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Resumen

Los sistemas integrados arroz-ganadería en rotación con pasturas son habituales en Uruguay, siendo la base del incremento del rendimiento del arroz desde la década de 1970. Existe una tendencia a intensificar los sistemas a través del aumento de la frecuencia del cultivo de arroz, la introducción de la soja y la reducción o eliminación de las pasturas. Paralelamente, ha crecido el interés por herramientas que permitan monitorear el cultivo en tiempo real para mejorar el manejo agronómico y anticipar el rendimiento. El objetivo de este trabajo fue evaluar el impacto de largo plazo de la intensidad de uso del suelo, generado por rotaciones de intensidad variable, sobre la productividad y la estabilidad del rendimiento del arroz, así como analizar la evolución del Índice de Vegetación de Diferencia Normalizada (NDVI) durante el ciclo para estimar el potencial productivo. El estudio se realizó en el experimento de largo plazo de la UEPL-INIA Treinta y Tres, que contrasta seis rotaciones arroceras. El principal efecto sobre el rendimiento y su estabilidad se observó según el cultivo antecesor. Independientemente de la rotación, el arroz sembrado sobre soja presentó la mayor productividad (11,33 Mg ha^{-1}), seguido del arroz sobre pasturas (10,60 Mg ha^{-1}) y del arroz sobre arroz (9,46 Mg ha^{-1}). La soja como cultivo antecesor incrementó el rendimiento del arroz en todas las rotaciones, aunque redujo la estabilidad del rendimiento. Por otro lado, se observó una relación positiva y significativa entre el NDVI y el rendimiento a inicio de primordio (PI), aunque modesta (R^2 = 0,16), pero al excluir del análisis los antecesores de arroz, esta mejoró notablemente (R^2 = 0,54). Sin embargo, un valor alto de NDVI a PI no garantiza obtener altos rendimientos, dado que aún resta gran parte del ciclo donde distintos factores pueden limitar o reducir la productividad. En sistemas arroz-pastura, existen alternativas de diseño de la rotación que permiten aumentos sostenidos de la productividad del arroz, incluso en condiciones de alto potencial productivo. A su vez, el uso de herramientas de teledetección contribuye a fortalecer el manejo agronómico y a sostener la productividad en el tiempo.

Palabras clave: agroecosistemas integrados, arreglo de cultivos, monitoreo remoto

Rice productivity, yield stability and NDVI across contrasting rotation systems

Summary

Integrated rice–livestock systems in rotation with pastures are common in Uruguay and have been the foundation of rice yield increases since the 1970s. There is a current trend toward system intensification through increased rice frequency, soybean introduction and pasture reduction or elimination. At the same time, interest has grown in tools that enable real-time crop monitoring to improve agronomic management and yield estimation. The objective of this study was to evaluate the long-term impact of soil use intensity—arising from crop rotations of varying intensity—on rice yield and yield stability, as well as to analyze the evolution of the Normalized Difference Vegetation Index (NDVI) throughout the growing season to estimate yield potential. The study was conducted within the long-term rotation experiment (LTE) established in 2012 at UEPL, INIA-Treinta y Tres, which contrasts six rice-based rotations. The highest effect on yield and yield stability was observed by previous summer crops. Regardless of rotation, rice following soybean achieved the highest productivity (11.33 Mg ha^{-1}), followed by rice after pasture (10.60 Mg ha^{-1}) and rice after rice (9.46 Mg ha^{-1}). Soybean as the previous crop increased rice yield across all rotations, although it reduced yield stability. A positive, though modest, relationship between NDVI and yield was observed at panicle initiation (PI) (R^2 = 0.16), but when rice-after-rice cases were excluded, model fit improved substantially (R^2 = 0.54). However, a high NDVI value at PI does not guarantee high yields, as much of the growing season remains, during which multiple factors can limit or reduce productivity. For rice-pasture systems, alternative rotation designs allow sustained increases in rice productivity, even under high-yielding potential conditions. Furthermore, the use of remote sensing tools supports agronomic management and helps maintain productivity over time.

Keywords: integrated agroecosystems, rotation design, remote sensing

1. Introducción general

Garantizar la seguridad alimentaria mundial para el 2050 es uno de los desafíos más apremiantes. Con el crecimiento sostenido de la población mundial, se proyecta que la demanda de arroz — segundo alimento de mayor importancia para más de la mitad de la población del mundo— aumentará en torno a un 30 % (Deng et al., 2025). Los agroecosistemas sudamericanos tienen el potencial de satisfacer una parte importante de las futuras demandas globales (OECD-FAO, 2019). Para enfrentar este desafío, es esencial aumentar significativamente los rendimientos de las tierras agrícolas actuales, mejorar el desempeño ambiental y proteger los recursos naturales, aspectos que se engloban en el concepto de intensificación sostenible (IS) (Cassman y Grassini, 2020; Garnett et al., 2013; Pittelkow et al., 2016; Pretty y Bharucha, 2014; Tilman et al., 2002). Impulsado por Pretty en la década de 1990 (Pretty, 1997), la IS ha ganado una atención creciente en los últimos tiempos, especialmente en el contexto del desarrollo agrícola internacional (United Nations, 2012). La intensificación sostenible exige el rediseño de los sistemas agrícolas y un cambio hacia una mayor diversidad de cultivos, como medio para mejorar la productividad, la calidad del suelo y reducir la necesidad de fertilizantes y pesticidas (Cassman y Grassini, 2020; He et al., 2021; Mabhaudhi et al., 2019; Pretty et al., 2018).

El arroz (*Oryza sativa* L.) utiliza el 11 % de las tierras cultivables mundiales (FAO, 2024). Existe un consenso generalizado de que la intensificación es la estrategia más adecuada para aumentar la producción (Cassman y Grassini, 2020; Caviglia et al., 2019; Godfray y Garnett, 2014). Para incrementar la producción de arroz y minimizar el impacto ambiental en las tierras agrícolas actuales, es necesario primero contar con información sobre las brechas de rendimiento y la eficiencia de uso de recursos en los sistemas (Carracelas et al., 2023; Yuan et al., 2021). La brecha de rendimiento explotable se define como la diferencia entre el potencial de rendimiento alcanzable y el rendimiento promedio del productor actual (Van Ittersum et al., 2013). Entre los factores clave para reducir esta brecha, se destacan la rotación de cultivos y el cultivo previo (Cassman et al., 2003; Cassman y Grassini, 2020; Ribas, Streck et al., 2021; Tseng et al., 2021). Por ejemplo, el arroz en rotación con pasturas o soja presenta brechas de rendimiento menores en comparación con el monocultivo de arroz (Macedo et al., 2021, 2022; Meus et al., 2020; Ribas, Zanon et al., 2021; Theisen et al., 2017).

Sin embargo, evaluar la intensificación únicamente a partir de incrementos en el rendimiento promedio resulta insuficiente. Se requieren enfoques más integradores y complejos que, además de lograr altas productividades, aborden la estabilidad del rendimiento a lo largo del tiempo (Andrade et al., 2016; Bommarco et al., 2013; Li et al., 2019). Desde esta perspectiva, para sostener rendimientos altos y estables es necesario la incorporación de tecnologías de agricultura de precisión en las prácticas de manejo, particularmente aquellas orientadas al monitoreo y diagnóstico del cultivo en etapas tempranas (Nelsen et al., 2025; Zsebó et al., 2024). Diversos estudios señalan que el seguimiento temporal del estado del cultivo permite obtener estimaciones tempranas y continuas de su desempeño, facilitando la anticipación de variaciones en el rendimiento y con esto, el ajuste oportuno de las prácticas de manejo. En este contexto, el desarrollo de herramientas de monitoreo no destructivo, preciso y en tiempo real ha cobrado especial relevancia en los últimos años, siendo el Índice de Vegetación de Diferencia Normalizada (NDVI) uno de los indicadores más utilizados y efectivos para evaluar el estado del cultivo y anticipar el desempeño productivo en arroz (Aguilar et al., 2016; Ali et al., 2015; Cao et al., 2015; De la Casa y Ovando, 2007; Farias et al., 2023; Fita et al., 2024; Harrell et al., 2011; Moreno-García et al., 2013; Piedad-Rubio et al., 2020; Rufasto et al., 2017; Shane, 2021). El uso del NDVI se presenta como una posible herramienta complementaria para el análisis de la productividad y la estabilidad del rendimiento, al permitir caracterizar de forma dinámica el estado del cultivo y aportar elementos para la interpretación de los patrones productivos observados.

