC_Corn	CC_Soybean	ROT-PC	Total	Error (%)
CC_Corn	9	0	0	9	0
CC_Soybean	1	20	0	21	5
ROT-PC	0	0	12	12	0
Total	10	20	12	42	2

Cross-classification table with apparent error rate.

2.5.4. Description of the Assessed Soil Quality

Results from the 64 selected sites fell within the expected value range reported in other regional studies (Morón et al., 2012; Beretta-Blanco et al., 2019) (Table 7).

PMN values varied as expected, falling within the range quantified by a similar study (Ernst et al., 2018) under similar conditions. CEC$_{0-15}$, SB$_{0-15}$ and pH$_{0-15}$ were within optimal ranges for extensive annual crops. K$_{0-15}$ and P$_{0-15}$ availability are considered non-limiting for soybeans under current production conditions (García, 2005; Coitiño-López et al., 2016).

Concerning soil physical properties, INF exhibited high variability among sites, with a mean value similar to those reported for sites with good physical condition (Ernst et al., 2018). PR7.5-15 values indicated potential limitations for crop growth, in line with other studies (Beulter and Centurion, 2004; Etchegoimberry, 2019). Soil aggregates showed CMWD considered stable to very stable (Le Bissonnais et al., 2002).

Table 7

Variables	Units	Mean	Median	Standard deviation	Minimum	Maximum
$PMN_{0-7.5}$	kg N ha^{-1}	29	24	14	10	77
P_{0-15}	mg P kg^{-1}	20	18	9	6	48
SOC_{0-15}	g kg^{-1}	30	30	6	17	44
EC_{0-15}	dS m^{-1}	1.0	1.0	0.3	0.6	2.0
pH_{0-15}	#	5.9	5.9	0.4	5.3	7.6
Ca_{0-15}	meq 100 g^{-1}	17.3	17.0	4.8	7.2	28.2
Mg_{0-15}	meq 100 g^{-1}	2.4	2.4	0.5	0.9	3.4
K_{0-15}	meq 100 g^{-1}	0.7	0.6	0.3	0.3	1.7
Na_{0-15}	meq 100 g^{-1}	1.0	1.0	0.2	0.7	1.6
TB_{0-15}	meq 100 g^{-1}	21.4	21.7	5.15	10.7	33.5
TA_{0-15}	meq 100 g^{-1}	4.1	4.1	1.0	0.1	6.2
CEC_{0-15}	meq 100 g^{-1}	25.5	26.0	5.1	14.6	36.6
SB_{0-15}	%	83	84	5	73	99
$PR_{7.5-15}$	kPa	1216	1168	292	577	1934
PR_{15-30}	kPa	1233	1241	221	782	1829
PR_{30-45}	kPa	1311	1276	282	760	2132
ECa_{0-10}	mS cm^{-1}	711	688	249	275	1256
ECa_{10-20}	mS cm^{-1}	772	786	248	287	1313
ECa_{20-30}	mS cm^{-1}	969	981	245	287	1456
INF	cm d^{-1}	24	7.7	56.1	0.1	340.9
CMWD	Mm	1.9	2.0	0.6	0.7	2.8
SWC_A	Mm	43.5	41.5	12.6	20.3	75.1

Summary of surveyed soil property information from the 64 selected sites representing the identified cropping systems, with the mean value of the two soil strata (0-7.5 and 7.5-15) sampled for chemical properties. PMN= Potential nitrogen mineralization; P= Bray phosphorus; SOC= Soil organic carbon; EC= Electrical conductivity (1:2.5); pH= Soil pH in water; Ca= Exchangeable Ca^{+2}; Mg= Exchangeable Mg^{+2}; K= Exchangeable K^{+}; Na= Exchangeable Na^{+}; TB= Total bases; TA= Tritable acidity at pH= 7; CEC= Cation exchange capacity at pH= 7; SB= Bases saturated at pH = 7; PR= Penetration resistance; ECa= Apparent electrical conductivity; INF= Water infiltration rate; CMWD= Weighted mean diameter of water-stable aggregates; SWC_A= Available water-holding capacity of A horizon.

2.5.5. Selection of Soil Properties

Through a PCA, 75% of the variability in soil properties was described using five PCs (Table 4A in Appendix). PC 1, representing 38% of the total variability, was chiefly composed of variables related to soil fertility. Notably, high correlations with PC 1 were observed for TB availability, Ca availability, CEC, EC, SB, SOC, pH, and K availability. Additionally, it exhibited associations with ECa, a property relevant not only to fertility but also to clay content, compaction, and soil water content. PC 2, which accounts for 15% of the variability in the data set, showed strong correlations with SOC, TA, and pH. PC 3 (10%) was linked to soil nutrient content, describing availability of K, P, Mg, and $ECa_{20\text{-}30}$. PC 4 (8%) correlated with variables describing soil physical condition, measured through PR, and included a chemical variable related to physical properties, such as Na concentration. PC 5 (5%) was once more associated with indicators of soil nutrient availability, such as EC and P levels. Except for PR, the level of correlation between PCs and soil physical properties (INF, SWC_A, and CMWD) was low.

The correlation analysis among the 46 soil quality indicators was significant in 365 cases ($P \leq 0.001$) and 201 cases ($0.001 \leq P < 0.05$) out of the 1035 possible combinations. Among these, 46 combinations exhibited a strong correlation (greater than 0.6) (Fig. 1A in Appendix). With a Pearson correlation coefficient matrix, the number of variables was reduced to those strongly correlated with their respective PC, while having weak correlations among themselves ($P \leq 0.6$). For instance, $SOC_{0\text{-}15}$ and $CEC_{0\text{-}15}$ showed a strong correlation (0.8) at the 0-15 cm depth, while $EC_{0\text{-}15}$ and $PR_{7.5\text{-}15}$ exhibited a weak correlation (0.1) (Fig. 4). A high correlation allowed the omission of one variable in future analyses. The correlation between the selected properties remained below 0.6, a threshold for what is considered a strong correlation in this study. Both $SOC_{0\text{-}15}$ and $ECa_{10\text{-}20}$ were strongly correlated with CEC, Ca and TB. However, the correlation between these variables was less than 0.3. None of the soil physical properties displayed strong correlations with any of soil chemical properties or with each other (Fig. 4).

Considering the first five PCs and the Pearson correlation a *minimum data set* (Arshad and Martin, 2002) was selected (Table 8). In summary, soil fertility was represented by $EC_{0\text{-}15}$, $SOC_{0\text{-}15}$, $P_{0\text{-}15}$, $TA_{0\text{-}15}$ and $ECa_{10\text{-}20}$; soil nutrient concentration by $K_{0\text{-}15}$, $P_{0\text{-}15}$ and $Mg_{7.5\text{-}15}$; and soil physical condition by $PR_{7.5\text{-}15}$ and $Na_{0\text{-}15}$.

Table 8

Principal component	Information	Selected soil properties
PC 1	Soil fertility and texture	$EC_{0\text{-}15}$, $SOC_{0\text{-}15}$ y $ECa_{10\text{-}20}$
PC 2	Organic carbon and soil acidity	$TA_{0\text{-}15}$ y $SOC_{0\text{-}15}$
PC 3	Soil nutrients	$K_{0\text{-}15}$ y el $Mg_{7,5\text{-}15}$
PC 4	Soil physical condition	$PR_{7.5\text{-}15}$ y el $Na_{0\text{-}15}$
PC 5	Soil nutrients	$P_{0\text{-}15}$ y $EC_{0\text{-}15}$

Summary of selected soil properties with the information each contributed to the analysis.

2.5.6. Relationship between Identified Cropping Systems and Surveyed Soil Quality

CSs were characterized by differences in chemical soil properties, summarized in $SOC_{0\text{-}15}$, $EC_{0\text{-}15}$ and $K_{0\text{-}15}$ in soil. Levels of $SOC_{0\text{-}15}$ and $K_{0\text{-}15}$ differentiated ROT-PC from continuous CSs, while $EC_{0\text{-}15}$ distinguished more diversified CSs from simpler ones (CC_Soybean). There were no differences in physical properties among CSs. Although some situations indicated potential yield limitations due to $PR_{7.5\text{-}15}$ values, this applied to all CSs. There were also no significant differences in $ECa_{10\text{-}20}$, an indicator used to detect B horizon textures (Table 9).

Table 9

Variables	Units	ROT-PC	CC_Corn	CC_Soybean
N	#	17	26	22
Indicators of land use				
Years of continuous cropping	#	2.9	8.3	7.3
PCR	#	1.3	0.1	0.2
SSbCF	#	0.9	0.7	1
Soil fertility				
SOC_{0-15}	g kg^{-1}	34 a	29 b	27 b
EC_{0-15}	dS m^{-1}	1.4 a	1.3 a	1.0 b
TA_{0-15}	meq 100 g^{-1}	4.4 a	4.0 a	4.0 a
P_{0-15}	mg P kg^{-1}	21.6 a	20.1 a	17.8 a
K_{0-15}	meq 100 g^{-1}	0.84 a	0.63 b	0.66 b
$Mg_{7,5-15}$	meq 100 g^{-1}	2.5 a	2.3 a	2.5 a
ECa_{10-20}*	mS cm^{-1}	792 a	797 a	725 a
Soil physical condition				
Na_{0-15}	meq 100 g^{-1}	1.0 a	1.0 a	1.1 a
$PR_{7,5-15}$	KPa	1302 a	1245 a	1116 a

Summary of land use indicators and soil properties by cropping system of the 64 sites. Different letters within rows indicate significant differences observed among cropping systems ($P \leq 0.05$).

*ECa_{10-20} may also represent soil physical condition.

The confidence intervals in Fig. 4 reveal the capacity to differentiate CSs based on their soil properties ($P \leq 0.05$). Axis 1, which accounts for 70% of the data's variability, was determined by SOC_{0-15}, CE_{0-15} (positive values) and P_{0-15} (negative values), discriminating ROT-PC and CC_Corn (positive values, left) from CC_Soybean (negative values, right) ($P \leq 0.05$). Meanwhile, axis 2, accounting for 30% of the variability, was associated with SOC_{0-15}, K_{0-15}, and $Mg_{7.5-15}$ (positive values), and ECa_{10-20} and EC_{0-15} (negative values), discriminated ROT-PC (positive values) from CC_Corn (negative values) ($P \leq 0.05$).

Therefore, significant disparities are linked to the level of diversification within CSs, with ROT-PC presenting the highest degree, followed by CC_Corn and CC_Soybean ($P \leq 0.05$). Axis 1 differentiate between more diversified CSs (ROT-PC and CC_Corn) and less diversified ones (CC_Soybean), both positioned towards the right. Axis 2 contrasts the type of diversification, such as rotating with pastures (upper right quadrant) vs. inclusion of corn and sorghum in the sequence (lower right quadrant).

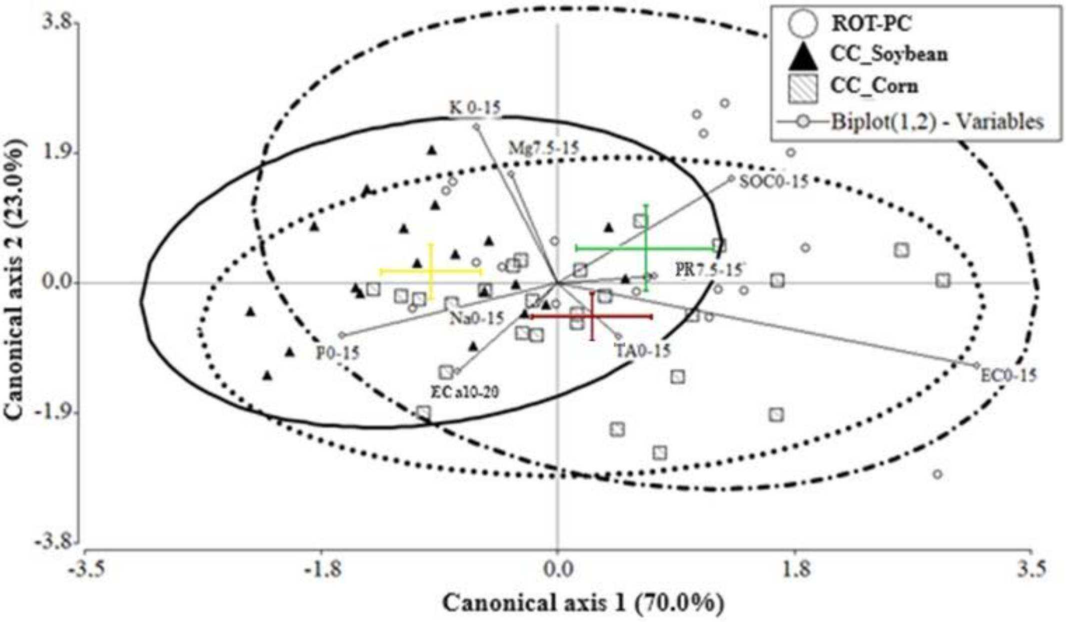

Fig. 4. Biplot with linear discriminant analysis (LDA) by cropping system (CC_Corn, CC_Soybean, and ROT-PC) for the selected soil properties that best represented the surveyed soil quality information. Crosses indicate confidence intervals (95%): ROT-PC (green), CC_Corn (brown) and CC_Soybean (yellow). Circles represent prediction ellipses (95%): ROT-PC (line and dot), CC_Corn (dotted line) and CC_Soybean (solid line).

However, the predictive power of CSs based on soil properties was not significant, as shown by the overlap among circles in Fig. 4 and the high error in the cross-classification rate (Table 10). The exception was the low error rate of CC_Soybean (25%). This implies that, without knowledge of land use history, it would only be possible to distinguish poorly diversified CSs (CC_Soybean) from highly diversified CSs (CC_Corn and ROT-PC).

Table 10

Groups	CC_Corn	CC_Soybean	ROT-PC	Total	Error (%)
CC_Corn	13	7	6	26	50
CC_Soybean	3	15	2	20	25
ROT-PC	4	5	10	19	47
Total	20	27	18	65	42

Cross-classification table with apparent error rate. Soil properties as independent variables.

2.6. DISCUSSION

The study effectively captures the recent change in land use, shifting from crop rotations with perennial pastures to intensive soybean CSs. A comparison of our results with national agricultural patterns (MGAP-DIEA, 2020) reveals that, in both cases, soybean dominates summer phases (0.87 vs. 0.83), reflecting consistent trends in cropping intensity (1.36 vs. 1.44) and land use (0.90 vs. 0.92). Hence, it can be considered that the results reasonably reflect the CSs of the region, rather than contrasting with systems far removed from actual production.

The three identified CSs can be associated with the recent agricultural trajectory in the region, where: i) ROT-PC, mirrors the historically dominant crop pasture rotations; ii) CC_Soybean, reflects the current primary CS; and iii) CC_Corn, which is like CC_Soybean but more diverse, notably featuring corn and sorghum, signifies a transition toward more sustainable systems adopted by some forward-thinking farmers. Exploiting the locally quantified advantages of rotating soybeans with corn (Mazzilli and Ernst, 2019; Ernst et al., 2020).

Although primary differences in land use strategies are associated with the diversification and integration of crops (Table 4 and Table 5), all three CSs exhibit intensive land use, with less than 10% fallow periods (on a bi-annual scale). Therefore, ISI was defined by IAI. Under the current national legal framework (Law 19.355, art. 76), which penalizes leaving bare soils, IAI provides more information than ISI regarding land use intensification. For example, in our study, the agricultural phase of ROT-PC exhibited an IAI = 1.6, significantly different from CSs under continuous cropping (IAI of CC_Soybean = 1.4 and of CC_Corn = 1.3). This difference may be attributed to the need for increasing the number of cash crops per unit of agricultural land area in ROT-PC to mitigate income loss due to the incorporation of pastures. Nevertheless, no significant differences in ISI were observed among CSs, with an average value of 0.92. Hence, the IAI served to differentiate the type of ISI, since increasing ISI through cover crops is not the same as building it from commercial crops, which require higher productivity thresholds to ensure profitability.

Among the identified *minimum data set*, which includes SOC_{0-15}, EC_{0-15}, ECa_{10-20}, TA_{0-15}, K_{0-15}, P_{0-15}, $Mg_{7.5-15}$, Na_{0-15} and $PR_{7.5-15}$, only soil fertility indicators (SOC_{0-15}, EC_{0-15} and K_{0-15}) respond to land use changes (Table 9 and Fig. 4). The study demonstrates the benefits of evaluating soil conditions using a set of indicators with low correlations, representing a range of properties that were eliminated post-analysis. For instance, CEC_{0-15} was associated with natural soil fertility (correlation with ECa_{10-20} = 0.73) and soil organic carbon (correlation with SOC_{0-15} = 0.77), suggesting its sensitivity to changes in land use.