En Uruguay, la producción comercial de arroz comenzó en la década de 1930. Desde entonces, el área cultivada ha aumentado y ha mantenido aproximadamente el 1 % de la superficie del país en las últimas décadas, mientras que la producción total se incrementó en un 75 % (MGAP-DIEA, 2023). Esto se debe al rápido incremento del rendimiento por hectárea, el cual alcanzó los 8,2 Mg ha^{-1} (Carracelas et al., 2023). Tradicionalmente, la rotación de cultivos típica ha consistido en dos años de cultivo de arroz, seguidos por un período de dos a cuatro años de pasturas perennes, destinadas a la producción ganadera. Este modelo ha sido históricamente prevalente debido al mantenimiento de la fertilidad del suelo y la maximización del rendimiento del cultivo de arroz, así como un bajo uso relativo de insumos (Deambrosi, 2003; Macedo et al., 2022; Pittelkow et al., 2016). Sin embargo, existe una tendencia a intensificar los sistemas, ya sea por aumento de la frecuencia del cultivo de arroz, la inclusión de otros cultivos como la soja o por la incorporación de pasturas productivas más cortas (Macedo et al., 2017). Por otro lado, existe un creciente interés en herramientas que permitan monitorear el cultivo de arroz en tiempo real, con el objetivo de mejorar el manejo agronómico y anticipar el rendimiento.

Los procesos de intensificación y diversificación son sostenibles en la medida en que mantengan o incrementen la productividad. Dado esto, el objetivo de este trabajo fue evaluar el impacto de largo plazo de la intensidad de uso del suelo, generado por rotaciones de intensidad variable, sobre la productividad y la estabilidad del rendimiento del cultivo de arroz, así como analizar la evolución del NDVI durante el ciclo para detectar las variaciones en el rendimiento.

2. Rice yield and yield stability in long-term rotations in temperate South America

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2.1. Summary

Understanding the long-term impacts of crop rotation systems on rice (*Oryza sativa* L.) yield and stability is key to redesigning agroecosystems, optimizing management, and refining sustainable intensification strategies. This study evaluated the impacts of the rotation system and the previous crops on irrigated rice yield and its stability over nine years, using a RCB design experiment in Uruguay. Rotations were: 1) Rice1-Rice2-Perennial Pasture (R-PP); 2) Rice-Biannual Pasture (R-BP); 3) Rice1-Soybean1-Soybean2-Rice2-Perennial Pasture (R-Sy-PP); 4) Rice1-Soybean-Rice2-Sorghum (R-Crops); 5) Rice-Soybean (R-Sy); and 6) Continuous Rice (CR); all with winter cover crops between grain crops. The highest yields were obtained in rotations including soybean (R-Sy, R-Sy-PP, R-Crops: 11.03 Mg ha^{-1}), that were 7% and 15% higher than those including only pastures (R-BP and R-PP) and CR, respectively. However, the highest effect on yield and yield stability was observed by previous crops. Independently of rotation, rice following soybean had the greatest productivity (11.33 Mg ha^{-1}), followed by rice after pastures (10.60 Mg ha^{-1}), and rice after rice (9.46 Mg ha^{-1}). These differences were amplified in high-yielding years, with rice after soybean (12.72 Mg ha^{-1}) yielding 5%, 17% and 22% more than after perennial pastures, biannual pastures and rice, respectively. Soybean as a previous crop increased rice yield in all rotations but decreased yield stability as demonstrated by an environmental index combining four parameters. For rice-pasture systems in temperate climates, rotation intensification integrating soybean offers a viable strategy for increasing rice productivity, particularly in high-yielding years, despite lower yield stability.

Keywords: Integrated agroecosystems, yield gap, conservation systems, environmental index.

Productividad y estabilidad del rendimiento del arroz en rotaciones de largo plazo en América del Sur templada

2.2. Resumen

Comprender los impactos a largo plazo de la rotación de cultivos sobre el rendimiento y la estabilidad del arroz (*Oryza sativa* L.) es fundamental para rediseñar los agroecosistemas, optimizar el manejo y perfeccionar las estrategias de intensificación sostenible. Este estudio evaluó los efectos de la rotación y los antecesores sobre el rendimiento y la estabilidad del arroz durante nueve años en un LTE en Uruguay. Las rotaciones fueron 1) Arroz1-Arroz2-Pastura Perenne (R-PP); 2) Arroz-Pastura Bianual (R-BP); 3) Arroz1-Soja1-Soja2-Arroz2-Pastura Perenne (R-Sy-PP); 4) Arroz1-Soja-Arroz2-Sorgo (R-Crops); 5) Arroz-Soja (R-Sy); y 6) Arroz continuo (CR); todas con cultivos de cobertura invernales. Los mayores rendimientos se obtuvieron en las rotaciones que incluyeron soja (R-Sy, R-Sy-PP, R-Crops: 11,03 Mg ha^{-1}), siendo 7 % y 15 % superior a aquellas con solo pasturas (R-BP y R-PP) y al arroz continuo, respectivamente. Sin embargo, el mayor efecto sobre el rendimiento y su estabilidad se observó según el cultivo antecesor. Independientemente de la rotación, el arroz sembrado después de soja alcanzó la mayor productividad (11,33 Mg ha^{-1}), seguido del arroz después de pasturas (10,60 Mg ha^{-1}) y del arroz después de arroz (9,46 Mg ha^{-1}). Estas diferencias se ampliaron en los años de alto rendimiento, donde el arroz posterior a soja (12,72 Mg ha^{-1}) rindió 5 %, 17 % y 22 % más que después de pasturas perennes, pasturas bianuales y arroz, respectivamente. La soja como cultivo antecesor incrementó el rendimiento del arroz en todas las rotaciones, pero redujo la estabilidad del rendimiento, según lo demostrado por el índice ambiental. En los sistemas arroz-pasturas de climas templados, la intensificación de la rotación mediante la integración de soja representa una estrategia viable para aumentar la productividad del arroz, especialmente en años de alto potencial de rendimiento, aunque con menor estabilidad.

Palabras clave: agroecosistemas integrados, brecha de rendimiento, sistemas de conservación, índice ambiental.

2.3. Introduction

The design and management of agroecosystems are key to boost productivity, optimize inputs, and preserve natural resources for sustainable intensification process (Cassman and Grassini, 2020; He et al., 2021; Mabhaudhi et al., 2019; Pretty et al., 2018). Rotations systems and previous crops are among the main factors associated with irrigated rice (*Oryza sativa* L.) yield gaps in some regions worldwide (Cassman et al., 2003; Cassman and Grassini, 2020; Ribas, Streck et al., 2021; Tseng et al., 2021). Closing the yield gap will require fine tuning management related to agroecosystems design and rotations to improve resource-use efficiency (Carracelas et al., 2023; Yuan et al., 2021).

It is known that grain yield in irrigated rice rotated with pastures, soybean or other crops is higher compared with continuous rice or rice-rice sequences (Carmona et al., 2018; Macedo, Roel, Ayala et al., 2022; Macedo, Terra et al., 2021; Meus et al., 2020, 2024; Ribas, Zanon et al., 2021; Theisen et al., 2017). In Brazilian farms rice yield after soybean (9.12 Mg ha^{-1}) was 8% and 20% higher than fallow-rice and continuous rice, respectively (Meus et al., 2020). Similarly, in Argentinian farms rice productivity following pastures or annual crops was 8% and 6% higher compared to rice after rice (7.77 Mg ha^{-1}) (Meus et al., 2024). However, the interaction between rotations design and previous crops with the yield potential of different years — determined by climatic conditions, seeding date and other management factors affecting yield— remains largely unexplored.

In addition to increasing productivity, more integrative and complex approaches are needed to address yield stability (Andrade et al., 2016; Bommarco et al., 2013; Li et al., 2019). Stable cropping systems reduce uncertainty and the risks associated with yield variability across years (Sanford et al., 2021). Evidence suggests that management approaches promoting crop rotation and diverse systems with greater perenniality (e.g., crop-pasture rotations) enhance yield stability (Bowles et al., 2020; De Albuquerque Nunes et al., 2021; Gaudin et al., 2015; Sanford et al., 2021). Yield stability can be assessed using different parameters (Eberhart and Russell, 1966; Finlay and Wilkinson, 1963; Francis and Kannenberg, 1978; Shukla, 1972). In our study, we define stability based in yield variability, considering a system stable if it exhibits minimal changes in response to environmental fluctuations (De Albuquerque Nunes et al., 2021; Li et al., 2019; Macedo, Roel, Velazco et al., 2022).

The temperate-subtropical transition region of South America offers significant potential for irrigated rice production, driven by high-yielding cultivars adapted to favorable climatic conditions, suitable soil for cropping, and adequate freshwater resources for irrigation (Meus et al., 2024; Yuan et al., 2021). Over the past 50 years, Uruguay has adopted diverse integrated rice-livestock systems with varying levels of intensification (Castillo et al., 2021; Deambrosi, 2003). In contrast, rice-based systems in other countries in the region tend to be more intensive and less diversified, with a higher frequency of rice cultivation (Meus et al., 2022; Ribas, Zanon et al., 2021). Although these systems were relatively segmented and often decoupled in the past, they have undergone progressive transformations and design adjustments in recent years (De Faccio Carvalho et al., 2021). Currently, Uruguay is trending toward intensifying and diversifying rice-pasture systems, whereas in the broader region farmers are shifting toward diversifying rice-fallow and continuous rice systems. In both cases, these adjustments involve integrating other crops (mostly soybean), and/or short-term pastures or cover crops into existing rice production systems (Carmona et al., 2018; Macedo, Roel, Ayala et al., 2022; Ribas, Zanon et al., 2021).

Long-term agricultural experiments (LTE) are strategic platforms for assessing the cumulative impacts of crop rotation systems, and soil management practices on agricultural systems (Johnston and Poulton, 2018). In 2012, an LTE was initiated in Uruguay to assess the sustainability of contrasting intensification and diversification strategies within existing rice-pasture agroecosystems (Macedo, Terra et al., 2021). This LTE involved shortening or eliminating the pasture phase and/or integrating additional crops into a stable rice-pasture system to evaluate the productive, economic, and environmental impacts (Castillo et al., 2023; Macedo, Roel, Velazco et al., 2022).

Understanding the long-term impact of different crop rotations and previous crops—including rice, other grain crops, cover crops and grazed pastures—on rice yield and its stability is a key step in optimizing rotation management, providing valuable insights for redesigning cropping systems and refining sustainable intensification strategies. We hypothesize that rice-pasture systems can be adjusted to intensify production and increase rice grain yield without compromising long-term yield stability. We analyzed rice grain yield data from a rice-based rotation systems LTE spanning nine consecutive cropping seasons under variable climatic conditions, aiming to: (a) quantify the effect of crop rotation and previous summer crops on rice yield and its stability; (b) assess whether the impact of rotation or previous crops varies depending on the yield potential of a given year; and (c) estimate the probability of achieving low or high rice yield based on rotation or previous crops.

2.4. Materials and methods

2.4.1. Site description

The long-term experiment was established in 2012 at the INIA "Paso de la Laguna" Experimental Unit, Treinta y Tres, Uruguay (33°16′22″S, 54°10′23″W). The site has a humid temperate climate, with a mean temperature of 22.3 ± 0.85 °C in summer and 11.5 ± 0.82 °C in winter. The annual average rainfall is 1,360 ± 315 mm, with substantial intra- and interannual variability. The dominant soil at the site is a Typic Argialboll according to the USDA Soil Taxonomy, in a flatland with a slope lower than 0.5% (Durán et al., 2006). Initial soil analysis (0 to 15 cm depth) indicated pH 5.7 (1:1 soil/water extract), a silty clay loam texture (clay 300 g kg^{-1}, silt 510 g kg^{-1}), bulk density of 1.25 g cm^{-3}, organic carbon content of 14.2 g kg^{-1}, total nitrogen of 1.4 g kg^{-1}, phosphorus content of 10.3 mg kg^{-1} (Bray 1), and exchangeable potassium, calcium and magnesium of 0.25, 7.0, and 2.8 cmol kg^{-1}, respectively (Macedo, Roel, Ayala et al., 2022). Before the experiment was established, the site maintained a stable rice-pasture rotation for 34 years, with rice occupying 33% of the time and mixed perennial pastures covering the remaining 67%. Between 2000 and 2009, the mean rice yield at the site was 7.27 ± 1.67 Mg ha^{-1}.

2.4.2. Treatments and experimental design

The experiment consisted of six rice-based rotation systems arranged in a randomized complete block design with three replications, with all rotation phases present in time and space (Patterson, 1964). The experiment was set across 60 plots of 1,200 m^2, each representing one phase of the six rotations. All rotations included irrigated rice that was flooded for 100-110 days, from the beginning of crop tillering to physiological maturity when plots were drained for mechanical harvest.

The rotations were: a) Rice1-Rice2-Perennial Pasture (3.5 years), composed of *Festuca arundinacea*, *Lotus corniculatus* and *Trifolium repens* (R-PP, 5 years rotation); b) Rice-Biannual Pasture (1.5 years), composed of *Lolium multiflorum* and *Trifolium pratense* (R-BP, 2 years rotation); c) Rice1-Soybean1-Soybean2-Rice2-Perennial Pasture (2.5 years), composed of *Festulolium* sp. and *Lotus corniculatus* (R-Sy-PP, 6 years rotation); d) Rice1-Soybean-Rice2-Sorghum (R-Crops, 4 years rotation); e) Rice-Soybean (R-Sy, 2 years rotation); Continuous Rice (CR) (Table 1). Annual cover crops of annual ryegrass (*Lolium multiflorum*) (Lm) and Egyptian clover (*Trifolium alexandrinum* L.) (Ta) were installed in all rotations between grain crops. Rotations were classified based on land-use intensity, defined by the number of crops per year and the frequency of rice cultivation per year. For instance, CR had the same overall cropping intensity as R-Sy and R-Crops but a higher rice frequency, whereas R-Sy had greater cropping intensity than R-BP but the same rice frequency.

Table 1. Scheme of crop rotation systems evaluated in the long-term experiment, organized by their sequence duration (years) and ordered by soil use intensity and crop diversity.

	Years											
	1		2		3		4		5		6	
Rotation	SS	AW	SS	AW	SS	AW	SS	AW	SS	AW	SS	AW
R-PP	Rice1	Lm	Rice2	Perennial Pasture								
R-BP	Rice	Biannual Pasture										
R-Sy-PP	Rice1	Lm	Sy1	Lm	Sy2	Ta	Rice2	Perennial Pasture				
R-Crops	Rice1	Lm	Sy	Ta	Rice2	Ta	Sg	Ta				
R-Sy	Rice	Lm	Sy	Ta								
CR	Rice	Ta										

Note: R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Lm: *Lolium multiflorum*, Ta: *Trifolium alexandrinum* L., Sy: Soybean, Sg: Sorghum, SS: Spring-Summer, AW: Autumn-Winter.

2.4.3. Site and crop management

The land was systematized, leveled, and tilled at the beginning of the experiment using disk harrows and a land plane. Rice was no-till seeded on dry soil each year between October 10th and November 10th, after a chemical fallow of 4–6 weeks. Adapted local high-yielding Indica rice cultivars (INIA Olimar or INIA Merín) and occasionally a Japonica cultivar (INIA Parao), targeting 200–250 plants m^{-2}, were seeded annually. Rice plots were flooded within 4 weeks after the emergence at the beginning of crop tillering. Cover crops and pastures were broadcast-seeded without tillage immediately after cash crops harvest in April-May.

Grain crops and pastures were fertilized annually, based on different criteria among rotations. In the CR and R-Sy rotations, phosphorus and potassium applications followed a replacement approach based on the nutrient extraction of the previous crop, whereas in the other rotations, they were based on the soil test critical levels for each crop. Perennial and biannual pastures were fertilized at sowing with an average of 14 kg N ha^{-1}, 38 kg P_2O_5 ha^{-1}, and 38 kg K_2O ha^{-1}, followed by annual fertilization with 42 kg P_2O_5 ha^{-1}. Cover crops of Ta and Lm were not fertilized. Nitrogen application rates for rice were determined based on the anaerobic soil nitrogen mineralization potential, except in the CR system, where fertilization was adjusted for a N absorption of a 10 Mg ha^{-1} yield crop. Nitrogen was broadcasted as urea in rice crops, splitting 70% of the recommended rate at tillering initiation (V4 stage) on dry soil immediately before flooding, and the remaining 30% at panicle initiation (R0 stage) on flooded soil (Counce et al., 2000). According to these criteria, the average nutrient application in rice had some differences shown in Table 2.

Table 2. Average nutrient units applied to rice crops across rotations systems and their phases during nine years in a long-term experiment in Uruguay.

Rotation		N	P_2O_5	K_2O
			kg ha^{-1}	
R-PP	Rice1	81	15	36
	Rice2	109	23	54
R-BP	Rice	110	22	55
R-Sy-PP	Rice1	84	24	36
	Rice2	106	15	33
R-Crops	Rice1	93	22	44
	Rice2	109	25	40
R-Sy	Rice	95	59	79
CR	Rice	153	78	52

Note: R: Rice, PP: Perennial Pasture, BP: Biannual Pasture,
CR: Continuous Rice, Sy: Soybean.

Pastures were rotationally grazed by sheep from March to December, while cover crops were not grazed. For a quick overview, the mean productivity of biannual and perennial pastures at the site was 3.45±2.09 Mg ha^{-1} yr^{-1} and 4.71±2.19 Mg ha^{-1} yr^{-1}, respectively. Conversely, the mean biomass production of Egyptian clover and ryegrass cover crops was 1.87±1.09 Mg ha^{-1} yr^{-1} and 1.60±0.81 Mg ha^{-1} yr^{-1}, respectively. Meanwhile, soybean yielded on average 2.45±0.97 Mg ha^{-1} yr^{-1}, and sorghum reached 4.80±0.82 Mg ha^{-1} yr^{-1} (Ayala and Terra, 2023; Macedo, Pravia et al., 2021).

All agricultural operations, including sowing, fertilization, pesticide applications, and harvesting, were carried out using commercial farmers equipment. Most management practices implemented in the experiment followed the existing extension recommendations for crops and pastures in the country (ACA, 2018).

2.4.4. Data collection and measurements

This study analyzed rice grain yield data collected over nine growing seasons (from 2014/2015 to 2022/2023) under varied climatic production conditions. Yield data from the first two seasons (2012/2013 and 2013/2014) were excluded from the analysis, as the experiment treatments were still undergoing stabilization.