Despite the potential effects of reduced SOC content on macroaggregate formation, soil compaction, and water retention capacity (Blanco-Canqui et al., 2013), no significant relationships were found between SOC and evaluated soil physical properties (CMWD, INF, Rp and SWC_A) (Fig. 1A). The lack of observed differences in soil physical properties among CSs might stem from the precision of measurements, as they are based on samples taken within a 10 m radius of each geo-referenced point. Also, it is possible that changes in SOC occurred within a range that did not significantly affect soil physical properties (Aparicio and Costa, 2007). A previous study (Sasal et al., 2017) noted that CSs with high land use intensification (ISI>0.6) had a greater likelihood of developing a fragmented soil structure with small, round aggregates, likely due to the impact of active roots on the soil surface. These results were obtained under such conditions, characterized by high ISI and, notably, high IAI. As a result, selected sites from the identified CSs did not exhibit severe soil quality degradation (Table 7).

When analyzing soil properties independently (Table 9), fertility indicators show significant differences in favor of ROT-PC, even though they didn’t differ significantly in crop intensification (Rubio et al., 2022) or tillage intensity (García-Préchac et al., 2004; Ernst and Siri-Prieto, 2009) from continuous CSs. When the combined effect of the *minimum data set* is considered (Fig. 4), it allows discrimination within continuous CSs.

In Uruguayan current context of CSs intensification, soil quality differences, result from the degree of diversification in the agricultural sequence. This concept represents what we define as "agricultural pathways," which lead to "soil quality pathways". Our findings provide new evidence on the benefits of diversifying CSs for agricultural sustainability, with a focus on valuing soil quality as a production resource (Table 9 and Fig. 4). This trajectory confirms that there is a loss in fertility and nutrient availability even in CSs with ISI > 0.9 and IAI > 1.3. These losses are a function of the degree of diversification in CS (CC_Soybean > CC_Corn > ROT-PC). CSs that tend toward simplification, resulting from reduced crop diversity (Novelli et al., 2011) and the elimination of pastures from the rotation (Ernst et al., 2018), experience a gradual decline in soil quality. This decline is associated with a reduced capacity to supply nutrients from soil (Ernst et al., 2020) and less efficient resource utilization (Foley et al., 2005). Therefore, these CSs are less stable and resilient (Sanford et al., 2021), and more susceptible to climatic variability, leading to increased issues with weeds, pests and diseases, increased input dependency and potential negative environmental impacts (Nicholls et al., 2022).

Under ROT-PC, superior soil quality is expected compared to continuous CSs (García-Préchac et al., 2004; Ernst et al., 2018; Sanford et al., 2021), due to increased biomass input (Baethgen et al., 2021) and higher microbial activity associated with extended periods of active vegetative growth (Acosta-Martínez et al., 2010; Rubio et al., 2022). Achieving these results in continuous CSs requires maximizing the intensity of use of environmental resources through highly intensive soil use (Rubio et al., 2022) and rotating with species that allow efficient resource use (Ernst et al., 2020). While our study categorized the degree of diversification into CS groups, results suggest that a trajectory in soil quality is generated. This is reflected in the fact that some sites identified as CC_Corn had intermediate values, similar to ROT-PC and CC_Soybean (Fig. 4). Similarities in soil quality resulting from sites identified with different CSs can be attributed to a combination of variables, including: i) the production and return of biomass from a sequence, which defines the carbon balance of the system (Domínguez et al., 2009); ii) differences in the quality of residues (e.g., C/N ratio) (Mazzilli et al., 2015) from specific crop sequence at each site, and iii) the lack of knowledge regarding land use prior to 2010.

Within the CC_Corn group, sites were grouped based on whether they rotated with corn every 2 years (SSbCF = 0.5) or every 4 years (SSbCF = 0.8). Consequently, CC_Corn sequences that achieved SSbCF = 0.5 and maintained a high soil use intensity could be associated with sites where soil quality similar to ROT-PC was observed. Conversely, sites with a higher frequency of soybean led to a trajectory in soil quality similar to sites identified as CC_Soybean. This concept aligns with the idea proposed by Novelli et al. (2011), where soil quality is negatively affected as the frequency of soybean increases due to a reduction in annual residue input and rapid decomposition.

Various authors have mentioned strategies such as tillage methods, crop diversification, and organic fertilization as tools capable of significantly improving soil quality (Tamburini et al., 2020). However, only diversification has consistently shown a positive relationship with increased crop yields (Tamburini et al., 2020). Rotations of annual and perennial crop species can support soil biological communities by increasing the quantity, quality and chemical diversity of residues, with positive effects on organic matter and soil fertility (Tiemann et al., 2015). These rotations are based on the existence of a dynamic balance, which, if it exists, is for a limited time. Therefore, maintaining diversity is a key element for the stability and resilience of CSs (Sanford et al., 2021).

The semi-annual records of land use history offer a reliable trajectory for identifying the three CSs, thus establishing a reliable trajectory in soil quality (Fig. 4). Furthermore, with only the chemical and physical properties of the soil at our disposal, we could distinguish poorly diversified CS (CC_Soybean) from other diversification strategies with a 25% error rate. However, overall, the predictive power of soil properties was low (Table 10). A more comprehensive understanding would require knowledge of the initial soil properties and historical land use. This would help discern from which CS the results were obtained and provide additional insights.

2.7. CONCLUSIONS

Our study supports the hypothesis that: i) the diversity of CSs generates different soil quality trajectories, which can be quantified using soil properties such as organic carbon, electrical conductivity and soil potassium availability; and ii) maintain high active plant growth periods and diversify the type of plant growth is necessary for maintaining soil fertility. This was confirmed through the PCR and SSbCF indicators, which quantified the importance of incorporating pastures and C_4 photosynthesis species into the rotation, always in high IAI and ISI CSs.

Preserving soil quality is crucial for an efficient use of resources and, consequently, to reduce environmental impact. Therefore, being able to predict the trajectory of soil quality through simple and interpretable indicators constructed from bi-annual land use records is a significant contribution to the development of sustainable CS strategies.

Future analyses should incorporate historical productivity records of CSs, simulation models, or the use of satellite imagery for better soil quality trajectory prediction.

2.8. DECLARATION OF COMPETING INTERESTS

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Oswaldo Ernst reports financial support, administrative support, article publishing charges, equipment, drugs or supplies, travel, and writing assistance were provided by National Agency for Research and Innovation (ANII). Other authors, declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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2.10. APPENDIX

Table 1A

Nro.	TC	CPR	YC	IAI	ISI	TSC	SSbCF	GWC	LWC	BWC	GSC	LSC	PP	Fallow
1	5.86	0.37	5.10	1.16	0.98	5.25	0.60	0.01	0.00	0.03	0.17	0.23	0.14	0.02
2	8.00	0.25	5.00	1.60	0.92	5.00	1.00	0.15	0.00	0.00	0.00	0.38	0.23	0.08
3	7.98	0.00	6.00	1.33	0.87	6.00	0.73	0.08	0.00	0.04	0.10	0.26	0.00	0.10
4	6.63	0.33	5.05	1.31	0.98	5.30	0.56	0.06	0.00	0.03	0.16	0.20	0.13	0.01
5	5.58	0.17	5.58	1.00	0.96	5.58	0.71	0.00	0.00	0.00	0.12	0.38	0.00	0.04
6	8.41	0.08	5.73	1.47	0.88	5.73	0.76	0.15	0.00	0.00	0.07	0.27	0.03	0.09
7	7.07	0.62	4.69	1.47	0.95	4.69	0.86	0.14	0.00	0.02	0.06	0.29	0.19	0.05
8	7.71	0.00	6.00	1.29	0.98	6.00	1.00	0.06	0.00	0.00	0.00	0.19	0.00	0.01
9	6.55	0.22	5.27	1.26	0.96	5.31	0.99	0.06	0.00	0.02	0.01	0.41	0.08	0.03
10	7.08	0.00	6.00	1.18	0.76	6.03	0.67	0.05	0.00	0.03	0.14	0.28	0.00	0.20
11	6.97	0.92	4.09	1.70	0.91	3.92	0.86	0.19	0.00	0.02	0.03	0.18	0.37	0.07
12	4.27	1.84	2.91	1.52	0.87	2.56	0.88	0.07	0.00	0.05	0.02	0.17	0.45	0.11
13	5.54	1.05	3.27	1.69	1.00	3.77	1.00	0.08	0.00	0.00	0.00	0.16	0.59	0.00
14	8.09	0.15	5.67	1.43	0.92	5.63	0.93	0.17	0.00	0.00	0.03	0.37	0.04	0.06
15	6.41	0.04	4.48	1.41	0.83	4.34	0.93	0.14	0.00	0.00	0.03	0.25	0.01	0.07
16	4.56	2.29	2.39	1.93	0.99	2.54	1.00	0.08	0.00	0.00	0.00	0.11	0.39	0.01
17	5.15	1.05	3.61	1.48	1.00	3.88	0.95	0.06	0.00	0.01	0.01	0.22	0.29	0.00
18	5.06	1.27	2.88	1.77	0.99	3.12	0.93	0.07	0.00	0.07	0.01	0.22	0.43	0.01
19	6.13	0.52	4.91	1.30	0.72	3.63	0.76	0.13	0.00	0.00	0.05	0.14	0.11	0.17
20	7.17	0.49	5.22	1.37	0.95	5.18	0.89	0.12	0.00	0.01	0.02	0.31	0.14	0.04
21	6.88	1.06	4.35	1.61	0.96	4.40	0.72	0.08	0.00	0.02	0.03	0.14	0.22	0.02
22	8.37	0.00	6.00	1.39	0.87	6.00	0.51	0.02	0.00	0.03	0.07	0.07	0.00	0.04
23	10.00	0.00	6.00	1.67	1.00	6.00	0.83	0.17	0.00	0.17	0.08	0.42	0.00	0.00
24	9.00	0.00	6.00	1.50	0.92	6.00	1.00	0.11	0.00	0.06	0.00	0.34	0.01	0.06
25	9.00	0.00	6.00	1.50	0.92	6.00	0.83	0.19	0.00	0.00	0.06	0.32	0.00	0.06
26	7.78	0.13	5.74	1.37	0.86	5.67	0.78	0.12	0.00	0.01	0.07	0.29	0.06	0.11
27	4.19	1.95	2.58	1.65	0.96	2.81	0.83	0.08	0.00	0.00	0.02	0.16	0.48	0.03
28	6.41	0.35	5.09	1.29	0.92	5.09	1.00	0.05	0.00	0.00	0.00	0.19	0.07	0.04
29	6.40	0.49	4.76	1.35	0.85	4.85	0.85	0.09	0.00	0.01	0.05	0.26	0.19	0.11
30	8.16	0.00	6.00	1.36	0.96	6.00	0.65	0.15	0.00	0.00	0.15	0.28	0.02	0.04
31	5.39	1.27	3.85	1.38	0.92	3.98	1.00	0.08	0.08	0.00	0.00	0.85	0.29	0.06
32	7.42	0.00	6.00	1.24	0.91	6.00	0.67	0.07	0.00	0.00	0.10	0.21	0.00	0.06
33	7.10	0.04	5.88	1.21	0.85	5.92	0.61	0.06	0.00	0.00	0.12	0.19	0.01	0.10
34	9.42	0.00	6.00	1.57	0.97	6.00	0.80	0.20	0.00	0.09	0.10	0.40	0.00	0.03
35	6.44	0.62	5.06	1.26	0.92	4.03	0.92	0.06	0.04	0.01	0.01	0.17	0.16	0.04
36	6.43	0.89	3.94	1.61	1.00	3.94	0.90	0.12	0.01	0.08	0.02	0.30	0.33	0.00
37	7.39	0.40	4.87	1.53	0.87	4.21	0.62	0.11	0.02	0.02	0.07	0.22	0.09	0.06
38	3.82	1.84	3.11	1.25	0.94	3.27	0.95	0.02	0.01	0.00	0.05	0.19	0.38	0.05
39	8.25	0.23	5.26	1.57	0.87	4.80	0.86	0.21	0.00	0.04	0.05	0.22	0.13	0.08
40	5.95	0.88	3.47	1.71	0.92	2.95	1.00	0.24	0.00	0.09	0.00	0.21	0.43	0.03
41	5.87	0.40	4.93	1.19	0.96	4.93	0.96	0.05	0.00	0.00	0.01	0.27	0.12	0.03
42	5.23	1.40	3.32	1.55	1.00	3.42	0.79	0.05	0.01	0.04	0.04	0.15	0.27	0.00
43	5.57	0.89	4.11	1.35	0.91	4.10	0.64	0.03	0.04	0.00	0.09	0.14	0.33	0.06
44	7.08	0.40	5.09	1.38	0.86	5.19	0.95	0.08	0.00	0.01	0.01	0.24	0.11	0.08
45	7.17	0.54	4.74	1.57	0.88	4.67	0.82	0.16	0.00	0.01	0.06	0.25	0.22	0.10

Land use indicator values per field.