Grain yield was quantified in each of the 27 plots (1,200 m^2 each) sown annually with rice, representing simultaneously the nine phases of the six rotation systems replicated three times in space. Harvesting was performed using a commercial New Holland TC5070 combine, and grain weight was measured with a Magris MTV 206 digital scale mounted on a self-unloading grain cart. Rice yield was reported at a standardized moisture grain content of 13% and clean.

2.4.5. Data analysis

To analyze productivity and yield stability a "de-trended yield data" approach was applied to remove potential biases associated with yield increases due to genetic and technological improvements over the years (De Albuquerque Nunes et al., 2021; Li et al., 2019). This effect was tested and found to be non-significant during the evaluated growing seasons; therefore, the actual yield data were used in the analysis.

2.4.5.1. Rice grain yield

We evaluated the effects of rotations, rotations phases and previous crops on rice yield, considering both overall effects across all seasons and within yield groups. The grouping was not arbitrary, but based on percentiles (low 33%, medium 33%, high 33%) of the observed rice yield potential across nine seasons, which conveniently coincided with distinct climatic periods. This approach allowed us to capture a gradient of environmental variability without assuming normality, consistent with standard practices in crop stability analyses (Finlay and Wilkinson, 1963). Rice yield analysis across rotations, rotations phases and previous crops was conducted using a linear mixed model, where block and rotation (or rotations phases or previous crops) were considered fixed effects, while year and rotation by year interaction were included as a random effects. Model selection was based on the

Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). Residual diagnostics were performed to check assumptions of normality and homoscedasticity using the Shapiro-Wilk and Levene tests, respectively. Mean comparisons were conducted using Tukey's test at a significance level of 0.05. All statistical analyses were performed in R (4.2.1) (R Core Team, 2022). The "lme" function from the "nlme" package was used to fit the linear mixed models, while mean comparisons were performed using the "multcomp" and "cld" packages. Graphical representations were generated using the "ggplot2" package.

2.4.5.2. Yield risk analysis

Risk analysis was conducted using the mean yield of each rotation phase and exceedance probability based on the cumulative frequency distribution (Roel et al., 2020).

$$\text{Exceedance probability} = 1 - \text{cumulative frequency.}$$

The exceedance probability was calculated for each rotation phase. Low yield was defined as the 20th percentile of the dataset (<9.23 Mg ha^{-1}), while high yield was defined as the 80th percentile (>11.76 Mg ha^{-1}).

2.4.5.3. Rice yield stability

An environmental index was analyzed by ranking the mean yield of each growing season (from lowest to highest productivity). A baseline environment (Env 0) was set as the mean yield across the nine growing seasons (10.59 Mg ha^{-1}). For better interpretation x-axis was displayed as deviation from Env 0 and plotted every 1 Mg ha^{-1}.

Four yield stability parameters were calculated and (De Albuquerque Nunes et al., 2021): yield range (YR), coefficient of variation (CV), standard deviation of yield (SD), and the Finlay-Wilkinson regression slope (FW) (Finlay and Wilkinson, 1963). Yield range (YR): the difference between the highest and lowest yield for each rotation phase (RP) across all years. Coefficient of variation (CV): calculated as the standard deviation divided by the mean yield. Standard deviation (SD): represents temporal variability over the nine years. Finlay-Wilkinson slope (FW): obtained by regressing yield from each rotation phase (RP) against the environmental index (EI). Rotation phases with lower YR, CV, SD, and FW slopes indicate higher yield stability. The overall yield stability ranking was determined as the average rank across the four stability parameters.

2.5. Results

2.5.1. Rice grain yield

The average rice yield at the site over nine years was 10.59 Mg ha^{-1}, with a coefficient of variation of 14% (Figure 1). The mean rice productivity of the three highest yielding seasons was 23% higher compared with the three lowest-yielding seasons (9.52 Mg ha^{-1}). Yield differences among years were significantly associated (R^2= 0.49) with solar radiation levels during the three weeks before and after panicle differentiation.

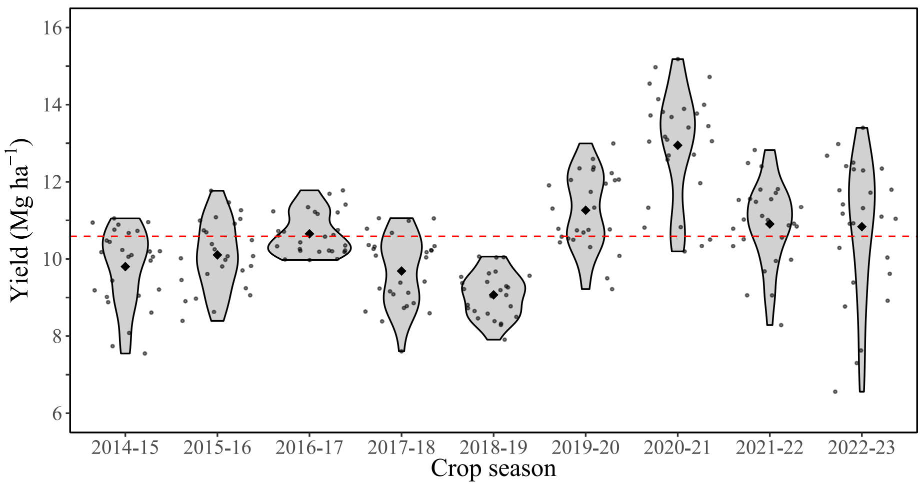


Figure 1. Violin plot showing rice yield path and distribution during nine growing seasons in a long-term rotation systems experiment in Uruguay. The dashed red line denotes the nine-year mean yield (10.59 Mg ha^{-1}). Black diamonds indicate the mean yield for each year. The shaded area represents the estimated shape of the data distribution.

There were significant effects of rotation on rice yield. The highest yields were obtained in all rotations that included soybean, whereas the lowest yield occurred under CR (Table 3). On average, yield in rotations including soybean (R-Sy, R-Sy-PP, R-Crops: 11.03 Mg ha^{-1}) was 7% and 15% higher than in rotations including only pastures (R-PP and R-BP: 10.27 Mg ha^{-1}) and CR, respectively. No significant yield differences were observed among the soybean-inclusive rotations or between the pasture-only rotations. Overall, rice yield increased with higher cropping intensity, except in CR that had the lower yield. However, no clear relationship was found between yield and rice frequency across rotations. For instance, R-BP, R-Crops, and R-Sy had the same rice frequency (one rice crop every two years), but yield differences were more closely associated with cropping intensity or previous crop.

Table 3. Mean rice yield and standard error by rotations during nine years in a long-term experiment in Uruguay. Letters indicate significant differences in adjusted means at a 0.05 significance level.

Rotation	Yield
	——Mg ha^{-1}——
R-Sy	11.14 ± 0.41 a
R-Sy-PP	11.07 ± 0.39 a
R-Crops	10.88 ± 0.39 ab
R-BP	10.41 ± 0.41 bc
R-PP	10.12 ± 0.39 c
CR	9.58 ± 0.41 d

Note: R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Sy: Soybean.

Regardless of the rotation, the highest yields were observed in rice preceded by soybean (11.33 Mg ha^{-1}), followed by rice preceded by perennial pastures (10.80 Mg ha^{-1}), while the lowest productivity was recorded in rice seeded after rice (9.46 Mg ha^{-1}) (Figure 2). No differences in rice yield were found among perennial or biannual pastures and sorghum as previous crops.

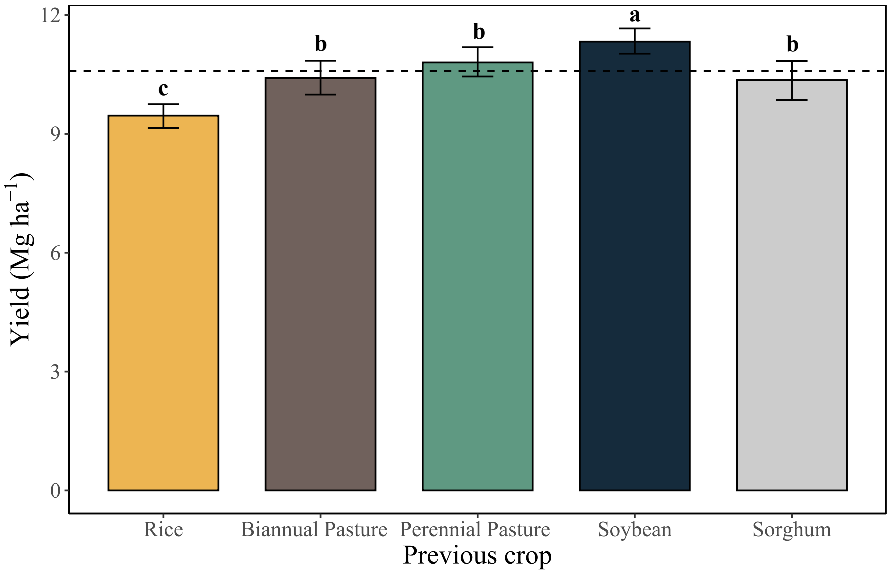
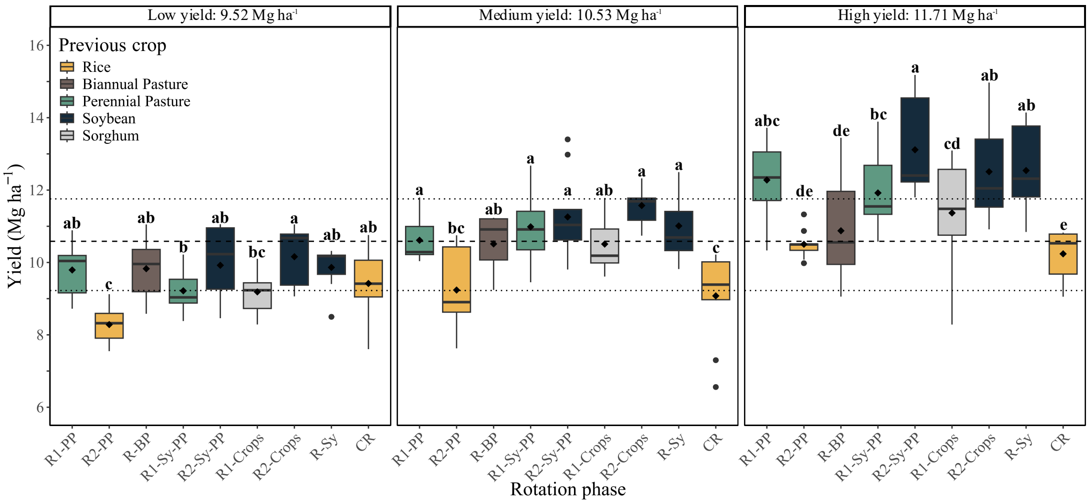


Figure 2. Mean rice yield and standard error by previous summer crop during nine years (2014/2015 to 2022/2023 seasons) in a long-term rotation systems experiment in Uruguay. The dashed line represents the nine-year mean yield (10.59 Mg ha^{-1}). Letters indicate significant differences in adjusted means at a 0.05 significance level.

To evaluate the effect of rotation phases or previous crops within years of contrasting yield potential at the site, analyses were conducted by grouping the nine growing seasons into the three of lowest, medium, and highest rice yielding categories (Figure 3). In rotations with two phases (R-PP, R-Sy-PP, R-Crops), significant overall yield differences were observed between Rice1 and Rice2 within the same rotation, highlighting the relevant effect of the previous crop. First, R1-PP (following pastures) had higher yields than R2-PP (following rice) across all yield categories. Secondly, R1-Sy-PP (after pastures) yielded less than R2-Sy-PP (after soybean) only in high-productivity years. Finally, R1-Crops (after sorghum) yielded less than R2-Crops (following soybean) in both low- and high-productivity years.

Grouping all rotations phases by previous crops, in low-productivity years, no significant yield differences were observed between rice sown after perennial pastures (9.50 Mg ha^{-1}) and soybean (9.98 Mg ha^{-1}); however, both yielded higher than rice following rice (8.85 Mg ha^{-1}). In contrast, in high-productivity years, rice yield after perennial pastures was 5% lower than those following soybean (12.72 Mg ha^{-1}) but 17% higher than rice grown after rice (10.37 Mg ha^{-1}). Regardless of seasonal productivity potential, rice seeded after rice exhibited regularly the lowest yields.

No rice yield differences were found among the different rotation phases following soybeans, regardless of the season productivity potential. However, in high-productivity years, perennial pastures increased subsequent rice yields by 11% compared to biannual pastures (10.89 Mg ha^{-1}). Although no significant yield differences were observed for rice seeded after rice in medium and high-productivity years, in low-productivity years, continuous rice yielded 14% more than rice following rice in rotation with pastures (R2-PP: 8.28 Mg ha^{-1}).

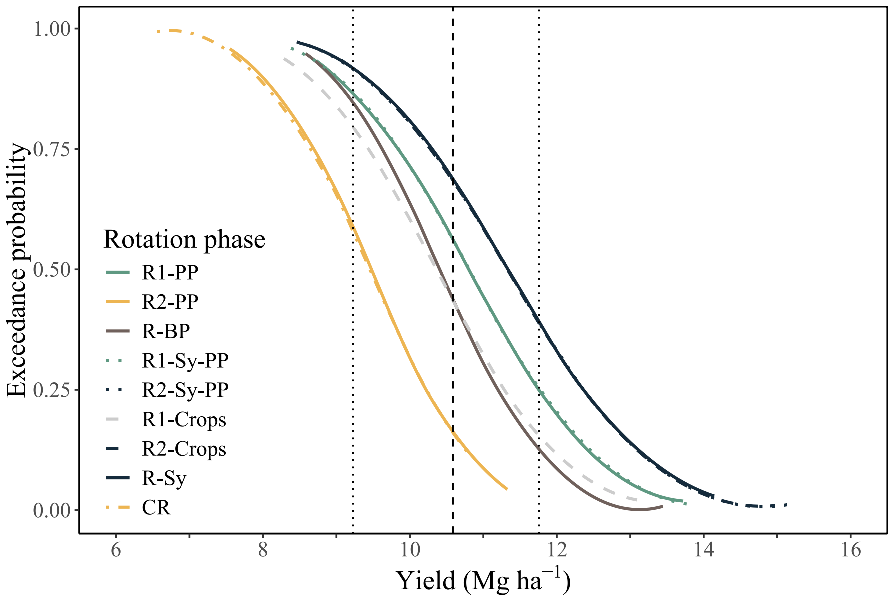


R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Sy: Soybean.

Figure 3. Mean rice yield by rotation phase (color-coded by the previous summer crop), grouped by low-, medium-, and high-productivity years in a long-term experiment in Uruguay. The dashed line denotes the nine-year average yield (10.59 Mg ha^{-1}). The dotted lines indicate the 20th (9.23 Mg ha^{-1}) and 80th (11.76 Mg ha^{-1}) percentiles. Black diamonds are the mean yield of each rotation phase. Letters indicate significant differences in mean yield at a 0.05 significance level within yield groups.

2.5.2. Yield risk analysis

Rotation phases with the same preceding crop exhibited analogous patterns in the probabilities of attaining low and high rice yields (Figure 4). Thus, the exceedance probability curves for R2-PP and CR were very similar, as were those for the two phases following perennial pastures and the three phases following soybean. The probability of obtaining rice yield above the nine years average (10.59 Mg ha^{-1}) was 16%, 43%, 56%, and 69% when the previous crop was rice, biannual pasture or sorghum, perennial pasture, and soybean, respectively. The probability of reaching high rice yields (percentile 80: >11.76 Mg ha^{-1}) was 39% when the predecessor was soybean and 25% when was a perennial pasture. However, there was no probability of achieving such high yields when rice was the previous crop. Conversely, when rice was the previous crop, the probability of obtaining low yields (percentile 20: <9.23 Mg ha^{-1}) was 42%, whereas for soybean and perennial pasture, the probabilities were 8% and 13%, respectively. Biannual pasture and sorghum as previous rice crops showed intermediate probabilities for both high (13% and 15%, respectively) and low yields (15% and 20%, respectively).



R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Sy: Soybean.

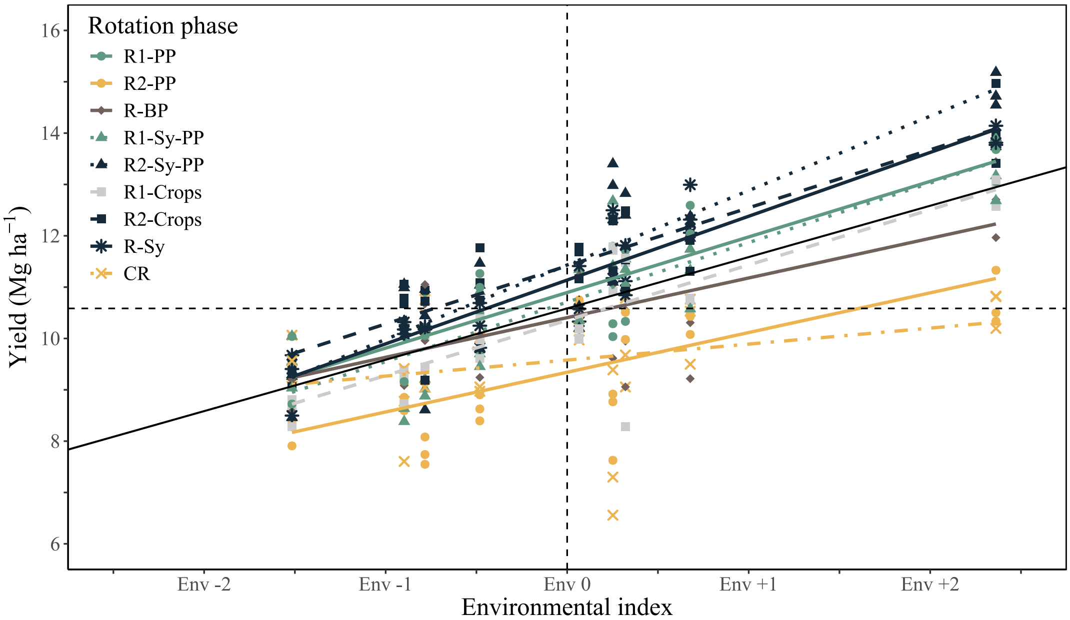
Figure 4. Probability of obtaining low and high rice yield across rotation phases analyzed during nine years in a long-term experiment in Uruguay. The dashed line represents the nine-year mean yield (10.59 Mg ha^{-1}). The dotted lines indicate the 20th and 80th percentiles (9.23 and 11.76 Mg ha^{-1}, respectively). Color-coded by the previous summer crop.