Table 2A

	2011		2012		2013		2014		2015		2016		2017		2018
Sitio	inv	ver	inv	ver	inv	ver	inv	ver	inv	ver	inv	Ver	inv	ver	inv
1	Tg	Sj2	BQ	Sg1	BQ	Sj1	Tg	Sj2	BQ	Sg1	BQ	Sj1	Ceb	Sj2	BQ
2	Tg	Sj2	Can	Sj2	Tg	Mz2	CSG	Sj1	Can	Sj2	Tg	Sj2	Can	Sj2	Tg
3	Tg	Sj2	Can	Sj2	Tg	Mz2	CSG	Sj1	Can	Sj2	Tg	Sj2	Can	Sj2	Tg
4	Tg	Sj2	Can	Sj2	Tg	Mz2	CSG	Sj1	Can	Sj2	Tg	Sj2	Can	Sj2	Tg
5	Tg	Mz2	CSG	Sj1	Tg	Sj2	CSG	Sj1	Tg	Mz2	CSG	Sj1	Can	Sj2	Av
6	Tg	Mz2	CSG	Sj1	Tg	Sj2	CSG	Sj1	Tg	Mz2	CSG	Sj1	Can	Sj2	Av
7	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Ceb
8	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Ceb
9	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Ceb
10	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Rg	Sj2	CSG
12	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Rg	Sj2	CSG
12	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Rg	Sj2	CSG
13	PP	PP	PP	PP	BQ	Sj1	BQ	Mz1	CSG	Sj1	BQ	Mz1	CSG	Sj1	CSG
14	PP	PP	PP	PP	BQ	Sj1	BQ	Mz1	CSG	Sj1	BQ	Mz1	CSG	Sj1	CSG
15	PP	PP	PP	PP	BQ	Mz1	CSG	Sj1	Ceb	Sj2	BQ	Mz1	CSG	Sj1	BQ
16	PP	PP	PP	PP	BQ	Mz1	CSG	Sj1	Ceb	Sj2	BQ	Mz1	CSG	Sj1	BQ
17	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Rg	Sj2	CSG
18	CSG	Sj1	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	Ceb
19	CSG	Sj1	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	Ceb
20	Tg	Sj2	Ceb	Sg2	BQ	Sj1	Tg	Sj2	PP	PP	PP	PP	PP	Sj1	Tg
21	Tg	Sj2	Ceb	Sg2	BQ	Sj1	Tg	Sj2	PP	PP	PP	PP	PP	Sj1	Tg
22	PP	PP	PP	PP	CSG	Sj1	CSG	Mz1	CSG	Sj1	CSG	Mz1	CSL	Sj1	CSG
23	PP	PP	PP	PP	CSG	Sj1	CSG	Mz1	CSG	Sj1	CSG	Mz1	CSL	Sj1	CSG
24	PP	PP	PP	PP	CSG	Sj1	CSG	Mz1	CSG	Sj1	CSG	Mz1	CSL	Sj1	CSG
25	PP	PP	PP	PP	CSG	Sj1	CSG	Mz1	CSG	Sj1	CSG	Mz1	CSL	Sj1	CSG
26	PP	PP	PP	PP	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG
27	BQ	Sj1	Ceb	Sj2	BQ	Sg1	BQ	Sj1	Tg	Sj2	BQ	Sj1	Tg	Sj2	Can
28	BQ	Sj1	Ceb	Sj2	BQ	Sg1	BQ	Sj1	Tg	Sj2	BQ	Sj1	Tg	Sj2	Can
29	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Rg	Sj2	CSG
30	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg	Sj2	CSG	Sj1	Rg	Sj2	CSG
31	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg
31	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	Tg
32	Tg	Sj2	CSG	Sj1	CSG	Sj1	Tg	Sj2	CSG	Sj1	CSG	Sj1	Tg	Sj2	CSG
33	CSG	Sj1	Tg	Sj2	Av	Sj2	CSG	Sj1	Tg	Sj2	Av	Sj2	CSG	Sj1	CSG
34	CSG	Sj1	Tg	Sj2	Av	Sj2	CSG	Sj1	Tg	Sj2	Av	Sj2	CSG	Sj1	CSG
35	Tg	Sj2	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG
36	Tg	Sj2	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG
37	CSG	Sj1	Tg	Sj2	CSG	Sj1	CSG	Sj1	Tg	Sj2	CSG	Sj1	CSG	Sj1	CSG
38	Tg	Sj2	CSG	Sj1	CSG	Sj1	Tg	Sj2	CSG	Sj1	CSG	Sj1	Can	Sj2	Tg
39	Tg	Sj2	CSG	Sj1	CSG	Sj1	Tg	Sj2	CSG	Sj1	CSG	Sj1	Can	Sj2	Tg
40	CSG	Sj1	CSL	Mz1	CSG	Sj1	CSL	Mz1	CSG	Sj1	Ceb	PP	PP	PP	PP
41	CSG	Sj1	CSL	Mz1	CSG	Sj1	CSL	Mz1	CSG	Sj1	Ceb	PP	PP	PP	PP
42	CSG	Sj1	CSL	Mz1	CSG	Sj1	CSL	Mz1	CSG	Sj1	Ceb	PP	PP	PP	PP
43	BQ	Sj1	Tg	Sj2	PP	PP	PP	PP	PP	PP	PP	PP	PP	Sj1	Ceb
44	Tg	Sg2	BQ	Sj1	Tg	Sj2	Ceb	Sj2	PP	PP	PP	PP	PP	Sj1	Tg
45	Tg	Sg2	BQ	Sj1	Tg	Sj2	Ceb	Sj2	PP	PP	PP	PP	PP	Sj1	Tg
46	Tg	Sg2	BQ	Sj1	Tg	Sj2	Ceb	Sj2	PP	PP	PP	PP	PP	Sj1	Tg
47	PP	PP	PP	PP	BQ	Sj1	BQ	Sj1	BQ	Mz1	CSG	Sj1	BQ	Sj1	BQ
48	PP	PP	PP	PP	PP	PP	PP	PP	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG
49	PP	PP	PP	PP	PP	PP	PP	PP	CSG	Sj1	CSG	Sj1	CSG	Sj1	CSG
50	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	CSG	Sj1	Rg	Sj2	CSG
51	PP	PP	PP	PP	PP	PP	PP	PP	BQ	Sj1	CSG	Sj1	Rg	Sj2	CSG
52	Tg	Sj2	BQ	Mz1	BQ	Sj1	Tg	Sj2	BQ	Mz1	Av	Sj2	BQ	Mz1	CSG
53	BQ	Sj1	Tg	Sj2	BQ	Mz1	CSG	Sj1	Ceb	Sj2	BQ	Mz1	CSG	Sj1	CSG
54	BQ	Sj1	Tg	Sj2	BQ	Mz1	CSG	Sj1	Ceb	Sj2	BQ	Mz1	CSG	Sj1	CSG
55	BQ	Sj1	Tg	Sj2	BQ	Mz1	Tg	Sj2	BQ	Mz1	CSG	Sj1	Ceb	Sj2	BQ
56	BQ	Sj1	Tg	Sj2	BQ	Mz1	CSG	Sj1	Ceb	Sj2	BQ	Mz1	CSG	Sj1	CSG
57	Tg	Sj2	Tg	Sj2	BQ	Mz1	CSG	Sj1	CSG	Sj1	CSG	Mz1	CSG	Sj1	CSG
58	BQ	Sj1	Tg	Sj2	BQ	Mz1	BQ	Mz1	CSG	Sj1	Tg	Sj2	BQ	Mz1	CSG
59	BQ	Sg1	BQ	Sj1	CSG	Sj1	Tg	Sj2	BQ	Sg1	BQ	Sj1	PP	PP	PP
60	BQ	Sj1	Tg	Sj2	Ceb	Sj2	Tg	Sj2	BQ	Mz1	CSG	Sj1	CSG	Sj1	CSG
61	BQ	Sj1	Tg	Sj2	Ceb	Sj2	Tg	Sj2	BQ	Mz1	CSG	Sj1	CSG	Sj1	CSG
62	BQ	Mz1	CSG	Sj1	Tg	Sj2	BQ	Mz1	CSG	Mz1	CSG	Sj1	Can	Sj2	CSG
63	BQ	Mz1	CSG	Sj1	Tg	Sj2	BQ	Mz1	CSG	Mz1	CSG	Sj1	Ceb	Sj2	CSG
64	BQ	Sj1	Tg	Sj2	BQ	Mz1	Tg	Sj2	BQ	Mz1	CSG	Sj1	Ceb	Sj2	BQ

Land use during the period 2011-2018. Summer 2018 and winter 2019 are shown in Table 3a as the previous crop for summer and winter, respectively.

Sj1: Soybean only crop; Sj2: soybean double crop; Mz1: Corn only crop; Mz2: Corn double crop; Tg: Wheat; Ceb: Barley; Av: Oat; Can: Canola; Rg: Ryegrass; CSG: Grass cover crop; CSL: Legume cover crop; BQ: Fallow; PP: Perennial pasture.

Table 3A

Site	Summer precrop	Winter precrop	IAI	YCC	SSbCF	Cropping System	Irrigated	Topography	Soil type
1	Mz1	CSG	1.3	9	0.7	CC_Corn	0	Hillside	T. Argiudoll
2	Mz2	CSG	1.8	9	0.8	CC_Corn	0	Hillside	T. Argiudoll
3	Mz2	CSG	1.8	9	0.8	CC_Corn	0	Hillside	T. Argiudoll
4	Mz2	CSG	1.8	9	0.8	CC_Corn	0	Low	T. Argiudoll
5	Mz2	CSG	1.6	9	0.7	CC_Corn	0	Hillside	T. Argiudoll
6	Mz2	CSG	1.6	9	0.7	CC_Corn	0	Low	T. Argiudoll
7	Mz2	BQ	1.4	5	0.8	ROT-PC	0	Hillside	T. Argiudoll
8	Mz2	BQ	1.4	5	0.8	ROT-PC	0	High	T. Argiudoll
9	Mz2	BQ	1.4	5	0.8	ROT-PC	0	Low	T. Argiudoll
10	Sj1	CSG	1.4	6	1.0	CC_Soybean	0	High	T. Argiudoll
12	Sj1	CSG	1.4	6	1.0	CC_Soybean	0	Hillside	T. Argiudoll
12	Sj1	CSG	1.4	6	1.0	CC_Soybean	0	Low	T. Argiudoll
13	Mz1	CSG	1.0	8	0.6	CC_Corn	1	Low	T. Argiudoll
14	Mz1	CSG	1.0	8	0.6	CC_Corn	0	Low	T. Argiudoll
15	Mz1	CSG	1.1	8	0.6	CC_Corn	0	Low	T. Argiudoll
16	Mz1	CSG	1.1	8	0.6	CC_Corn	0	Low	T. Argiudoll
17	Sj1	CSG	1.4	6	1.0	CC_Soybean	0	High	T. Argiudoll
18	Sj2	CSG	1.3	3	1.0	ROT-PC	0	Hillside	T. Argiudoll
19	Sj2	CSG	1.3	3	1.0	ROT-PC	0	Low	T. Argiudoll
20	Sj2	CSG	1.7	3	0.9	ROT-PC	0	High	T. Argiudoll
21	Sj2	CSG	1.7	3	0.9	ROT-PC	0	Hillside	T. Argiudoll
22	Mz1	CSL	1.0	7	0.6	CC_Corn	0	Hillside	V. Argiudoll
23	Mz1	CSL	1.0	7	0.6	CC_Corn	0	Low	V. Argiudoll
24	Mz1	CSL	1.0	7	0.6	CC_Corn	0	High	V. Argiudoll
25	Mz1	CSL	1.0	7	0.6	CC_Corn	1	High	V. Argiudoll
26	Sj1	CSG	1.0	5	1.0	CC_Soybean	0	Hillside	V. Argiudoll
27	Sj2	CSG	1.5	9	0.9	CC_Soybean	0	Hillside	T. Argiudoll
28	Sj2	CSG	1.5	9	0.9	CC_Soybean	0	Hillside	T. Argiudoll
29	Sj1	CSG	1.4	6	1.0	CC_Soybean	0	High	T. Argiudoll
30	Sj1	CSG	1.4	6	1.0	CC_Soybean	0	Hillside	T. Argiudoll
31	Sj2	CSG	1.3	3	1.0	ROT-PC	0	Hillside	V. Argiudoll
31	Sj2	CSG	1.3	3	1.0	ROT-PC	0	Low	V. Argiudoll
32	Sj1	CSG	1.2	9	1.0	CC_Soybean	0	High	V. Argiudoll
33	Sj1	CSG	1.4	9	1.0	CC_Soybean	0	High	V. Argiudoll
34	Sj1	CSG	1.4	9	1.0	CC_Soybean	0	Hillside	V. Argiudoll
35	Sj1	CSG	1.0	9	1.0	CC_Soybean	0	High	V. Argiudoll
36	Sj1	CSG	1.0	9	1.0	CC_Soybean	0	Hillside	V. Argiudoll
37	Sj1	CSG	1.2	9	1.0	CC_Soybean	0	High	T. Argiudoll
38	Sj2	CSG	1.4	9	1.0	CC_Soybean	0	Hillside	V. Argiudoll
39	Sj2	CSG	1.4	9	1.0	CC_Soybean	0	Low	V. Argiudoll
40	PP	BQ	1.2	1	1.0	ROT-PC	1	High	V. Argiudoll
41	PP	BQ	1.2	1	1.0	ROT-PC	1	Hillside	V. Argiudoll
42	PP	BQ	1.2	1	1.0	ROT-PC	0	Low	V. Argiudoll
43	Sj2	CSG	1.6	3	1.0	ROT-PC	0	Hillside	T. Argiudoll
44	Sj2	CSG	1.7	3	0.9	ROT-PC	0	High	V. Argiudoll
45	Sj2	CSG	1.7	3	0.9	ROT-PC	0	Hillside	V. Argiudoll
46	Sj2	CSG	1.7	3	0.9	ROT-PC	0	Low	V. Argiudoll
47	Sj1	BQ	1.0	8	0.9	CC_Soybean	0	Low	V. Argiudoll
48	Sj1	CSG	1.0	5	1.0	ROT-PC	0	Hillside	T. Argiudoll
49	Sj1	CSG	1.0	5	1.0	ROT-PC	0	Low	V. Argiudoll
50	Sj1	CSG	1.2	5	1.0	CC_Soybean	0	High	T. Argiudoll
51	Sj1	CSG	1.2	5	1.0	CC_Soybean	0	High	T. Argiudoll
52	Sg1	BQ	1.3	9	0.6	CC_Corn	0	High	T. Argiudoll
53	Mz1	CSG	1.2	9	0.7	CC_Corn	0	High	T. Argiudoll
54	Mz1	CSG	1.2	9	0.7	CC_Corn	1	High	T. Argiudoll
55	Mz1	CSL	1.3	9	0.7	CC_Corn	1	High	T. Argiudoll
56	Mz1	CSG	1.2	9	0.7	CC_Corn	0	Hillside	T. Argiudoll
57	Mz1	CSG	1.2	9	0.7	CC_Corn	0	Low	T. Argiudoll
58	Sg1	BQ	1.2	9	0.6	CC_Corn	1	Low	T. Argiudoll
59	Sg1	BQ	1.2	2	0.6	ROT-PC	0	High	T. Argiudoll
60	Mz1	CSL	1.3	9	0.8	CC_Corn	1	High	T. Argiudoll
61	Mz1	CSL	1.3	9	0.8	CC_Corn	0	High	T. Argiudoll
62	Mz1	CSG	1.2	9	0.6	CC_Corn	1	High	T. Argiudoll
63	Mz1	CSG	1.2	9	0.6	CC_Corn	0	Hillside	T. Argiudoll
64	Mz1	CSL	1.3	9	0.7	CC_Corn	0	High	T. Argiudoll

Characteristics and land use indicators of the surveyed sites. V= Vertic; T= Typic.

Table 4A

Variables	PC 1	PC 2	PC 3	PC 4	PC 5
TA_{0-15}	-0.24	**0.94**	0.01	0.16	0.00
$TA_{0-7.5}$	-0.17	0.90	0.06	0.09	0.14
$TA_{7.5-15}$	-0.30	0.86	-0.05	0.21	-0.13
SB_{0-15}	0.74	-0.43	0.02	-0.13	-0.04
$SB_{0-7.5}$	0.74	-0.46	0.03	-0.07	-0.10
$SB_{7.5-15}$	0.63	-0.41	0.20	-0.15	-0.03
TB_{0-15}	0.97	0.07	0.16	0.06	-0.07
$TB_{0-7.5}$	0.97	0.06	0.14	0.02	-0.05
$TB_{7.5-15}$	0.94	0.07	0.17	0.10	-0.09
Ca_{0-15}	0.97	0.02	0.14	0.15	-0.04
$Ca_{0-7.5}$	0.96	0.01	0.13	0.12	-0.03
$Ca_{7.5-15}$	0.93	0.03	0.13	0.17	-0.05
EC_{0-15}	**0.69**	-0.09	-0.28	-0.16	**0.45**
$EC_{0-7.5}$	0.52	-0.04	-0.19	-0.18	0.54
$EC_{7.5-15}$	0.76	-0.15	-0.36	-0.06	0.14
ECa_{0-10}	**0.79**	-0.11	0.40	0.12	0.23
ECa_{10-20}	0.77	-0.17	0.42	0.12	0.13
ECa_{20-30}	0.64	-0.05	0.54	0.01	0.02
CEC_{0-15}	0.94	0.27	0.16	0.09	-0.07
$CEC_{0-7.5}$	0.93	0.27	0.15	0.04	-0.01
$CEC_{7.5-15}$	0.90	0.25	0.16	0.14	-0.12
K_{0-15}	0.57	0.14	**-0.65**	-0.12	-0.27
$K_{0-7.5}$	0.55	0.14	-0.66	-0.16	-0.17
$K_{7.5-15}$	0.54	0.10	-0.62	-0.08	-0.37
Mg_{0-15}	0.30	0.32	0.67	-0.45	-0.12
$Mg_{0-7.5}$	0.43	0.33	0.60	-0.45	-0.06
$Mg_{7.5-15}$	0.14	0.29	**0.71**	-0.41	-0.15
Na_{0-15}	0.08	0.24	0.08	-0.58	-0.15
$Na_{0-7.5}$	0.04	0.14	0.01	**-0.56**	0.02
$Na_{7.5-15}$	0.04	0.18	0.11	-0.39	-0.24
P_{0-15}	0.46	0.26	-0.38	-0.47	**0.50**
$P_{0-7.5}$	0.40	0.23	-0.25	-0.47	0.62
$P_{7.5-15}$	0.43	0.25	-0.53	-0.35	0.11
pH_{0-15}	0.63	-0.69	-0.10	0.05	-0.08
$pH_{0-7.5}$	0.56	-0.62	-0.16	0.18	-0.23
$pH_{7.5-15}$	0.59	-0.68	-0.02	-0.03	0.09
$PMN_{0-7.5}$	0.34	0.04	-0.45	-0.19	-0.15
$PR_{7.5-15}$	0.39	0.30	-0.04	**0.55**	0.20
PR_{15-30}	0.48	-0.05	-0.03	0.61	0.20
PR_{30-45}	0.22	0.38	-0.02	0.56	0.21
SOC_{0-15}	**0.65**	**0.65**	-0.18	0.09	-0.11
$SOC_{0-7.5}$	0.67	0.58	-0.22	0.02	-0.08
$SOC_{7.5-15}$	0.59	0.68	-0.10	0.14	-0.14
SWC_A	0.24	0.04	-0.39	0.15	-0.21
CMWD	0.21	-0.02	-0.13	-0.21	-0.25
INF	0.30	-0.10	-0.22	-0.04	-0.40
Variance (λ)	17.5	6.7	4.7	3.5	2.2

Proportion of variance (%)	38	15	10	8	5
Cumulative proportion (%)	38	53	63	70	75

Correlation with principal components (PCs), variance and percentage of total and cumulative variance explained by the first 5 PCs in the principal component analysis of the surveyed soil variables. Bold values indicate the selected soil property for the corresponding principal component.