2.5.3. Rice yield stability

Stability analyses were conducted to examine the interaction between rotation phases or previous crops along the environmental index gradient. In general, rice yield exhibited a positive response to increases in the environmental index across nearly all rotation phases (Figure 5). However, CR was the only system where the slope was not significantly different from zero, yet its productivity was higher than that of R2-PP under low-yielding environments, despite sharing the same previous crop. Rice yield was higher under all environmental conditions when preceded by soybean or a perennial pasture rather than by sorghum, biannual pasture, or rice. Additionally, a rotation trend was observed, with steeper yield slopes achieved within the same predecessor (soybean or rice) when the rotation also included pastures, maximizing productivity in high-yielding environments. In low-productivity environments, rice yield differences among rotation phases were relatively small. However, in high-productivity environments, these yield gaps widened significantly both, in absolute and relative terms. The gap between the highest rotation phase yield and the mean productivity for each year increased from 0.80 Mg ha^{-1} (8%) in the three lowest-yielding environments to 1.22 Mg ha^{-1} (12%) in the three medium-yielding environments and 1.49 Mg ha^{-1} (13%) in the three highest-yielding environments.

The overall yield stability ranking first classified rotations and then ranked individual phases within each rotation (Table 4). Although the four stability parameters did not produce identical rankings, they contributed differently to the overall stability classification of the various rotation phases. There are stable rotations phases but with low yield levels, and unstable phases that respond positively to environmental improvements. Rice in rotations that included soybeans was the most productive but the least stable, indicating highest responses to environmental gradients (Table 4, Figure 5). Rice in CR exhibited the most stable yield, with the lowest standard deviation and Finlay-Wilkinson (FW) slopes among all rotation phases. While the second rice in rotation with pastures (R2-PP) had the narrowest yield range and ranked third in terms of standard deviation and FW slope. The lowest coefficient of variation (CV) was observed in rice in R-BP, followed by

CR. The less stable rotation phase was R2-Sy-PP, which exhibited the highest values for all stability parameters but also the highest productivity. The CV of R2-Sy-PP was 1.12, 1.25, and 1.34 times greater than that of R1-Sy-PP, R1-PP, and CR, respectively. Similarly, its standard deviation was 20%, 31%, and 61% higher than that of R1-Sy-PP, R1-PP, and CR, respectively. Despite similar productivity, rice yield stability following pastures was lower when the rotation included soybeans (R1-Sy-PP) compared to pastures-only rotations (R1-PP and R-BP). Rice following pastures in the R1-PP phase accomplished both high productivity, similar to rice after soybean, and greater yield stability.



R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Sy: Soybean.

Figure 5. Relationship between rotation phase productivity and environmental index (EI) as indicator of rice yield stability during nine years in a long-term experiment in Uruguay. Env 0: 10.59 Mg ha^{-1}, Env +1: 11.59 Mg ha^{-1}, Env +2: 12.59 Mg ha^{-1}, Env -1: 9.59 Mg ha^{-1}, Env -2: 8.59 Mg ha^{-1}. Black dashed lines represent the nine-year mean yield (10.59 Mg ha^{-1}). The solid black line indicates the 1:1 reference line.

Table 4. Rice yield stability parameters and overall ranking for different rotation phases during nine growing seasons (2014/2015 to 2022/2023) in a long-term experiment in Uruguay. Numbers in parentheses indicate the individual ranking within each stability parameter. RR represents the yield range, CV the coefficient of variation, SD the standard deviation, and FW the Finlay-Wilkinson regression slope.

Rotation Phase	Previous crop	Rice Yield	Stability Parameters				Ranking
			RR	SD	CV	FW	
		———— Mg ha^{-1} ————			%		
CR	Rice	9.58d	4.27 (2)	1.09 (1)	11.44 (2)	0.31 (1)	1.50
R-BP	BP	10.41c	4.86 (4)	1.14 (2)	10.99 (1)	0.77 (2)	2.25
R2-PP	Rice	9.34d	3.78 (1)	1.17 (3)	12.56 (5)	0.77 (3)	3.00
R1-PP	PP	10.90abc	4.99 (5)	1.34 (4)	12.29 (4)	1.08 (5)	4.50
R1-Crops	Sorghum	10.36c	4.81 (3)	1.36 (6)	13.09 (7)	1.08 (4)	5.00
R2-Crops	Soybean	11.41a	5.91 (8)	1.35 (5)	11.85 (3)	1.13 (6)	5.50
R-Sy	Soybean	11.14ab	5.65 (7)	1.44 (7)	12.92 (6)	1.24 (8)	7.00
R1-Sy-PP	PP	10.71bc	5.51 (6)	1.47 (8)	13.73 (8)	1.16 (7)	7.25
R2-Sy-PP	Soybean	11.43a	6.72 (9)	1.76 (9)	15.38 (9)	1.45 (9)	9.00

Note: Letters indicate significant differences in adjusted yield means at a 0.05 significance level. R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Sy: Soybean.

2.6. Discussion

This study contributed to understanding the long-term effects of crop rotation systems and previous crops on rice yield and its stability. This long-term experiment provided valuable insights into the cumulative effects of rotations on rice yield, generating robust data to support the design and management of rice production systems (De Albuquerque Nunes et al., 2021; L. Zhang et al., 2022). We adapted a stability analysis commonly used in genotype-by-environment interaction studies (Eberhart and Russell, 1966; Finlay and Wilkinson, 1963; Shukla, 1972) to assess rice yield stability across different rotations and growing seasons, rather than focusing solely on mean yield. Overall, our findings revealed significant effects of crop rotation and previous crops on rice yield and yield stability over nine years. We identified alternatives for intensifying rice–pasture rotation systems; however, those that increased rice grain yield tended to reduce long-term yield stability.

Unlike findings in rainfed cropping systems (Ernst et al., 2016; Grover et al., 2009; Rizzo et al., 2021), our study revealed mostly no significant or minimal yield differences among rotation phases in low-yielding years. However, in high-yielding years, these differences became more pronounced, with significant variations based on rotation phase and previous crops (Figures 3 and 5). Linquist et al. (2025) found that the rice yield gap in California varied across years, with larger gaps in high-yielding years and smaller gaps in low-yielding years. They suggested that best management practices in irrigated rice have a greater impact in favorable environments than in unfavorable ones, as was found in our study. According to Finlay and Wilkinson (1963), regression slopes greater than 1.0—observed in all rotations including soybeans indicate greater sensitivity to environmental changes (below-average stability) and increased adaptability to high-yield environments. Conversely, slopes below 1.0, as found in CR, R-BP and R2-PP, reflect greater resilience to environmental variability (above-average stability) and better adaptation to low-yield environments.

The CR exhibited high yield stability, but productivity was consistently low across all years, not capitalizing high-yielding environments. In contrast, rice in R2-Sy-PP had the lowest stability ranking but the highest mean productivity, reaching up to 94% of the country's yield potential (13.90 Mg ha^{-1}) in high-yielding seasons (Carracelas et al., 2023). These findings align with previous research indicating that the most stable systems are not necessarily the highest yielding (X. Fan et al., 2007) and that rice yield gaps are higher in high-yielding environments (Linquist et al., 2025). The fact that rotations integrating soybean reached high rice yield in all environments, but ranked lower in stability, suggests that their benefits were more pronounced in high-yielding environments without penalizing low-yielding ones, making them a valuable opportunity to intensify and/or diversify current production systems. Ribas, Zanon et al. (2021) reported that soybean as a previous crop increased rice productivity but, in contrast with our findings, decreased yield variability. The similar yield but better stability of rice in R1-PP compared to other phases after soybean strengthens the findings of Macedo, Roel, Velazco et al. (2022) regarding the greater stability of sustainability in rice-pasture systems, as shown through multiple indicators. The reason why rice yield stability decreases following soybeans remains unclear, as does the reduction in stability observed when soybean is integrated into a rice-pasture rotation, as inferred from the comparison between R1-PP and R1-Sy-PP, which showed similar yields but different stability rankings. Hence, the design of rice rotation systems—particularly the choice of the previous summer crop—emerges as a key factor in narrowing the rice yield gap in the region (Cassman and Grassini, 2020; Ribas, Streck et al., 2021; Tseng et al., 2021).

Rice rotations systems including soybeans or pastures have positive impacts on rice yield (Carmona et al., 2018; Denardin et al., 2022; Meus et al., 2020, 2024; Ribas, Zanon et al., 2021). Legumes in rotation contribute to biological nitrogen fixation and produce low C/N ratio residues that enhance microbial activity and nitrogen cycling (Benintende et al., 2008; Castillo et al., 2023; Denardin et al., 2022; Ghosh et al., 2019; Xing et al., 2023; Zhou et al., 2023). In Australia, legume-based pastures played a key role in sustaining productivity and soil fertility in temperate rice systems (Lattimore, 1994). Beecher et al. (1994) found that rice productivity following short- and long-term pastures was approximately 20% greater than under continuous cropping (≈10.30 Mg ha^{-1}). These results are consistent with our findings, where rice following perennial pastures yielded 14% more than continuous rice. Additionally, rotating with pastures increases microbial community size and activity due to the quantity and quality of plant residues supplied during the pasture phase, increasing soil nitrogen availability for following crops (Benintende et al., 2008; Carlos et al., 2020). This aligns with historical nutrient application rates in our LTE, which suggest differential soil nutrient supply capacity among rotations.

Rice residues lead to the accumulation of phenolic oxidation compounds and dissolved organic carbon, that can reduce nitrogen mineralization and promote immobilization (Aumtong et al., 2023; Olk et al., 1996; Yu et al., 2020; Z. Zhang et al., 2025). As soil nitrogen supply capacity declines under intense rice cropping (Heenan et al., 2004), legume cover crops aim to emulate the benefits of pastures in the short term. For example, a 10% positive effect of a subterranean clover cover crop on rice yield was observed at several nitrogen rates in rice-based systems including soybean and sorghum in the southern United States (Dabney et al., 1989). More recently, a meta-analysis found that winter legume cover crops increased subsequent rice yield by 16% in China, an effect mostly explained by nitrogen fixation but not exclusively (F. Fan et al., 2021). Another meta-analysis by Yao et al. (2025), which included studies from 17 countries and several rice-based systems, reported that legume inclusion increased subsequent rice yields by an average of 16% worldwide. The greatest yield responses were observed under low nitrogen input, conservation tillage, and low diversity cropping systems. In southern Brazil, Weinert et al. (2023) observed that including a legume cover crop in continuous rice systems not only increased rice yield by 8% but also reduced the crop's response to nitrogen fertilization. Thus, it is plausible that in our study we may have overestimated the contribution attributed to soybean, as part of the yield response could be explained by the effect of winter Egyptian clover. This may also help explain the relatively good performance observed in the CR compared with R2-PP, which was not preceded by a winter legume despite rotating with pastures. When analyzing the entire rotation systems in the LTE, Castillo et al. (2023) found that the nitrogen balance in R-PP was nearly neutral, while in R-Sy a deficit was observed despite the presence of both a winter legume cover and soybean. Conversely, in CR, nitrogen inputs exceeded crop requirements, generating a surplus.

The combined effect of rice-rice sequences with high nitrogen rates raises the possibility of negative effects associated with yield-reducing factors. The incidence of weeds and diseases may be exacerbated by the higher nitrogen fertilization required to compensate for lower soil nitrogen mineralization potential (Keim and Webster, 1973; Konthoujam et al., 2007). Growing rice in rotation with pastures and/or other crops reduces weed pressure (Lattimore, 1994; Scherner et al., 2018) and lowers the incidence of stem and sheath diseases compared with continuous rice, where greater inoculum buildup often occurs (Martinez, 2023). Additionally, rice grown after rice often exhibits uneven plant stands due to volunteer plants, which, combined with the higher nitrogen rates typically applied and the presence of stressed or diseased plants, make the crop more susceptible to cold-induced sterility during the reproductive stages (Gunawardena and Fukai, 2005). Furthermore, high-intensity rice systems have been associated with soil structure degradation, including reduced aggregate stability and macroporosity, which limit gas exchange and microbial activity (Quintero et al., 2004). The incidence of these yield-reducing factors in our study likely had a greater impact during high productivity years, explaining the more stable but lower yields observed in CR and R2-PP. While multiple factors contribute to rice yield differences, the results highlight the benefits of designing diverse production systems that, regardless of cropping intensity, avoid rice-rice sequences.

Our study enabled the evaluation and characterization of the effects of crop rotations and previous crops on rice yield and yield stability across all phases over nine consecutive seasons in a long-term experiment. However, certain limitations should be recognized. First, the study contrasted six rice-based rotations, representing a gradient of intensification scenarios in the region, but does not encompass all possible system combinations. Second, the experiment was conducted under strictly no-till, whereas in actual production systems, several tillage methods, either conventional or conservation, are used for soil preparation and leveling after a pasture or rice phase that eventually can minimize positive effects of rotation systems on yields (Yao et al., 2025). Third, since rice was sown on the same date each year in our study to evaluate rotations —unlike in commercial farming—we were unable to assess the interaction with seeding date, given its critical influence on rice yield (Ribas, Streck et al., 2021; Tseng et al., 2021). Nevertheless, we speculate that the positive impacts of the rotation system and the previous crops on rice yield would be more pronounced under optimal sowing dates that capitalize on favorable climate conditions for rice growth. Fourth, we acknowledge that, with only nine years of data, the classification into low, medium, and high yield groups based on terciles may be somewhat limited. Nevertheless, the mean yields of these groups were statistically different, and the approach provides a robust demonstration of the environmental modulation of rotation and previous crop effects. Finally, our analysis focused solely on rice yield and its stability, and did not include the performance of other crops and pastures or broader sustainability aspects that were already examined at the LTE (Ayala and Terra, 2023; Castillo et al., 2023; Macedo, Pravia et al., 2021; Macedo, Terra et al., 2021). However, it is important to mention that, unlike rice — which reached the attainable yield for the region (Carracelas et al., 2023)— the average productivity of the other summer crops and pastures was slightly above that of commercial farms but remained below their potential, for reasons that are beyond the scope of this study. Despite this, the work of Macedo, Roel, Velazco et al. (2022), which integrated multiple productivity, economic, and environmental sustainability indicators at the system level, highlighted the stability and overall benefits of integrated rice–pasture systems.

Increased crop yields significantly enhance gross margins and the economic viability of farms (Palosuo et al., 2021). This study found that the rotation system and previous crops affected both rice productivity and yield stability, with the previous summer crop being the most significant factor. The importance of the previous crop on rice yield became evident in those rotations with two rice phases, where significant differences between them were observed. However, no differences in stability ranking were detected between the two phases within the same rotation. The productivity of the other system components was below its potential and not the focus of this study; however, given that the temperate–subtropical transition region of South America is among the world's largest producers and exporters of soybean, beef, and rice, there is substantial opportunity to close existing yield gaps through the integration of these components. However, some constraints make farmers difficult from adjusting or redesigning their systems to integrate these three elements into their agroecosystems. First, land tenure dynamics create a "positive" competition between rice and livestock production, where rice farmers primarily operate as tenants, while landowners are often livestock producers (Carmona et al., 2018; Tommasino and Hernandez, 2003). Second, soybean-rice rotations are not feasible for all farmers, as soybean production in lowlands is risky due to frequent flooding and poor natural soil drainage (Ribas, Zanon et al., 2021). Third, erratic seasonal rainfall variability leads to unpredictable fluctuations in soybean yields, whereas irrigated rice is subject to lower production risks (Ribas, Zanon et al., 2021). While we contemplate these three factors to be the most limiting, other social and economics constraints must also be considered (Goulart et al., 2020; Rosenberg et al., 2022).

Designing integrated production systems that combine rice with livestock and soybean is complex. However, such systems achieve higher yields, improving ecoefficiency indicators, reducing labor demands, and enhancing resilience to high climate variability (Ekroos et al., 2016; Lamb et al., 2016; Macedo, Roel, Velazco et al., 2022; Tseng et al., 2020).

2.7. Conclusions

Integrated rotation systems achieved higher rice yields than CR, which predominates in South America and globally. However, further intensification and/or diversification strategies within Uruguay's prevailing integrated rice-pasture systems may further increase rice yields.

The previous summer crop was the most influential factor prompting rice yield in all rotation systems, highlighting the importance of crop sequence design and management. Rotation designs that avoided planting rice after a previous rice crop, such as in CR or in the second rice crop in R-PP, enhanced rice yield. Soybean boosted rice yield but reduced yield stability across all rotation systems that included it, whether integrated with rice and pastures, in a pinpoint rotation with rice, or in a more diverse system with rice and sorghum. Perennial pastures as previous crops in R1-PP sustained both high rice productivity and yield stability. Thus, intensifying the R-PP by eliminating the second rice crop, or including a soybean crop between both rice crops as in R-Sy-PP, or eventually shortening the pasture phase as in R-BP are valid strategies to enhance rice productivity across all yielding environments.

The positive impacts of well-designed rotations were maximized in high-yielding years, as rice yield differences between rotations or between previous crops became more pronounced. Rice yield stability was influenced by rotation and the previous crops, with less productive systems exhibiting greater stability, while higher-yielding systems, particularly those including soybeans, showing increased sensitivity to the environmental index.

Although there are alternatives for intensifying integrated rice-livestock systems or diversifying continuous rice systems to enhance rice yield in temperate regions with suitable soils and water availability, such as those prevalent in South America, these strategies in general reduce yield stability.