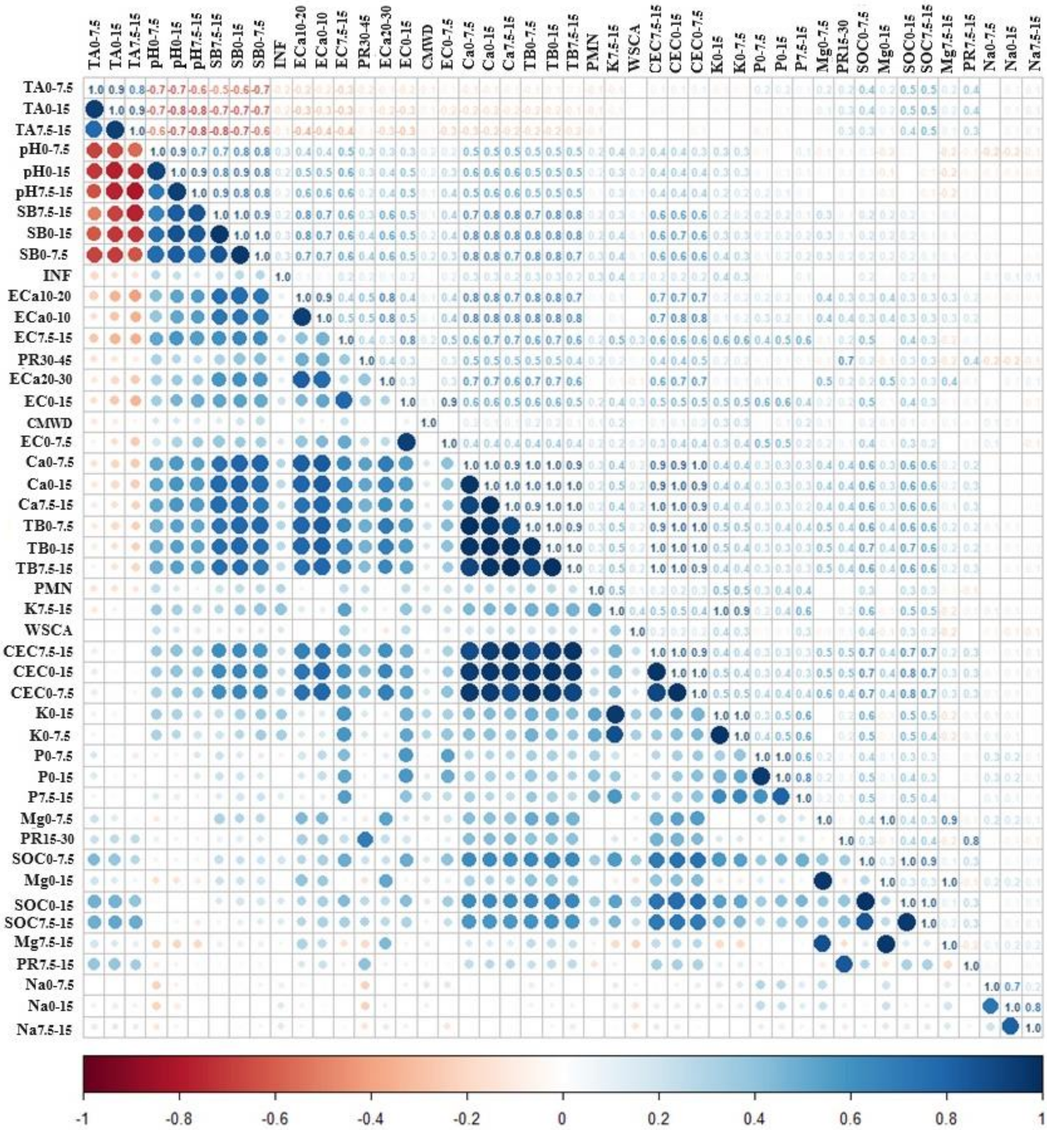

Fig. 1A. Correlation matrix of estimated coefficients for each variable combination. The visualization method is shown with circles on the left. The area of the circles represents the absolute value of the corresponding correlation coefficients. The values of the coefficients are displayed on the right. For both visualization methods, a colour gradient was applied for correlation: red (negative), white (no correlation) and blue (positive).

3. DIVERSIFIED CROPPING SYSTEMS REDUCE SOYBEAN YIELD GAP

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3.1. RESUMEN

El aumento en la superficie cultivada del litoral del Uruguay ocurrió en gran medida por la sustitución de sistemas de rotaciones de cultivos-pasturas por sistemas de cultivos (CS, sigla en inglés) anuales continuos con una alta frecuencia de soja. Se planteó la hipótesis de que el diseño del CS modifica la brecha de rendimiento explotable de soja (Yg^{Exp}), pudiendo ser explicada por cambios en la calidad del suelo y mejoras tecnológicas. Se propuso explicar Yg^{Exp} en suelos de buena capacidad de uso agrícola y sin problemas graves en el uso del suelo. El estudio se realizó a través de una red de 65 experimentos instalada en chacras representativas de los principales CSs implementados en la región. Cada experimento consideró dos manejos de nutrientes: (1) limitado por nutrientes, y (2) nutriente no limitante. El rendimiento actual (Ya) fue de 3,1 Mg ha^{-1}. Siguiendo la metodología desarrollada por Silva et al. (2017), se realizó un análisis de frontera estocástica de producción (SFPF) para calcular el rendimiento alcanzable (Yatt, 4,4 Mg ha^{-1}) y, a partir del percentil 90 del Yatt, se determinó el máximo rendimiento alcanzable (Ymax, 6,2 Mg ha^{-1}). La diferencia entre Ya e Ymax nos permitió determinar Yg^{Exp} (3,1 Mg ha^{-1}), mientras que Yatt nos permitió desagregar la Yg^{Exp} en una brecha de eficiencia (Yg^{Ef} = Yatt–Ya = 1,3 Mg ha^{-1}) y en una brecha atribuible a la diferencia en la disponibilidad de recursos (Yg^{Re} = Ymax–Yatt = 1,8 Mg ha^{-1}). Acoplando una función de ineficiencias a la SFPF, se encontró que la Yg^{Ef} estuvo parcialmente explicada por mejoras en el diseño del CS y el riego suplementario; mientras que la calidad del suelo, medida a través de la resistencia a la penetración del suelo, y mejoras tecnológicas, como aumentar el agua suministrada o un aumento de la fertilización en ambientes de alto nivel productivo, fueron identificados como determinantes de Yg^{Re}.

Palabras clave: brecha explotable, brecha de eficiencia, brecha por recursos, intensificación sostenible

3.2. SUMMARY

The increase in cultivated area of the eastern Pampas of South America has been achieved through the substitution of crop-pasture rotation systems with continuous annual cropping systems with a high frequency of soybean. We hypothesized that cropping system (CS) design modifies exploitable soybean yield gap (Yg^{Exp}), which could be explained by changes in soil quality and technological improvements. We aimed to explain Yg^{Exp} in soils with good agricultural suitability and without extreme land use constraints. The study was conducted through a network of 65 on-farm experiments established on commercial farms representative of the main CSs in the region. Each experiment considered two nutrient management approaches: (1) nutrient-limited, and (2) non-limiting nutrient. Average actual yield (Ya) was 3.1 Mg ha^{-1}. We use a stochastic frontier production analysis (SFPF) to calculate attainable yield (Yatt, 4.4 Mg ha^{-1}), and from 90th percentile of Yatt, we determined the maximum attainable yield (Ymax, 6.2 Mg ha^{-1}). The difference between Ya and Ymax allowed us to determine Yg^{Exp} (3.1 Mg ha^{-1}). While Yatt enabled us to disaggregate Yg^{Exp} into an efficiency yield gap (Yg^{Ef} = Yatt - Ya = 1.3 Mg ha^{-1}) and a yield gap attributable to differences in resource availability (Yg^{Re} = Ymax - Yatt = 1.7 Mg ha^{-1}). By incorporating an inefficiencies function into the SFPF, we found Yg^{Ef} was partially explained by improvements in farmer's crop system design and incorporation of supplementary irrigation. Soil quality, measured through soil penetration resistance, and technological improvements, such as increasing the amount of water supplied or enhancing fertilization in high-productive environments, were identified as determining factors of Yg^{Re}.

Keywords: exploitable yield gap, efficiency yield gap, resource yield gap, sustainable intensification

3.3. INTRODUCTION

The grasslands of Río de la Plata, a globally significant biome, are experiencing unprecedented land use alterations. This process involves expanding agricultural lands into former grasslands and natural pastures (Baeza and Paruelo, 2020). The shift from diversified cropping systems (CSs), rotating between annual crops and perennial pastures, to continuous CSs centered on soybean crops (Franzluebbers et al., 2014) has been supported by two modern agricultural paradigms: i) no-till practices improving soil quality (Peiretti and Dumanski, 2014) and ii) crop rotation enhancing crop yields (Tilman et al., 2002; Tamburini et al., 2020). However, dominant CS was limited only to implementation of the former, undermining fundamental tenets of sustainable agriculture intensification defined by Cassman et al. (1999).

Local and regional evidence suggests eliminating perennial pastures and reducing crop sequence diversification may gradually reduce soil quality, limit productivity and generate adverse environmental effects (García-Préchac et al., 2004; Aparicio and Costa, 2007; Ernst and Siri-Prieto, 2009; Bacigaluppo et al., 2011; Díaz-Zorita et al., 2014; Mazzilli et al., 2015; Beretta-Blanco et al., 2019; Mazzilli and Ernst, 2019; Ernst et al., 2016, 2018, 2020). While diversifying CSs could alleviate these issues, it poses a conflict between sustainable intensification goals and economic returns derived from reducing the area allocated to the most profitable crop in the rotation cycle (Garnett et al., 2013; Ernst et al., 2018). To resolve this conflict, quantifying the impact of CS design on the yield of the dominant crop in this region -soybean- is crucial.

Within Uruguay's agricultural west coastal area, there are still producers engaged in agriculture by rotating with pastures and, among those practicing continuous cropping, there are producers whose CS integrates different levels of crop diversity, all located on soils with similar agricultural capacity. This presents an opportunity to quantify the influence of CSs trajectories on soybean crop yield, despite it being a relatively recent primary crop in the region, thus lacking comprehensive medium-term data.

Identifying production strategies to enhance crop productivity requires two steps: (i) quantifying the yield gap, defined as the difference between a reference yield level and the current yield obtained at commercial field level (Ya), and (ii) understanding its causes to propose changes in CS management (van Ittersum and Rabbinge, 1997).

This study aims to quantify the impact of recent CSs trajectories of soybean yield gap. Three yield levels were considered: (i) Ya, obtained through in situ samplings; (ii) attainable yield (Yatt), achieved by producers employing best management practices, considering both potential yield factors and limiting factors (Fischer and Edmeades, 2010; Van Ittersum et al., 2013); and (iii) maximum attainable yield (Ymax), representing the maximum production level achievable with optimal resource utilization in the area. If database used for calculating Yatt includes the highest resource availability and the best technology available for the area, Ymax is a practical value to determine the margin producers have to increase crop yields.

The difference between Yatt and Ya, under the same resource availability, signifies the efficiency yield gap (Yg^{Ef}), highlighting variations in yield attributable to efficient resource utilization among producers (Silva et al., 2017). The fact that two producers achieve different yield levels with the same level of resources implies an inefficient management for the lower-yield producer. Inefficiencies could result from differences in crop management practices (Silva et al., 2017) and/or problems associated with CS design (Mazzilli et al., 2016). Moreover, differences between Ymax and Yatt, called yield gap attributable to resource allocation differences (Yg^{Re}), indicate additional yield limitations stemming from circumstantial, economic, or environmental factors (Silva et al., 2017). A Yg^{Re} greater than zero indicates that the farm cannot take advantage of the available resources in the best possible way and suggests limitations in the resources allocated for production. Adding both gaps generates the exploitable yield gap (Yg^{Exp}), conceptually equivalent to that defined by Cassman et al. (2003), quantified as 20% of the total yield gap.

Our hypothesis posits that soybean Yg^{Exp} can be explained by CS design and resource allocation. This study aims to elucidate these disparities in CS and quantify their impact on soybean yield gap.

3.4. MATERIALS AND METHODS

For the estimation of Yg^{Exp} along with its components, Yg^{Ef} and Yg^{Re}, a network of 65 experiments was established across representative farms, within three different CS identified from FUCREA and AUSID agricultural producer's database (refer to chapter 2.4 in this thesis). Analysis of this information was performed adapting the methodology outlined by Silva et al. (2017) for quantifying Yg^{Ef} and Yg^{Re} and identifying factors influencing crop yield.

3.4.1. Description of Study Area

The study area was situated in southwestern Uruguay within a 60 km radius from the coordinates -33.1722 latitude and -57.7969 longitude Uruguay's most influential agricultural area. The main soils in the region are Typic and Vertic Argiudolls (Baillie, 2001). Pre-experiment soil surveys indicated average soil organic carbon of 30.0 ± 6.4 g kg^{-1}, pH of 5.9 ± 0.4, cation exchange capacity of 25.5 ± 5.1 meq.100 g^{-1}, and 83 ± 5% base saturation within the 0 to 15 cm soil layer (Alvarez and Ernst, in this thesis). This region experiences a sub-humid mesothermic climate, receiving an average annual precipitation of approximately 1200 mm, with notable intra and interannual variations. Water deficits typically occur between November and March.

Agriculture predominantly relies on rainfed practices, allowing for two annual crops (winter and summer crops). Over the last decade, soybean crop covered about 80% of summer crop area, ranging between 0.9 and 1.3 million ha. Nearly half of the planted area comprises first-season soybeans while the remaining half follows a double annual crop sequence (MGAP-DIEA, 2020). No-tillage remains the standard practice (MGAP-DIEA, 2022). Land use strategies were classified in three groups: (i) CSs integrating perennial pastures for animal production (ROT-PC), prevalent until the early 21st century; (ii) continuous CS characterised by frequent soybean crop (CC_Soybean), the prevailing system; and (iii) continuous CS akin to CC_Soybean but exhibiting greater crop diversity, marked by a higher occurrence of corn and sorghum crops (CC_Corn) (Alvarez and Ernst, in this thesis).

National average soybean yield from 2010 to 2020 was 2.4 Mg ha^{-1}, with the country's yield potential reaching 6.6 Mg ha^{-1} and the water-limited potential at 3.6 Mg ha^{-1} (Rizzo et al., 2021). National data indicates a strong association between high yields (3.1 to 4.7 Mg ha^{-1}) and soils defined as prime agricultural land (González, 2013), primarily associated with increased water storage capacity (Rizzo et al., 2021).

3.4.2. Site Selection Criteria

Site selection prioritised Typical and Vertic Argiudolls (Baillie, 2001) and systems without soil management restrictions (no-tillage and high soil use intensity). Sites were chosen based on varying years under continuous cropping (YCC) and differences in frequency of soybeans in summer agricultural phase (SSbCF). This decision aligns with previous findings indicating rotation with pastures (García-Préchac et al., 2004; Ernst et al., 2018, 2020) and including C4 species at least once every four years to enhance crop yields (Gerster and Bacigaluppo, 2009; Díaz-Zorita et al., 2014; Mazzilli and Ernst, 2019).

Soybean crops were sown within the optimal dates, cultivars, and plant density for the region, according to local recommendations. All soybeans were sown following winter fallow or cover crops. The 65 selected sites had complete information on a minimum set of soil properties (Arshad and Martin, 2002), previously selected from multivariate analyses in this thesis to depict soil quality variations (chapter xx). To ensure a wide range of water availability, 10 out of the 65 selected sites were under supplementary irrigation.

3.4.3. Experiment Network Configuration

An experiment was installed in each site, experiments had two treatments with two replicates in 5 x 10 m plots. The treatments were defined as:

i) Nutrient-limited, where fertilization followed the current best management practices (García, 2005), defined by Fischer and Edmeades (2010), considering the economic response and risk;

ii) Non-limiting nutrient, adding to (i) non-limiting amounts of phosphorus (35 kg ha^{-1} of P), potassium (50 kg ha^{-1} of K), sulphur (30 kg ha^{-1} of S), calcium (260 kg ha^{-1} of CaO) and magnesium (130 kg ha^{-1} of MgO).

The experiments were meticulously managed to prevent any crop yield-reducing factors from weeds, diseases, or pests. Phenology was recorded *in situ* at 20, 40 and 90 days after sowing, utilising the scale devised by Fehr et al. (1971). Leveraging sowing dates, cultivars, field-recorded phenology, and a locally developed prediction model for soybean phenological stages (FENOsoja), the critical period determining the primary numerical yield component, grains m-2 (stages R4 to R6), was estimated.

3.4.4. Stochastic Frontier Analysis

A stochastic production frontier function (SFPF) model (Aigner et al., 1977) was employed to gauge and elucidate Yg^{Ef}. The SFPF provided Yatt, also known as technical efficiency yield (Silva et al., 2017), for each combination of different factors (environmental and inputs) defining and limiting soybean yield.

The SFPF included the simultaneous fitting of an inefficiency function. The deterministic components of the SFPF represent Yatt, while variables in the inefficiency function represent Yg^{Ef}. The model was estimated using the FRONTIER 4.1 software, employing maximum likelihood estimation to concurrently estimate the inefficiency effects (Coelli, 1996).

3.4.4.1. Used Database

SFPF and Yg^{Ef} (Eq. (1)) were estimated using a quantitative input-output database (climate - soil quality - fertilization management) – product (Ya). Ya was derived through manual harvesting of a 17.1 m^2 area, corrected to 0% moisture content, and utilised as the dependent variable (y, Mg ha-1). Independent variables (x) employed in the function (Eq. 1) were selected to assess factors defining and limiting soybean yield and are presented in Table 1.

The continuous *x* and *y* variables included in SFPF were logarithmically transformed before analysis. Used SFPF was specified as:

(Eq.1) Production frontier function:

$$\ln(Ya_i) = \beta 0 + \sum \beta_j \ln(X_{ji}) + V_i + u_i$$

Where Ya_i = actual yield (Mg ha^{-1}) of the i^{th} site (i = 1, 2, …, 74), β symbolises the coefficient to be estimated for each independent variable X_{ji}, V_i is the random error (mean = 0), and $ų_i$ is the inefficiency function (estimated $Yatt_i$ - Ya_i, only positive values) of each site. β_j is interpreted as the percentage response of Ya to a one percent increase in a particular input (j), and $ų_i$ as $Yg^{Ef}{}_i$.

The inefficiency function was explained using a second-stage multiple regression (Eq. 2) coupled with the SFPF following Battese and Coelli (1995) framework. The variables included in the inefficiency function underwent two stages: (i) forming a group of variables associated with land use and selection where soybean crops were seeded, and (ii) initially including all variables in the model, progressively eliminating no significant ($p \geq 0{,}05$) variables until a final run comprised only of variables significantly impacting the inefficiency function.

The initial group of variables is presented in table 1. The inefficiency function was structured as:

(Eq. 2) Inefficiency function:

$$ų_i = \delta 0 + \sum \delta_j \ \ln(X_{ji}) + W_i$$

Where $ų_i$ represents $Yg^{Ef}i$, δ_j denotes the parameter to be estimated for each independent variable X_{ji}, and W_i symbolises the random error to be estimated.

The efficiency of each Ya record is determined as the relationship between Ya and Yatt (Coelli et al., 2005):

(Eq. 3) Attainable yield calculation:

$$Yatt_i = \frac{Ya_i}{Efficiency_i}$$

Inclusion of variables describing land use (winter previous crop) or arising from it (YCC, SSbCF, or IAI) in the inefficiency function is based on: i) CS management decisions and ii) potential impacts on soil quality reflected in soil properties, thus influencing yield.

Table 1
Description of the variables used in the production frontier and inefficiency functions.

Variable	Description	Symbol	Unit	Performance level[1]	Metodology
Production frontier function					
Actual soybean yield	Continuos	Ya	Mg ha^{-1}	-	Manual harvest
Soybean sowing date	Continuos	Sowing date	DOY	Define	Producer records
Soybean cycle duration	Continuos	Cycle duration	DOY	Define	In-situ survey
Water supplied between R4-R6 stages	Continuos	Water_PC	mm	Limits	Producer records
Profile water storage capacity	Continuos	WSC	mm	Limits	(Fernández, 1979; Silva et al., 1988)
Fertilisation strategy	Dummy	Limitant, Non-limitant	#	Limits	Treatment
Organic carbon in soil 0-15 cm	Continuos	SOC_{0-15}	g kg^{-1}	Limits	(Nelson and Sommers, 1996)
Phosphorus Bray in soil 0-15 cm	Continuos	P_{0-15}	mg kg-^{1}	Limits	(Bray and Kurtz, 1945)
Electrical conductivity (1:2.5) in soil 0-15 cm	Continuos	EC_{0-15}	dS m^{-1}	Limits	(Chapman, 1965)
Exchangeable Mg^{+2} from 7.5 to 15 cm	Continuos	$Mg_{7.5-15}$	meq 100 g^{-1}	Limits	1 M acetate extraction
Exchangeable K^{+} from 0 to 15 cm	Continuos	K_{0-15}	meq 100 g^{-1}	Limits	1 M acetate extraction
Exchangeable Na^{+} from 0 to 15 cm	Continuos	Na_{0-15}	meq 100 g^{-1}	Limits	1 M acetate extraction
Titratable acidity at pH=7 in soil 0-15 cm	Continuos	TA_{0-15}	meq 100 g^{-1}	Limits	(Quiaggio and van Raij, 2001)
Apparent electrical conductivity from 10 to 20 cm	Continuos	ECa_{10-20}	mS cm^{-1}	Limits	Spectrum EC 110
Penetration resistance from 7.5 to 15 cm	Continuos	$PR_{7.5-15}$	kPa	Limits	FieldScout SC 900
Inefficiency function					
Summer previous crop	Dummy	C4 Species Soybean Pasture	#		Producer records
Winter previous crop	Dummy	Fallow CC[2] legume CC grass	#		Producer records
Intensity of agricultural phase index	Continuos	IAI	#		Producer records
Years under continuous cropping per soybean frequency in summer agricultural phase	Continuos	YCC*SSb CF	#		Producer records
Supplementary irrigation	Dummy	NO, YES	#		Producer records
Topography	Dummy	High Low Slope	#		Field survey

[1]van Ittersum and Rabbinge (1997); [2]CC = Cover crop

3.4.4.2. Analysis of Yield Gap attributable to Differences in Resource Availability

The Yg^{Re} signifies the variance between attainable field yield with available resources and the maximum attainable with optimal resource availability and use efficiency.

(4) Resource yield gap calculation:

$$Yg^{Re}{}_{i} = Ymax - Yatt_{i}$$

Ymax was calculated from the 90th percentile of Yatt, eliminating inefficiencies integrated into the 90th percentile of Ya. Therefore, our Ymax solely values the application of best management practices (maximum efficiency) in environments featuring optimal resource availability.

To explain Yg^{Re}, the minimum limit of Yatt (Ymin) was calculated as the 10th percentile of Yatt. A Mann-Whitney U test was performed to compare the percentiles associated with variables determining (radiation and temperature) and limiting (water and soil quality) soybean yield. These variables constituted the Ymax and Ymin groups.

3.4.4.3. Analysis of Exploitable Yield Gap according to Productive Level

To conduct a comprehensive analysis and observe the trajectory of Yg^{Exp} based on the current production level, the outcomes were grouped into three groups:

i) Superior Ya (Ysup), determined from the mean of 90th percentile of Ya;

ii) Medium Ya (Ymed), determined as the mean between 45th and 55th percentiles of Ya;

iii) Inferior Ya (Yinf), determined as the mean of 10th percentile of Ya.

For elucidating the differences among the drivers of yields gaps among production levels, Yg^{Exp} was dissected into Yg^{Re} and Yg^{Ef}. This division was rooted in the varying production levels. To associate the behavior of the different production groups with the availability of resources and the efficiency with which they were managed, percentiles were compared using the Mann-Whitney U test for quantitative variables and contingency tables of two factors (Chi^2) for dummy variables.

3.5. RESULTS

3.5.1. Description of the Study Season

Sowings occurred around November 12 (315 ± 7 DDA), falling within recommended optimal sowing window for first-cycle soybean crops in region. Crop cycle length remained consistent across all sites (139 ± 9 days). Due to the spatial variability of rainfall in the region and the presence of sites with supplemental irrigation, considerable variations were observed in water received throughout crop cycle (VE-R8), particularly during the critical period for yield determination (R4-R6). Soybean yield exhibited normal distribution, with a mean of 3.1 Mg ha^{-1} (Table 2).

Table 2.
Parameter details of variables defining and limiting soybean crop yield. Modified Shapiro-Wilks test (W*) for soybean yield in western coast of Uruguay for 2019-2020 season based on 128 recorded cases.

Variables	**Units**	**Mean**	**S.D.**	**C.V. (%)**	**W***	**p**
Daily solar radiation	MJ m^{-2} d^{-1}	21.4	1.4	6.3		
Mean temperature	ºC d^{-1}	21.2	0.3	1.3		
Sowing date (day of the year)	#	31.5	7	38.7		
Cycle length (day of the year)	#	13.9	9	6.8		
Water supplied between VE-R8	mm	501	164	32.7		
Water supplied between R4-R6	mm	112	53	47.3		
Actual soybean yield	Mg ha^{-1}	3.1	0.9	27.3	0.97	0.5

3.5.2. Soybean Production Frontier

Production frontier was primarily defined by the sowing date, significantly reducing within the evaluated range (24/10 to 30/11) with no effect from the cycle length of the cultivar. Both variables affected radiation and temperature during crop growth. Significant limitations to the production frontier were observed due to Water_PC, its interaction with nutrient supply, defined as fertilization strategy, subsurface soil compaction PR$_{7.5-15}$, apparent electrical conductivity (ECa$_{10-20}$), and the availability nutrient such as Mg and K ($p \leq 0.05$) (Table 3).

Table 3
Parameters of the stochastic frontier model for soybean cultivation in the surveyed cases. Significance codes: "": $p \leq 0.05$; "": $p \leq 0.01$; "": $p \leq 0.001$; "NS": $p > 0.1$.

Variables	Coefficient	Standard Error	p
Production frontier			
Intercept	12.03	1.02	***
Sowing date	-0.08	0.04	*
Cycle length	0.15	0.16	NS
Water supplied during R4-R6 (Water_PC)	0.14	0.07	*
Fertilisation strategy[1]	-0.38	0.17	*
Water_PC * fertilisation strategy[1]	0.08	0.04	*
Organic carbon in soil 0-15 cm (SOC_{0-15})	-0.10	0.13	NS
Electrical conductivity in soil 0-15 cm (EC_{0-15})	0.05	0.14	NS
Titratable acidity in soil 0-15 cm (TA_{0-15})	-0.01	0.07	NS
Phosphorus Bray in soil 0-15 cm (P_{0-15})	-0.01	0.05	NS
Exchangeable magnesium from 7.5 to 15 cm ($Mg_{7,5-15}$)	0.30	0.12	**
Exchangeable potassium from 0 to 15 cm (K_{0-15})	0.09	0.05	*
Exchangeable sodium from 0 to 15 cm (Na_{0-15})	-0.11	0.13	NS
Penetration resistance from 7.5 to 15 cm ($PR_{7.5-15}$)	-0.51	0.06	***
Apparent electrical conductivity from 10 to 20 cm (ECa_{10-20})	-0.25	0.06	***
Profile water storage capacity (WSC)	0.08	0.08	NS
Inefficiency effects			
Intercept	-0.31	0.15	*
Years under continuous cropping per soybean frequency in summer cropping phase (YCC*SSbCF)	0.37	0.09	***
Soybean as previous summer crop[1]	0.17	0.05	**
Pasture as previous summer crop[1]	0.70	0.22	***
Supplementary irrigation[1]	-0.43	0.21	*
Model evaluation			
σ^2	0.03	0.01	***
γ	1.00	0.01	***
Likelihood ratio	71.2		
n	128		
Mean efficiency	0.72		

[1] Dummy variable.

Regarding the inefficiency function, the gamma parameter was significantly different from zero ($p \leq 0.05$), indicating that technical inefficiencies affecting Ya were identified. The land use indicator YCC*SSbCF increased inefficiencies ($p \leq 0.05$). The higher the value of YCC*SSbCF, the lower the frequency of pastures and C4 photosynthesis species in CS. Soybean as previous crop and sowing after pasture increased inefficiencies compared to summer previous crops such as maize or sorghum (C4 photosynthesis species) ($p \leq 0.05$). Additional water supply through irrigation reduced inefficiencies ($p \leq 0.05$). The rest of the variables included in the inefficiency function were not significant ($p > 0.05$) and were subsequently removed (Table 6 in supplementary material).

3.5.3. Yield Gap attributed to Differences in Resource Availability

The Yatt was 4.4 ± 0.8 Mg ha^{-1}, and the best combination of resources with the most efficient use determined a Ymax of 6.2 Mg ha^{-1}. Consequently, Yg^{Re} was 1.8 ± 0.8 Mg ha^{-1}. A negative linear relationship ($p \leq 0.05$) existed between Yg^{Re} and Yatt (Fig. 1a). About 10% of the evaluated sites operated in environments with high resource availability (Yg^{Re} < 10%), while 50% operated in environments with Yg^{Re} greater than 30% (Fig. 1b). The Ymin was 3.4 Mg ha^{-1} (Table 4).

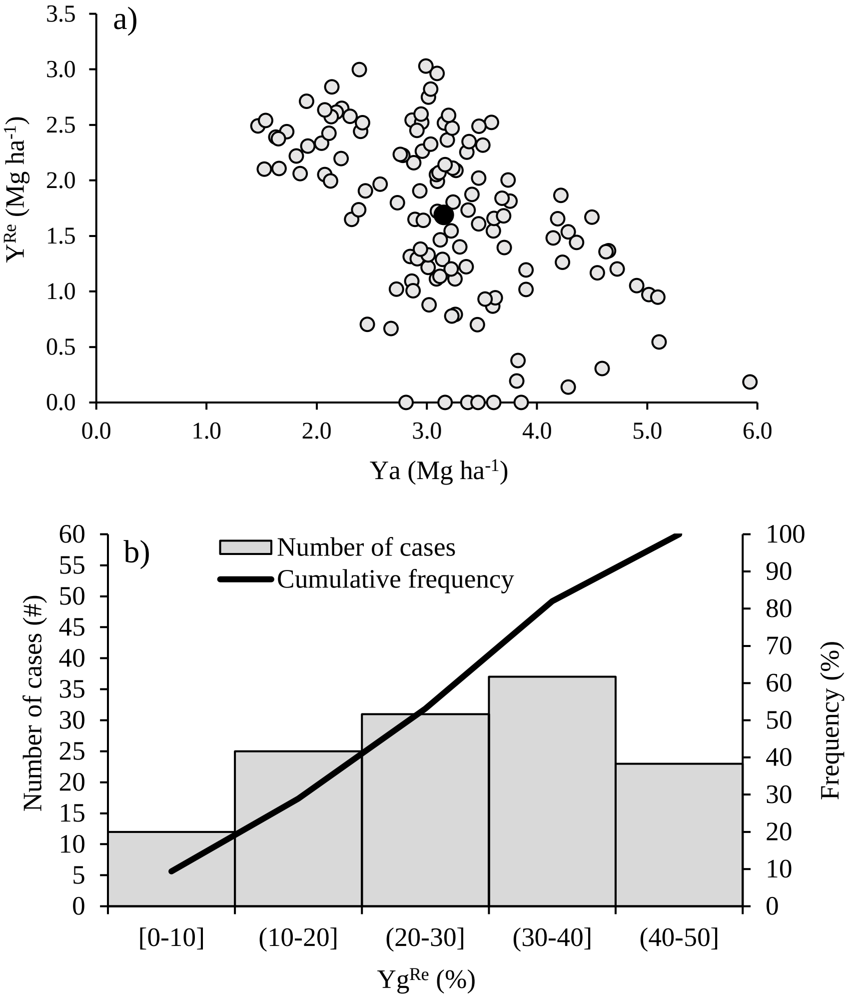

Fig. 1. Yield gap attributed to differences in resource availability (Yg^{Re}) of soybeans cropping systems on eastern Pampas of South America: a) Illustrates relationship between Yg^{Re} (Mg ha^{-1}) and actual yield (Ya; Mg ha^{-1}) for each analysed soybean yield sample (n = 128); b) frequency histogram of Yg^{Re} (%) showing the number of cases (gray columns) and cumulative frequency (solid black line).

3.5.3.1. Determinants of the Yield Gap Attributed to Differences in Resource Availability

The Yg^{Re} between the groups of sites that made up Ymax and Ymin was significantly different ($p \leq 0.05$), indicating that resource supply limited Yatt (Table 4).

Most of the variables estimating nutrient availability and soil fertility, such as P_{0-15}, K_{0-15}, pH_{0-15}, SB_{0-15}, or EC_{0-15}, did not differ statistically between the groups (p

> 0.05); except for CEC_{0-15} and SOC_{0-15}, which, contrary to expectations, high values were associated with lower Yatt, all within a range of high fertility values.

Concerning soil physical properties, CEa_{10-20} (also associated with soil fertility) and $PR_{7.5-15}$ differed between groups ($p \leq 0.05$). Water_PC and water supply from emergence to physiological maturity also showed significant differences between Ymax and Ymin ($p \leq 0.05$) (Table 4).

Table 4 summarizes a group of variables relevant for interpreting the results. Complete information is available in Table 7 in supplementary material.

Table 4
Summary of Mann-Whitney U test to compare variables limiting attainable soybean yield, grouped from cases that constituted Ymax and Ymin. Significance codes: "*": $p \leq 0.05$; "**": $p \leq 0.01$; "***": $p \leq 0.001$; "NS": $p > 0.05$.

Variable	**Units**	**Ymin**	**Ymax**	**W**	**P**
Attainable yield (Yatt)	Mg ha^{-1}	3.4 ± 0.2	6.2 ± 0.4	78	***
Resource yield gap (Yg^{Re})	Mg ha^{-1}	2.8 ± 0.2	0.2 ± 0.2	222	***
Phosphorus Bray (P_{0-15})	ppm	17 ± 5	17 ± 4	146	NS
Exchangeable potassium (K_{0-15})	meq 100 g^{-1}	0.6 ± 0.1	0.7 ± 0.4	146	NS
pH (pH_{0-15})	#	5.8 ± 0.2	5.7 ± 0.3	183	NS
Base saturation (SB_{0-15})	%	83 ± 4	81 ± 4	168	NS
Cation exchange capacity (CEC_{0-15})	meq 100 g^{-1}	28 ± 3	21 ± 4	216	***
Electrical conductivity (EC_{0-15})	ds m^{-1}	108 ± 32	92 ± 18	178	NS
Soil organic carbon (SOC0-15)	g kg^{-1}	34 ± 4	25 ± 6	208	***
Penetration resistance ($PR_{7,5-15}$)	kPa	1546 ± 291	891 ± 238	214	***
Apparent electrical conductivity (ECa_{10-20})	mS cm^{-1}	839 ± 212	506 ± 194	206	**
Available water storage capacity (WSC)	mm	162 ± 15	155 ± 27	162	NS
Water supplied between R4-R6 (Water_PC)	mm	73 ± 25	132 ± 62	88	***
Water supplied between VE-R8	mm	397 ± 70	558 ± 171	104	**

Fig. 2 illustrates the relationship between Yatt with $PR_{7.5-15}$ and ECa_{10-20}, soil quality-related variables determining Yg^{Re}. $PR_{7.5-15}$ was the only variable with an R^2 greater than 0.5.

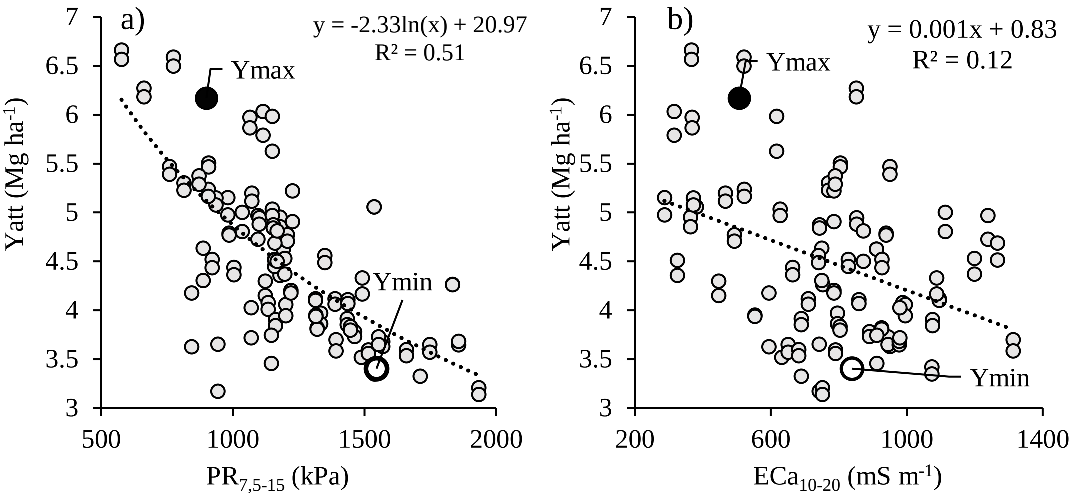

Fig. 2. Regression graph between attainable soybean yield (Yatt; Mg ha−1) and (a) penetration resistance of 7.5-15 cm soil ($PR_{7.5-15}$; kPa) and (b) apparent electrical conductivity of 10-20 cm (ECa_{10-20}; mS m^{-1}). R^2 indicates if the function is significant ($p \leq 0.05$).

The SFPF captured significant interaction between Water_PC and fertilization strategy ($p \leq 0.05$) (Fig. 3). Yatt increased significantly with Water_PC only under non-limiting nutrient fertilization strategy ($p > 0.05$). The equation fitting for each fertilization strategy was low, resulting from high variability in Yatt for Water_PC range between 90 and 100 mm.

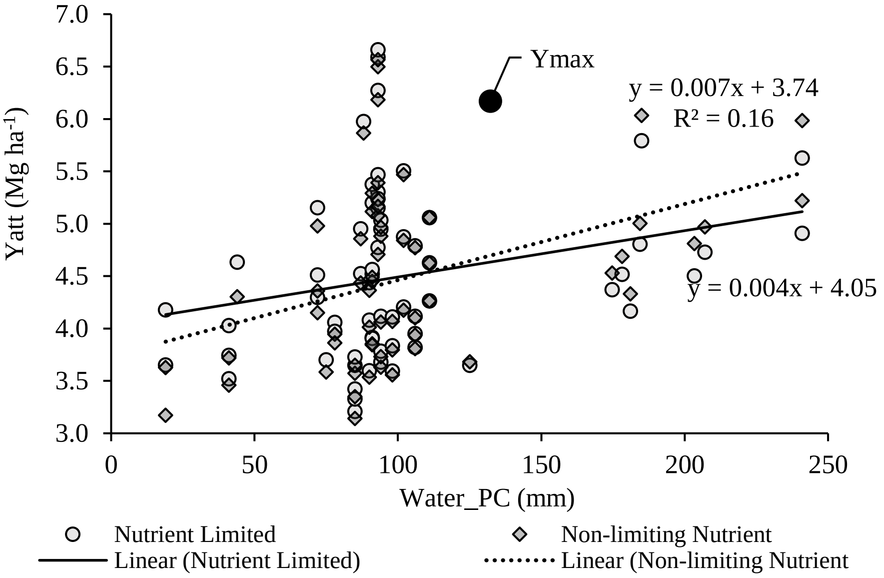

Fig. 3. Regression graph between attainable soybean yield (Yatt; Mg ha^{-1}) and water supply during the critical period of crop yield determination (Water_PC; mm) under two fertilisation strategy: Nutrient limited (dark gray circles) and non-limiting nutrient (gray rhombus). R^2 indicates if function is significant.

3.5.4. Yield Gap attributable to Inefficiencies in Management

The average Yg^{Ef} was 1.3 ± 0.8 Mg ha^{-1}. As expected, it decreased as Ya increased (Fig. 1a). Median efficiency was 30%, and the maximum and minimum efficiency values were 63% and 0% respectably (Fig. 4b).

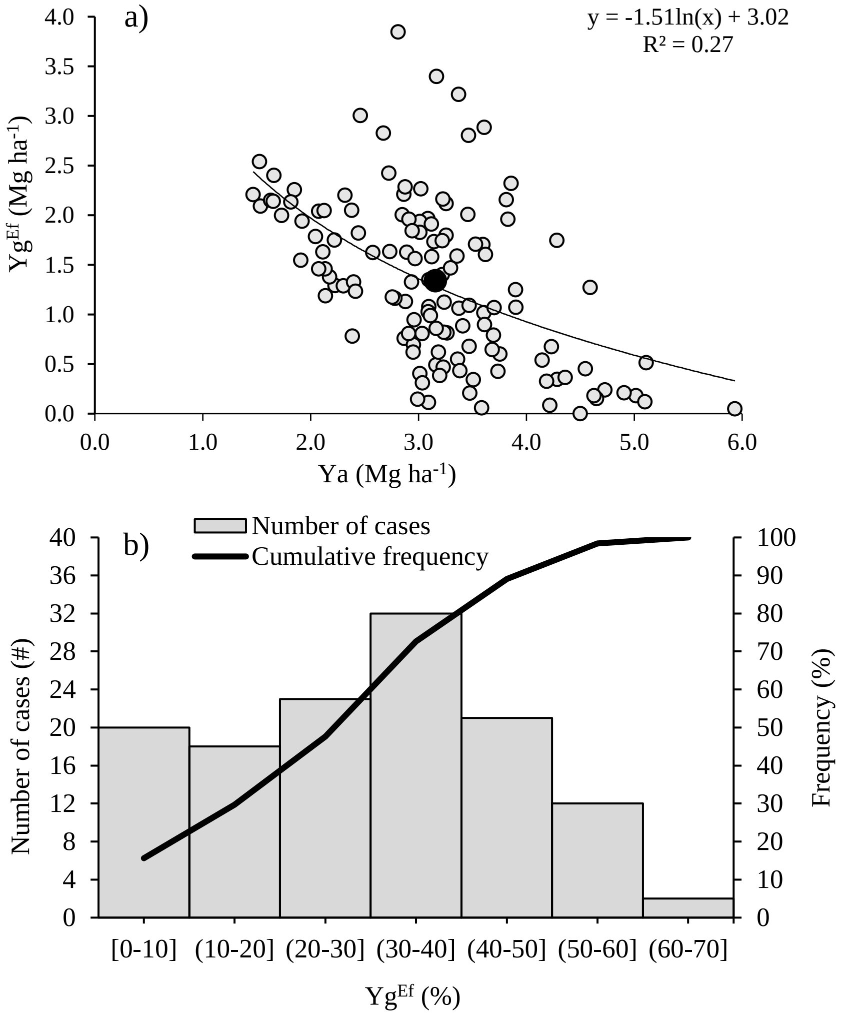

Fig. 4. Efficiency yield gap (Yg^{Ef}) of soybeans in CSs on fields of eastern Pampas of South America: (a) illustrates the relationship between Yg^{Ef} (Mg ha^{-1}) and actual yield (Ya; Mg ha^{-1}) for each analysed soybean yield sample (n = 128). R^2 indicates if function is significant; (b) distribution of Yg^{Ef} (%) in a frequency histogram showing the number of cases (gray columns) and cumulative frequency (solid black line).

3.5.4.1. Determining the Efficiency Yield Gap

As the years under continuous cropping per soybean frequency in summer cropping phase (YCC*SSbCF) increased, inefficiencies in resource use increased, resulting in loss of Ya (Fig. 5a). When CS lost diversity, the rate of Ya reduction began to accentuate ($p \leq 0.05$). This loss is additive to planting soybeans on soybean residue, which was also significant ($p \leq 0.05$) (Table 5). Supplementary water supply decreased losses due to inefficiencies in resource use, reducing Yg^{Ef} from 1.5 to 0.5 Mg ha^{-1} when comparing rainfed vs. supplementary irrigation systems ($p \leq 0.05$), respectively (Fig. 5b).

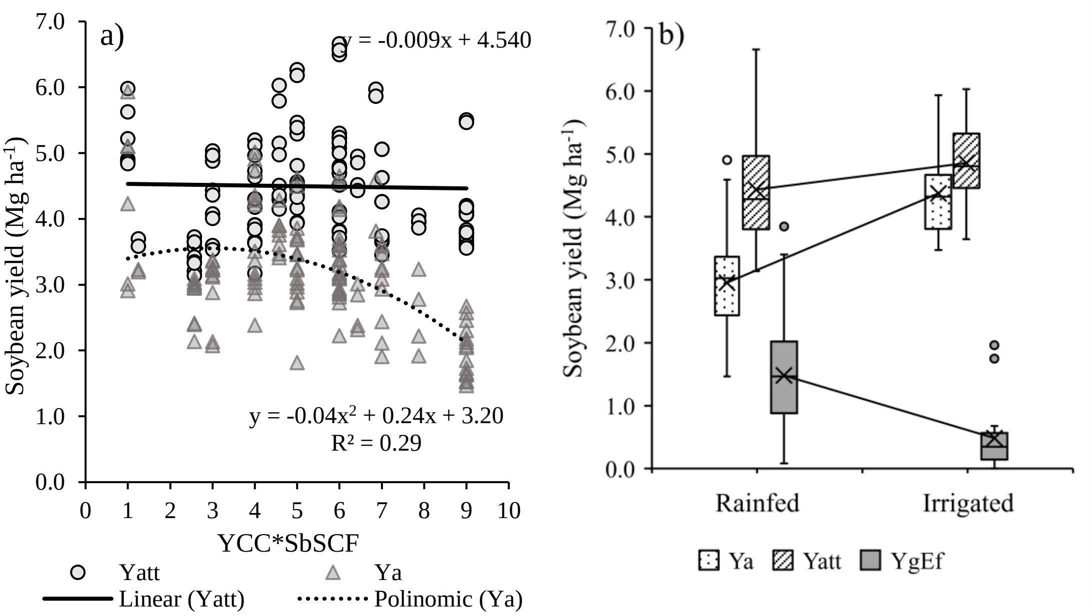

Fig. 5. a) Actual yield (Ya; Mg ha^{-1}) (triangles) and attainable yield (Yatt; Mg ha^{-1}) (circles) based on the number of years under continuous cropping weighted by the frequency of soybeans in the summer agricultural phase (YCC*SSbCF). R^2 indicates if function is significant. b) Box plot for Ya (Mg ha^{-1}) (dotted bars), Yatt (Mg ha^{-1}) (striped bars), and efficiency yield gap (Yg^{Ef}; Mg ha^{-1}) (gray bars) based on water supply (category). Rainfed indicates no supplementary irrigation (n = 110). Irrigated indicates supplementary water supply apart from rainfall (n = 18). Cross inside boxes indicate data set's mean.

3.5.5. Decomposing the Exploitable Yield Gap by Production Level

Significant differences ($p \leq 0.01$) in soybean exploitable yield gap (Yg^{Exp}) among different levels of current production were observed (Fig. 6). High yield environments had a better combination of resources than medium and low yield environments ($p \leq 0.05$, Table 5). However, medium and low yield environments presented a higher efficiency ($p \leq 0.01$, Table 5).

Specifically, Ysup significantly differed ($p \leq 0.05$) from the next production level due to higher Water_PC, higher EC_{0-15}, and being in 75% of cases under irrigation. Ysup and Ymed differed significantly ($p \leq 0.05$) from Yinf due to lower $PR_{7.5\text{-}15}$ values, not planting soybeans on the same residue, and being in CSs characterized by lower values of YCC*SSbCF, associated with CS diversification under continuous cropping (Table 5).

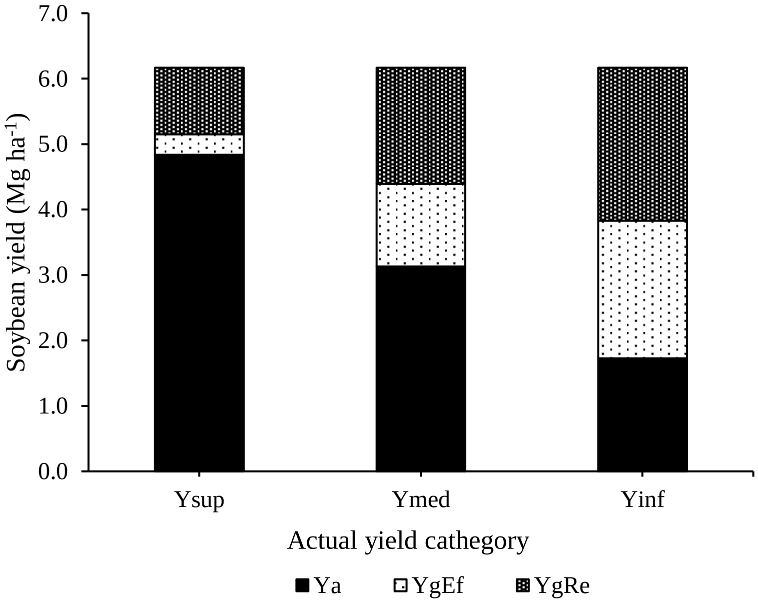

Fig. 6. Stacked column chart of soybean exploitable yield gap (Yg^{Exp}), decomposed into a gap attributed to the difference in resource availability (Yg^{Re}; column with high dot density) and technical efficiency gap (Yg^{Ef}; column with low dot density), based on production level. Ysup is the mean of 90th percentile of actual yield (Ya); Ymed is the mean of Ya between P45 and P55; Yinf is the mean of 10th percentile of Ya. Significant differences in Table 5.

Table 5
Summary of Mann-Whitney U test to compare means of each variable based on production level. Significance code "*" indicates significant differences ($p \leq 0.05$) between production levels (consecutive columns) for each continuous variable. Contingency table for dummy variables, values show adjusted residuals.

Variable	**Unidades**	**Ysup**	**t-test**	**Ymed**	**t-test**	**Yinf**
Ya	Mg ha^{-1}	4.8 ± 0.4	*	3.1 ± 0.0	*	1.7 ± 0.2
Yg^{Exp}	Mg ha^{-1}	1.3 ± 0.4	*	3.1 ± 0.1	*	4.4 ± 0.2
Yg^{Re}	Mg ha^{-1} %	1.0 ± 0.4 80	*	1.8 ± 0.7 58	*	2.3 ± 0.2 52
Yg^{Ef}	Mg ha^{-1} %	0.3 ± 0.4 20	*	1.3 ± 0.8 42	*	2.1 ± 0.2 48
Resources						
Water_PC	Mm	182 ± 59	*	79 ± 33	NS	91 ± 17
PR$_{7,5-15}$	kPa	1111 ± 60	NS	1160 ± 326	*	1418 ± 115
EC$_{0-15}$	mS m^{-1}	127 ± 21	*	107 ± 26	NS	99 ± 19
SOC$_{0-15}$	g kg^{-1}	33 ± 5.6	NS	32 ± 7.3	NS	32 ± 4.9
Management efficiency						
YCC*SSbCF	#	4 ± 2	NS	5 ± 1	*	8 ± 1
C4 species as previous summer crop[1]	#	1.9	*	0.5	*	-2.4
Soybean as previous summer crop[1]	#	-3.3	*	0.2	*	3.1
Pasture as previous summer crop[1]	#	2.6	*	-1.3	*	2.6
Supplementary irrigation[1]	#	4.9	*	-2.5	*	-2.5

[1] Dummy variable

3.6. DISCUSSION

Even on CSs without significant soil management deficiencies, we quantified a soybean exploitable yield gap (Yg^{Exp}) of 3.1 Mg ha^{-1}. This gap was chiefly due to factors such as water supply during the critical period (Water_PC), soil physical quality indicated by $PR_{7.5\text{-}15}$, and advancements in technology that diminished inefficiencies. These advancements involved supplementary irrigation and diversified crop sequence, incorporating pastures, corn, or sorghum. (Tables 3 and 4 and Fig. 2, 3 and 5). Notably, Yg^{Exp} was not estimated referencing 80% of the resulting potential yield from a crop simulation model (Cassman et al., 2003). Instead, we used Ymax (6.2 Mg ha^{-1}) ascertained in this study, representing 94% of the potential yield calculated by Rizzo et al. (2021) for the study area. This method suggests that Yg^{Exp}, except for fertilization strategy under irrigation conditions, could be reduced within the current technology package.

As Yatt was estimated from an SFPF and incorporates sites managed under supplementary irrigation, it considers variations in water supply that might occur between years (558±171 and 132±62 mm for VE-R8 and R4-R6 periods, respectively, Table 2). By combining this information with sites having no resource constraints, Ymax (90th percentile of Yatt) became a valuable reference for gauging potential soybean yield enhancements on farm. We consider Ymax a better reference value than the higher farmer yield proposed by Silva et al. (2017) to calculate Yg^{Re}. According to their methodology, Ymax would equate to our Ysup, estimated only at 4.8 Mg ha^{-1}. The difference lies in the fact that Ysup does not consider the inclusion of those who also work with limited resources and experience losses due to inefficient resource management (Fig. 6 and Table 5).

The frontier function enabled the quantification of the impact of environmental variables, as yield-determining factors, and crop management and soil quality, as yield-limiting factors. Among these factors, Water_PC emerged as the most impactful variable within the first group, known to significantly affect crop yield (Doss et al., 1974; Giménez, 2017; Rovegno, 2021). During the critical yield-determining period, the difference between Ymax and Ymin was 59 mm (132 vs. 73 mm) (Table 4). However, results suggest that achieving Ymax was feasible with just 100 mm of

Water_PC (Fig. 5). Confirming, what has been proposed by other researchers, water use efficiency seems to be more important that water amount (Torrion et al., 2014; Adeboye et al., 2015; Rovegno, 2021). Moreover, despite that only soybeans planted within the optimal seeding date were evaluated here, delaying the seedling date limited the production frontier, with November 12th being the date associated with Ymax (Table 7, in supplementary material), a date within the optimal range reported by different authors for the region (Giménez, 2007; Di Mauro et al., 2018). The effect of cultivar cycle and seedling date quantifies the temporal location of R4-R6 period defining in turn the radiation and temperature harvested at each site.

In relation to soil quality, among the physical properties, although WSC did not show a significant effect on the production frontier, soil properties related to soil water availability for plants such as $PR_{7.5\text{-}15}$ and $ECa_{10\text{-}20}$ were highlighted. $PR_{7.5\text{-}15}$ was the sole soil property within a range of values (Fig. 2a and Table 4) reported to limit soybean crop growth (Beulter and Centurion, 2004; Etchegoimberry, 2019). Meanwhile, properties linked with soil fertility did not have a clear impact on the production frontier (Table 3 and Table 4), possibly due to the high fertility level of the study area (Alvarez and Ernst, in this thesis; Bordoli et al., 2012) and the crop's own characteristics, making it less sensitive to soil fertility under dryland conditions (majority of evaluated sites).

The average production efficiency stood at 72% (Table 3), resulting in a Yg^{Ef} of 1.3 Mg ha^{-1}. Although this aligns with estimates by Rizzo et al. (2021) following the Global Yield Gap Atlas (GYGA) protocol, in this study only it does not represent the soybean yield gap value in the region, as it results from selected sites without serious management defects or factors reducing yield we evaluated.

Our study unveils two significant findings; i) it highlights nutrition as a yield limiting factor under no limiting water conditions; ii) it underscores the CS design as a determinant of the efficiency of allocated crop resources. The first observation stemmed from quantifying the interaction between Water_PC and the fertilization strategy. Results indicate an increase in soybean yield of 7 kg ha^{-1} $mm^{-1}$of water received during R4-R6 when nutrients were managed as non-limiting (Fig. 3). This suggests that the current criteria for nutrient supply may align with conditions defined for Yatt by Lobell et al. (2009) and Fischer and Edmeades (2010) as "achievable yield by producers using best management practices for an agroecological condition but considering risks and economic factors". In our environment, the risk factors include the uncertainty of Water_PC under natural rainfall conditions. Conversely, under supplementary irrigation conditions, yield could be limited by the availability of nutrients due to applying current criteria for their correction. As the qualification of yield non-limiting nutrients results from adding P, K, and S, and correcting the pH at a fixed incremental dose over the resulting decision from current criteria, it is not possible to separate the effect of each nutrient or assess the deficit. Yet, the need of generating fertilization criteria that contemplate situations in which water availability is lifted as a yield-limiting factor is confirmed.

The second insight arose from quantifying the effect of CS design, measured as YCC*SSbCF and summer previous crop, on Yg^{Ef}. Although the negative effect of extending the cropping phase (YCC) has been previously quantified for wheat (Ernst et al., 2018), the contribution of this work results from identifying the importance of the crop sequence design within the cropping phase. YCC alone was also significant in the inefficiency function in this study (Table 8, in supplementary material). However, considering the interaction with SSbCF allows us to conclude that, apart from the acknowledged effect of rotation with pastures, there is also an additional effect associated with the sequence diversification by systematically including C_4 photosynthesis crops that are independent and additive to planting soybeans on their own residue (Fig. 5a and Table 5). This could be one of the mechanisms contributing to increased production inefficiencies, quantified as an expanded yield gap between Yatt (maximum technical efficiency yield for the allocated resources managed by each producer) and Ya (Fig. 5a). The increase in frequency of soybeans in the cropping phase reflects a move towards monoculture, affecting soil quality (Novelli et al., 2013, 2011; Rubio et al., 2022), potentially leading to increased unquantified factors reducing yield (Mazzilli and Ernst, 2019). Therefore, while deteriorating soil properties decreased the soybean production frontier, the effect of YCC*SSbCF remained significant, summarizing the impact of soil functions altered by CS.

Our study did not aim to evaluate water use efficiency. However, by incorporating sites with supplementary irrigation to account for variability in water supply between years, this categorical variable was introduced into the inefficiency model, as it is manageable within the CS. The inclusion of supplementary irrigation reduced Yg^{Ef} by 78% compared to sites under dryland conditions (Fig. 5b). As Yg^{Ef} represents changes in yield for the same resource supply, it implies that water productivity (kg of soybeans mm^{-1} of water) improved. These differences in water use efficiency can explain why there were sites in the Ymax and Ymin groups with a similar Water_PC level and within the monthly average range of precipitation for this area (100 - 120 mm) (Table 4). In rain-dependent CSs where soil fertility is not a limiting factor, water use efficiency depends on environmental characteristics such as precipitation events (intensity and frequency) or soil water storage capacity, but it may also be affected by management measures such as irrigation, crop spatial arrangement, or the CS's own design (Hatfield and Dold, 2019).

Decomposing Yg^{Exp} by current production level (Fig. 6) allowed us to identify in which productive stratum the main properties that defined, limited, and reduced soybean yield had a more relevant role in our study (Table 5). Sites forming Ysup featured soybean crops within diversified CSs, operating in an environment with ample water availability, often supplemented by irrigation, and free from soil quality issues. Ymed were also obtained in diversified CSs but faced water shortages due to dryland conditions. Yinf emerged when the CSs, apart from being under dryland conditions, trended towards soybean monoculture in summer and was seeded in a soil quality-limited environment.

3.7. CONCLUSION

The results confirm our initially hypothesized thesis about the favorable impact of intentionally incorporating diversity into the CS on soybean yield. Our study uncovers the susceptibility of soybean yield to the diversity of the CSs. This effect was captured through the land use indicator YCC*SSbCF, quantifying the significance of rotations with perennial pastures and/or incorporating corn and sorghum into the rotation. Replacing both components in the CS resulted in decreased Ya, explaining the increase in inefficiencies in the use of resources allocated to the crop.

When examining the Yg^{Re}, we did not find clear evidence that it was affected by the CS. The main factors in determining Yatt were water supply, the fertilization strategy when water is not limiting, and surface compaction.

Through the analysis by productive levels, we managed to discern the relative importance of each variable in the composition of Yg^{Exp}. This provides valuable insights for strategies aimed at minimizing yield losses or expanding the production frontier.

3.8. DECLARATION OF COMPETING INTERESTS

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Oswaldo Ernst reports financial support, administrative support, article publishing charges, equipment, drugs, or supplies, travel, and writing assistance were provided by National Agency for Research and Innovation (ANII). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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3.10. APPENDIX

Table 6
Parameters of the stochastic frontier model for soybean cultivation in the surveyed prior to the elimination of variables that were not significant in the inefficiency function. Values in black in t-ratio column indicate significance ($p < 0.05$).

		Coefficient	**S.E.**	**t-ratio**
Variables				
Intercept	beta 0	10.94	0.94	11.58
Sowing Date	beta 1	-0.08	0.04	**-1.80**
Cycle Length	beta 2	0.07	0.16	0.44
Water supplied during R4-R6 (Water_PC)	beta 3	0.21	0.03	**7.92**
Fertilisation Strategy[1]	beta 4	0.02	0.04	0.66
Water_PC * Fertilisation Strategy[1]	beta 5	-0.11	0.15	-0.73
Organic Carbon in soil 0-15 cm (SOC_{0-15})	beta 6	-0.16	0.17	-0.96
Electrical Conductivity in soil 0-15 cm (EC_{0-15})	beta 7	0.07	0.10	0.70
Titratable Acidity in soil 0-15 cm (TA_{0-15})	beta 8	0.09	0.08	1.17
Profile Water Storage Capacity (SWC)	beta 9	0.31	0.05	**5.93**
Exchangeable Potassium from 0 to 15 cm (K_{0-15})	beta10	0.10	0.05	**1.84**
Phosphorus Bray in soil 0-15 cm (P_{0-15})	beta11	-0.04	0.06	-0.72
Exchangeable Magnesium from 7.5 to 15 cm ($Mg_{7,5-15}$)	beta12	0.13	0.12	1.13
Exchangeable Sodium from 0 to 15 cm (Na_{0-15})	beta13	0.10	0.16	0.64
Penetration Resistance from 7.5 to 15 cm ($PR_{7.5-15}$)	beta14	-0.58	0.06	**-9.85**
Apparent Electrical Conductivity from 10 to 20 cm (ECa_{10-20})	beta15	-0.16	0.05	**-2.92**
Inefficiency effects	delta 0	-0.79	0.30	-2.66
Intensification agricultural phase index (IAI)	delta 1	0.16	0.34	0.48
Years under continuous cropping per summer soybean cropping frequency (YCC*SSbCF)	delta 2	0.52	0.11	**4.76**
Supplementary irrigation[1]	delta 3	-0.59	0.25	**-2.33**
Grass cover crop as winter previous crop[1]	delta 4	0.17	0.24	0.70
Legume cover crop as winter previous crop[1]	delta 5	-0.19	0.44	-0.43
Soybean as summer previous crop[1]	delta 6	0.17	0.10	**1.75**
Pasture as summer previous crop[1]	delta 7	1.10	0.31	**3.57**
Topography_Low[1]	delta 8	-0.05	0.11	-0.41
Topography_Slope[1]	delta 9	-0.01	0.09	-0.09
	sigma-squared	0.05	0.01	3.34
	gamma	1.00	0.00	5255.1

[1] **Dummy variable**

Table 7

Mann-Whitney U test by percentiles of achievable performance. P10 = Ymin; P90 = Ymax. n = 12.

Variable	Group 1	Group 2	Mean(1)	Mean(2)	SD(1)	SD(2)	W	P
Yatt	P10	P90	3.4	6.0	0.1	0.4	78	0.000
Yg^{Re}	P10	P90	2.6	0.2	0.1	0.2	222	0.000
Sowing date	P10	P90	17.8	22.0	2.9	7.3	127	0.179
Cicle length	P10	P90	138.0	141.7	5.3	8.6	127	0.178
PMN	P10	P90	21.4	25.9	7.6	12.3	140	0.563
$P_{0-7.5}$	P10	P90	25.5	25.5	8.9	6.7	142	0.644
$P_{7.5-15}$	P10	P90	8.8	8.5	2.6	2.5	144	0.729
P_{0-15}	P10	P90	17.1	17.0	4.7	4.1	146	0.817
$SOC_{0-7.5}$	P10	P90	38.5	29.2	4.5	7.9	198	0.005
$SOC_{7.5-15}$	P10	P90	30.7	20.2	3.7	3.8	220	0.000
SOC_{0-15}	P10	P90	34.6	24.7	3.7	5.8	208	0.001
$EC_{0-7.5}$	P10	P90	129.5	109.5	59.0	27.2	172	0.203
$EC_{7.5-15}$	P10	P90	88.0	75.1	12.0	10.9	190	0.021
EC_{0-15}	P10	P90	108.7	92.3	32.4	17.9	178	0.105
$pH_{0-7.5}$	P10	P90	5.6	5.7	0.1	0.3	162	0.488
$pH_{7.5-15}$	P10	P90	5.9	5.8	0.3	0.4	169	0.271
pH_{0-15}	P10	P90	5.8	5.7	0.2	0.3	183	0.056
$Ca_{0-7.5}$	P10	P90	18.2	12.3	2.3	4.3	202	0.003
$Ca_{7.5-15}$	P10	P90	20.3	13.0	2.8	3.9	214	0.000
Ca_{0-15}	P10	P90	19.2	12.6	2.4	4.0	208	0.001
$Mg_{0-7.5}$	P10	P90	2.5	2.6	0.3	0.6	156	0.729
$Mg_{7.5-15}$	P10	P90	2.1	2.5	0.2	0.7	140	0.563
Mg_{0-15}	P10	P90	2.3	2.5	0.2	0.6	158	0.644
$K_{0-7.5}$	P10	P90	0.7	0.8	0.2	0.5	146	0.817
$K_{7.5-15}$	P10	P90	0.5	0.5	0.1	0.3	156	0.729
K_{0-15}	P10	P90	0.6	0.7	0.1	0.4	146	0.817
$Na_{0-7.5}$	P10	P90	0.9	1.0	0.2	0.2	138	0.488
$Na_{7.5-15}$	P10	P90	1.0	0.9	0.3	0.2	174	0.165
Na_{0-15}	P10	P90	1.0	0.9	0.1	0.1	170	0.247
$TB_{0-7.5}$	P10	P90	22.4	16.6	2.6	4.9	198	0.005
$TB_{7.5-15}$	P10	P90	24.0	16.9	3.0	4.3	214	0.000
TB_{0-15}	P10	P90	23.2	16.7	2.6	4.5	204	0.002
$SB_{0-7.5}$	P10	P90	80.5	79.4	3.0	4.7	162	0.488
$SB_{7.5-15}$	P10	P90	84.5	82.2	4.6	4.9	164	0.418
SB_{0-15}	P10	P90	82.5	80.8	3.7	4.4	168	0.298
$TA_{0-7.5}$	P10	P90	5.4	4.1	0.7	0.4	213	0.000
$TA_{7.5-15}$	P10	P90	4.4	3.5	1.2	0.4	194	0.011
TA_{0-15}	P10	P90	4.9	3.8	0.9	0.2	210	0.001
$CEC_{0-7.5}$	P10	P90	27.7	20.7	2.6	4.8	204	0.002
$CEC_{7.5-15}$	P10	P90	28.3	20.3	2.7	4.1	218	0.000
CEC_{0-15}	P10	P90	28.0	20.5	2.5	4.4	216	0.000
$PR_{7.5-15}$	P10	P90	1545.7	890.6	291.3	238.1	214	0.000
PR_{15-30}	P10	P90	1443.8	934.4	175.8	134.7	218	0.000
PR_{30-45}	P10	P90	1473.0	1028.3	156.7	147.8	216	0.000

ECa$_{0-10}$	P10	P90	802.5	471.8	202.1	166.5	210	0.001
ECa$_{10-20}$	P10	P90	838.4	506.4	211.6	193.6	206	0.001
ECa$_{20-30}$	P10	P90	1033.9	670.8	250.5	283.9	192	0.015
INF	P10	P90	20.6	3.7	14.2	2.2	218	0.000
WSC	P10	P90	161.9	155.1	14.7	27.1	162	0.488
WSC$_A$	P10	P90	46.5	47.9	8.8	15.2	152	0.908
CMWD	P10	P90	1.4	1.9	0.6	0.6	114	0.037
mm VE-R8	P10	P90	397.1	557.9	69.8	170.6	104	0.007
WATER_PC	P10	P90	72.8	132.2	24.8	62.1	88	0.000
RAD VE-R8	P10	P90	3293.0	3305.2	109.6	186.4	138	0.484
Daily RAD VE-V8	P10	P90	23.9	23.5	0.3	0.6	191	0.017
Temp VE-R8	P10	P90	23.0	22.7	0.4	0.2	198	0.005

Table 8
Parameters of the stochastic frontier model for soybean cultivation in the surveyed prior to the elimination of variables that were not significant in the inefficiency function. values in black in t-ratio column indicate significance ($p < 0.05$). YCC in substitution of YCC*SSbCF.

		Coefficient	**S.E.**	**t-ratio**
Variables				
Intercept	beta 0	10.51	0.75	14.00
Sowing Date	beta 1	-0.10	0.03	**-3.18**
Cycle Length	beta 2	0.19	0.14	1.35
Water supplied during R4-R6 (Water_PC)	beta 3	0.19	0.02	**8.78**
Fertilisation Strategy[1]	beta 4	0.04	0.03	1.39
Water_PC * Fertilisation Strategy[1]	beta 5	-0.19	0.13	-1.47
Organic Carbon in soil 0-15 cm (SOC_{0-15})	beta 6	-0.19	0.12	-1.57
Electrical Conductivity in soil 0-15 cm (EC_{0-15})	beta 7	0.10	0.07	1.43
Titratable Acidity in soil 0-15 cm (TA_{0-15})	beta 8	0.07	0.05	1.35
Profile Water Storage Capacity (WSC)	beta 9	0.26	0.06	**4.41**
Exchangeable Magnesium from 7.5 to 15 cm ($Mg_{7.5-15}$)	beta10	0.08	0.05	**1.68**
Phosphorus Bray in soil 0-15 cm (P_{0-15})	beta11	-0.02	0.04	-0.49
Exchangeable Potassium from 0 to 15 cm (K_{0-15})	beta12	0.19	0.09	**2.00**
Exchangeable Sodium from 0 to 15 cm (Na_{0-15})	beta13	-0.04	0.13	-0.30
Penetration Resistance from 7.5 to 15 cm ($PR_{7.5-15}$)	beta14	-0.54	0.04	**-12.12**
Apparent Electrical Conductivity from 10 to 20 cm (ECa_{10-20})	beta15	-0.17	0.04	**-3.98**
Inefficiency effects	delta 0	-0.72	0.31	-2.37
Intensification agricultural phase index (IAI)	delta 1	0.17	0.19	0.88
Years under continuous cropping (YCC)	delta 2	0.42	0.09	**4.56**
Supplementary irrigation[1]	delta 3	-0.40	0.17	**-2.38**
Grass cover crop as winter previous crop[1]	delta 4	0.17	0.18	0.93
Legume cover crop as winter previous crop [1]	delta 5	-0.04	0.20	-0.19
Soybean as summer previous crop[1]	delta 6	0.27	0.08	**3.20**
Pasture as summer previous crop[1]	delta 7	1.15	0.30	**3.87**
Topography_Low[1]	delta 8	-0.10	0.09	-1.14
Topography_Slope[1]	delta 9	-0.02	0.08	-0.23
	sigma-squared	0.03	0.01	4.28
	gamma	1.00	0.00	895.09

[1]Dummy variable

4. DISCUSIÓN GENERAL Y CONCLUSIONES GLOBALES

Para avanzar en el proceso de intensificación sostenible de la agricultura de Uruguay, el Departamento de Producción Vegetal de la Facultad de Agronomía (Udelar) ha desarrollado una línea de investigación que ha tenido como objetivo identificar las principales causas de la variación de rendimientos entre y dentro de chacras y cuantificar la brecha existente entre el rendimiento actual y el alcanzable (Rizzo et al., 2021, Etchegoimberry, 2019, Ernst et al., 2018).

Rizzo et al. (2021) realizaron un aporte relevante al identificar, con una metodología transparente y conocida (GYGA), la brecha de rendimiento de soja para las tres principales zonas agroecológicas del país. Sin embargo, para profundizar el análisis de las causas de estas brechas, era necesario trabajar a escala de chacra. Este trabajo de investigación en campo de productores fue realizado para trigo (Ernst et al., 2018), principal cultivo de renta de invierno, pero no para soja, cultivo dominante de la secuencia de cultivos actual.

En nuestro estudio se encontró que las diferencias en la Yg^{Exp} (3,1 Mg ha^{-1}) de soja de productores del litoral agrícola del Uruguay están explicadas tanto por diferencias atribuibles a la disponibilidad de recursos (Yg^{Re} = 1,8 Mg ha^{-1}) como por la eficiencia con la que estos son utilizados (Yg^{Ef} = 1,3 Mg ha^{-1}) (artículo 2, tabla 5). La metodología utilizada permitió identificar al suministro de agua, la compactación subsuperficial, el riego suplementario y el diseño de los CSs como los principales factores en determinar el rendimiento de soja. Al agrupar los rendimientos obtenidos a campo en niveles (Ysup, Ymed e Yinf), se logró caracterizarlos e identificar estrategias de manejo que permitan acercarse a Ymax (6,2 Mg ha^{-1}), el máximo rendimiento de soja al que los agricultores pueden aspirar con la tecnología disponible para la zona en estudio.

Nuestro foco estuvo puesto en cuantificar el rol de la planificación del CS. En este sentido, el conocimiento científico nacional acumulado (Rubio et al., 2022, Baethgen et al., 2021, Ernst et al., 2020, Mazzilli y Ernst, 2019, Ernst et al., 2018, Mazzilli et al., 2015, Ernst y Siri-Prieto, 2009, García-Préchac et al., 2004) y la disponibilidad de base de datos de manejo y uso del suelo de productores nos permitieron construir (artículo 1, tabla 1) y seleccionar (artículo 1, tabla 4 y figura 2) indicadores de uso del suelo de escala semestral de fácil interpretación, que lograron inferir las posibles trayectorias de los CSs que imperan en la actualidad (artículo 1, figura 5 y artículo 2, figura 5a).

Tres claros CSs fueron clasificados (artículo 1, figura 3 y tabla 5): (I) ROT-PC, que mantienen el esquema productivo similar al dominante en el país hasta principios del siglo XXI con relaciones pastura/cultivo de renta cercanas a 1:1; (II) CC_Soybean, dominante en la actualidad, el cual se caracteriza por el monocultivo de soja en la fase agrícola de verano; (III) CC_Corn, sistema de más reciente implementación, en el que, manteniéndose en agricultura continua, rota de manera sistemática con especies de fotosíntesis C4 (principalmente maíz) al menos una vez cada cuatro años en sustitución de soja, incrementando la diversidad de los CSs que eliminaron la fase de pastura de la rotación.

Sobre estos CSs se encontró que, aun manteniéndose en siembra directa y con solo un 10 % del área en barbecho, explicado por una alta frecuencia de doble cultivo de renta (30-50 % del área) y de cultivos de servicio, disminuir la diversidad del CS (ROT-PC > CC_Corn > CC_Soybean) generó una trayectoria negativa en la calidad del suelo, medida a través de pérdidas en SOC_{0-15}, EC_{0-15} y K_{0-15} (artículo 1, figura 5 y tabla 10), y en el rendimiento de soja, lo que ocasiona pérdidas debido a ineficiencias en el manejo de los recursos (artículo 2, figura 5). Lo cual implica, en el caso de CC_Corn, una valorización de la fase agrícola luego de la pastura (YCC) cuando se incorporan especies de fotosíntesis C_4 en sustitución de soja, y escenifica la mejora en la provisión de servicios ecosistémicos de regulación y soporte al aumentar la diversidad del CS. Es un efecto aditivo al efecto antecesor, ya que el modelo también capturó las ineficiencias por sembrar soja sobre soja y no hacerlo sobre especies de fotosíntesis C_4. Por lo tanto, es un efecto legado que confirma lo observado por otros autores tanto en pasturas perennes (Hoeffner et al., 2021, Ernst et al., 2018) como en rotaciones con maíz (Díaz-Zorita et al., 2014, Gerster y Bacigaluppo, 2009).

Se cuantificó en condiciones de secano, donde sembrar soja sobre CSs más diversos (ROT-PC o CC_Corn) fue una de las causas de subir el escalón productivo de Yinf a Ymed (artículo 2, tabla 5). Si bien resultados similares han sido reportados en experimentos locales (Rubio et al., 2022, Ernst et al., 2020, 2018, Ernst y Siri-

Prieto, 2009, García-Préchac et al., 2004), no lo ha sido, a saber de los autores, reportado sobre CS comerciales sin graves deficiencias de manejo.

YCC como único criterio de clasificación de los CSs fue utilizado para cuantificar cambios en la calidad del suelo, que no pudieron ser medidos por propiedades del suelo, y determinar el rendimiento alcanzable de trigo (Ernst et al., 2018). Sin embargo, las condiciones de manejo de los CSs en nuestro estudio (sin graves deficiencias) y las propias características del cultivo de soja, que le confieren una mayor capacidad para sostener el rendimiento en condiciones de menor fertilidad, hicieron que considerar no solo la rotación con pasturas (YCC o PCR), sino también SSbCF haya permitido una mejor descripción de la trayectoria agrícola, lo que demuestra que una mejor clasificación de los CSs permite una mejor cuantificación de la trayectoria de estos.

Si bien se logró inferir una trayectoria en la calidad del suelo y el rendimiento de soja con indicadores de uso del suelo, solo con las propiedades químicas y físicas del suelo no se tendría la capacidad de saber de qué CSs se obtuvieron (tabla 11), lo cual revela que es necesario continuar con una mejora del indicador YCC que permita mejorar el nivel de predicción sobre la trayectoria en la calidad del suelo y su impacto en el rendimiento de los cultivos. Esta descripción parcial de la trayectoria de los CS se debe en parte a que un aspecto relevante en definir cambios en el SOC y propiedades asociadas, y por lo tanto la calidad del suelo, es la productividad del CS (Novelli et al., 2011). Al no haber dispuesto de registros de la productividad histórica de los sitios relevados se limitó la capacidad de predicción de nuestro estudio. Por otro lado, incorporar variables de manejo de los cultivos como el número y momento de las aplicaciones de fitosanitarios o fertilizantes podría permitir una discriminación más precisa de los problemas asociados a ineficiencias en el uso de los recursos (Silva et al., 2017), para lo cual sería necesario trabajar con bases de datos de productores más amplias.

Se pudo cuantificar que la diversidad del CS es parcialmente responsable de los cambios en la Yg^{Exp} de soja, pero no se observó a partir de la degradación de la calidad del suelo medida como se preveía *a priori*, sino a partir de un aumento en la Yg^{Ef} (artículo 2, tabla 3 y 5 y figura 5a). Dos explicaciones parecen tener lugar: i) que a pesar de los cambios en la fertilidad del suelo observados (artículo 1), estos ocurrieron dentro de un rango de fertilidad en los que la soja puede mantener su nivel de producción, especialmente si el cultivo se realiza en condiciones de secano, donde el agua y la capacidad de almacenarla pasan a ser las principales limitantes de su rendimiento; y que ii) en este estudio se incorporó la interacción YCC*SSbCF en la función de ineficiencias (ec. 2), bajo la lógica de que son las propias decisiones de manejo de los productores al planificar los CSs las que condicionan a mediano plazo la eficiencia con la que los recursos son utilizados. Sin embargo, si se partiera de una condición dada, YCC*SSbCF debería incluirse en la función de frontera de producción (ec. 1), representando los cambios en las propiedades del suelo asociados a la historia de uso del suelo que no pudieron ser medidas a partir del relevamiento de la calidad del suelo, pero que se encuentran limitando el Yatt de soja, tal como fue planteado por Ernst et al. (2018) para trigo. Nuestra propuesta permite concluir que los tomadores de decisiones pueden evitar una reducción del rendimiento de soja a mediano plazo de hasta 1,4 Mg ha^{-1} (de 3 a 9 YCC*SSbCF) si planifican de la manera correcta la rotación de cultivos.

Los dos principales factores que limitaron el Yatt estuvieron asociados al suministro de agua (Water_PC) y a características del suelo que condicionan la capacidad de almacenarla y acceder a esta -en nuestro caso, medido a través de la PR$_{7,5-15}$-, similar a lo reportado con modelos de simulación por Rizzo et al. (2021) para la zona de estudio. Si bien al monitorear la calidad del suelo, la PR$_{7,5-15}$ no se asoció a ningún CS (artículo 1, figura 5 y tabla 10), esta se encontró dentro de un rango de valores que ha sido reportado como limitante para el crecimiento de soja en condiciones de secano para la región (Etchegoimberry, 2019, Beulter y Centurion, 2004), lo que lleva a concluir que, en nuestras condiciones, además del impacto del diseño del CS en las ineficiencias, pasar de Yinf a Ymed requiere sembrar sobre suelos que no tengan afectada su capacidad de almacenamiento de agua (artículo 2, figura 2a y tabla 5). Existen distintas causas para la compactación subsuperficial del suelo; si bien algunas dependen del tipo del suelo (presencia de un horizonte b textural), otras pueden evitarse a partir de un correcto tráfico de maquinaria o pisoteo animal (Hamza y Anderson, 2005).

El agua y la eficiencia con la que está fue utilizada fueron las principales características en levantar el escalón productivo de Ymed a Ysup. Un aporte relevante de nuestro estudio es que bajo estas condiciones existió respuesta a la fertilización a una dosis incremental fija de P, K, S, Ca y Mg, lo que sugiere la necesidad de generar criterios de fertilización que contemplen situaciones en las que se levante la limitante hídrica. Por el contrario, en condiciones de secano, ningún sitio respondió a un incremento en la fertilización, lo cual permite suponer que los criterios de fertilización actual no limitan la producción de soja. Pero, además, dado el valor de algunos de los nutrientes esenciales relevados (artículo 1, tabla 7), no impide cuestionar si el manejo de la fertilización actual no excedió las necesidades del cultivo de soja.

Nuestro estudio se destaca porque los resultados fueron obtenidos en campos de productores sin graves deficiencias de manejo y sobre el principal cultivo de la región, lo que valida la trayectoria de los CSs prevista con anterioridad por experimentos de largo plazo instalados en la zona en estudio. Concluimos que no es suficiente mantener una alta intensidad de uso del suelo y sembrar sin laboreo, sino que también es necesario aumentar la diversidad del CS mediante la inclusión de especies de fotosíntesis C_4 y la rotación con pasturas perennes. Cuando estos componentes no fueron incluidos en la rotación, se generó una trayectoria negativa en la calidad del suelo asociada a pérdida de servicios ecosistémicos de regulación y soporte que se tradujo en un incremento en las pérdidas por un uso ineficiente de los recursos. En condiciones de secano, sembrar soja sobre soja (YCC*SSbCF = 8 ± 1) implicó una pérdida de rendimiento de 0,9 Mg ha^{-1} al comparar con CSs que se encuentran en rotación (YCC*SSbCF < 7). Si pasar de secano a riego genera una disminución en la Yg^{Ef} de 1,1 Mg ha^{-1}, entonces la planificación de la diversidad del CS es el principal espacio para incrementar el rendimiento previo a regar y, por ende, explica en gran medida la transición de Yinf (Yg^{Ef} = 2,1 Mg ha^{-1}) a Ymed (Yg^{Ef} = 1,2 Mg ha^{-1}). Para quienes ya riegan y realizan un correcto uso del suelo, entonces su foco debería estar en ajustar la estrategia de nutrición del cultivo.

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