2.8. References

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3. Influence of previous crop on the relationship between rice yield and NDVI in temperate-subtropical rotations

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3.1. Summary

The Normalized Difference Vegetation Index (NDVI) is widely used for agronomic management and yield estimation in rice. Crop rotation design influences nutrient dynamics and rice productivity, yet its effects on NDVI remain poorly understood. We investigated how previous summer crops affect the NDVI-yield relationship in rice using an active sensor during the 2022–2023 and 2023–2024 seasons in a long-term rotation experiment in Uruguay. Twenty-seven annually rice sown plots were grouped by previous summer crops: perennial pasture, biannual pasture, soybean, sorghum or rice. The strongest relationship between NDVI and yield observed at panicle initiation, though it was modest (R^2 = 0.16) when not accounting for previous crops, showing similar patterns across years. However, excluding rice after rice cases improved the relationship to 0.54, with a yield increase of 957 kg ha^{-1} per 0.1 NDVI unit increase. No relationship was found between NDVI and yield in rice-on-rice systems. NDVI values at panicle initiation above ~0.65 and nitrogen uptake higher than 50 kg ha^{-1} increased the probability of achieving high yields while reducing the likelihood of low yields. In temperate–subtropical regions, accounting for the previous crop enhances NDVI's reliability for yield estimation and agronomic decision-making.

Keywords: remote sensing, yield potential, crop rotations

Influencia del cultivo antecesor en la relación entre el rendimiento del arroz y el NDVI en rotaciones de clima templado-subtropical

3.2. Resumen

El índice de vegetación de diferencia normalizada (NDVI) se utiliza ampliamente para el manejo agronómico y la estimación del rendimiento en arroz. El diseño de la rotación de cultivos influye en la dinámica de nutrientes y en la productividad del arroz; sin embargo, sus efectos sobre el NDVI siguen siendo poco comprendidos. En este estudio se evaluó como los antecesores de verano afectan la relación entre el NDVI y el rendimiento del arroz, utilizando un sensor activo durante las zafras 2022-2023 y 2023-2024 en un experimento de rotaciones de largo plazo en Uruguay. Se analizaron las veintisiete parcelas sembradas anualmente con arroz, agrupadas según el antecesor de verano: pastura perenne, pastura bianual, soja, sorgo o arroz. La relación más fuerte entre NDVI y rendimiento se observó a inicio de primordio (PI), aunque fue modesta (R^2 = 0,16) al no considerar el cultivo antecesor, mostrando patrones similares entre años. Sin embargo, al excluir los casos de arroz sobre arroz, la relación mejoró (R^2 = 0,54), con un aumento de 957 kg ha^{-1} por cada incremento de 0,1 unidades de NDVI. No se encontró relación entre NDVI y rendimiento cuando el antecesor al arroz era arroz. Valores de NDVI superiores a ~0,65 y absorciones de nitrógeno mayor a 50 kg ha^{-1} a PI, aumentaron la probabilidad de alcanzar altos rendimientos y redujeron la de obtener rendimientos bajos. En regiones templado-subtropicales, considerar el cultivo de verano mejora la confiabilidad del NDVI para evaluar el potencial productivo del cultivo y para la toma de decisiones.

Palabras clave: monitoreo remoto, potencial productivo, rotaciones

3.3. Introduction

Cereal yield is a cornerstone of global food security (Wang et al., 2014). Precision agriculture technologies, including crop monitoring supports the sustainability of production systems (Zsebó et al., 2024). Non-destructive, real-time, and accurate estimation of crop status through remote sensing contributes both to farm management decisions and to broader food policy planning (De la Casa and Ovando, 2007; Jiang et al., 1999; Marshall et al., 2018).

The Normalized Difference Vegetation Index (NDVI) calculated as NDVI=(NIR-R)/(NIR+R) from red (R) and near-infrared (NIR) bands reflectance is among the most widely used tools for monitoring crop status and productivity (Piedad-Rubio et al., 2020). Numerous studies have reported significant relationships between NDVI and yield, cropped area, and crop nutritional status (Aguilar et al., 2016; Farias et al., 2023; Rehman et al., 2019; Shane, 2021). Proper interpretation of NDVI can provide rapid, targeted assessments of crop nutritional status (particularly nitrogen), physiological condition and stress incidence (Inman et al., 2005). The index is also sensitive to detect slight changes in vegetation status (Panek and Gozdowski, 2020). The NDVI can be obtained using passive multispectral or hyperspectral sensors mounted on drones or satellites, as well as proximal active radiometric sensors (Aguilar et al., 2016; Ovando et al., 2021; Rivas et al., 2011), such as the GreenSeeker (Trimble Inc., Sunnyvale, CA, USA), a widely used active sensor in agriculture that collects reflectance data at any time of the day, regardless of ambient light conditions or cloud cover (Nakano et al., 2023; Rehman et al., 2022).

In rice croplands, the NDVI has been related to biomass accumulation, nitrogen content and uptake, yield, among other traits using both multi/hyperspectral and proximal active radiometers (Ali et al., 2015; Cao et al., 2015; Fita et al., 2024; Harrell et al., 2011; Rehman et al., 2019). NDVI measured before panicle emergence showed a linear relationship with yield, with R^2 values of 0.74 (Moreno-García et al., 2013) and 0.57 (Rufasto et al., 2017). The phenological stage at which NDVI is measured is critical for relating it to the variable of interest (Ali et al., 2014). Chang et al. (2005) identified the period between panicle initiation and booting stages as optimal, while Harrell et al. (2011), Rehman et al. (2019) and Tubaña et al. (2012) found a strong relationship between rice yield and NDVI immediately to panicle initiation. However, the relationship between NDVI and rice yield is not uniform; it may be also influenced by cultivar, rice subtypes and nitrogen rate (Rehman et al., 2019; Zhang et al., 2019).

Cropping sequences and system design also affect rice crop performance (Carmona et al., 2018; Macedo et al., 2022; Meus et al., 2020; Ribas et al., 2021). In temperate South America, rice production systems are relatively diverse, encompassing continuous rice, integrated rice–livestock systems and rotations where rice alternates with other crops such as soybean or sorghum (Carlos et al., 2020; Castillo et al., 2023; De Faccio Carvalho et al., 2021). To date, however, no studies have explicitly examined the relationship between NDVI, nutritional status and rice yield in different phenological stages under contrasting rotation systems. Understanding these interactions is crucial to improve yield estimation and to design more efficient management strategies for rice agroecosystems. Long-term experiments with stabilized contrasting sequences provide an ideal framework for such analyses.

This study investigated whether differences in rice yield potential, driven by crop rotation design, can be detected through NDVI during the growing cycle. We hypothesized that, given the influence of crop sequences on rice yield and the relationship between NDVI and productivity, NDVI could differentiate yield variation across different sequences. Accordingly, our objective was to assess the relationship between NDVI, measured with a proximal active radiometric sensor (Trimble® GreenSeeker) and rice yield across different crop sequences in a long-term rotation experiment over two growing seasons.

3.4. Materials and methods

3.4.1. Site description

The study was conducted over two growing seasons within a rotation long-term experiment (LTE) established in 2012 at the Paso de la Laguna Experimental Unit, located in Treinta y Tres, Uruguay (33°16´22´´S 54°10´23´´O). The dominant soil at the site is classified as a Typic Argialboll according to USDA Soil Taxonomy, with slopes <0.5% (Durán et al., 2006). The regional climate is classified as humid mesothermal.

3.4.2. Experimental design and crop management

The experiment comprised six rice-based rotation systems arranged in a randomized complete block design with three replications. All rotation phases were concurrently present across years and plots to ensure a balanced cyclic design (Patterson, 1964), distributed across 60 plots of 1,200 m^2 each. All rotations included flood-irrigated rice, totaling 27 plots sown with rice each year.

The rotations were: a) Rice1-Rice2-Perennial Pasture (3.5 years), composed of *Festuca arundinacea*, *Lotus corniculatus* and *Trifolium repens* (R-PP, 5 years rotation); b) Rice-Biannual Pasture (1.5 years), composed of *Lolium multiflorum* and *Trifolium pratense* (R-BP, 2 years rotation); c) Rice1-Soybean1-Soybean2-Rice2-Perennial Pasture (2.5 years), composed of *Festulolium* sp. and *Lotus corniculatus* (R-Sy-PP, 6 years rotation); d) Rice1-Soybean-Rice2-Sorghum (R-Crops, 4 years rotation); e) Rice-Soybean (R-Sy, 2 years rotation); Continuous Rice (CR) (Table 1). Annual cover crops of *Lolium multiflorum* (Lm) and *Trifolium alexandrinum* L. (Ta) were established between grain crops in all rotations. Rotations were classified based on land-use intensity, defined by the number of crops per year and the frequency of rice cultivation per year.

Table 1. Rotation systems evaluated and their duration (years).

<table>
<tr><th rowspan="3">Rotation</th><th colspan="12">Years</th></tr>
<tr><th colspan="2">1</th><th colspan="2">2</th><th colspan="2">3</th><th colspan="2">4</th><th colspan="2">5</th><th colspan="2">6</th></tr>
<tr><th>SS</th><th>AW</th><th>SS</th><th>AW</th><th>SS</th><th>AW</th><th>SS</th><th>AW</th><th>SS</th><th>AW</th><th>SS</th><th>AW</th></tr>
<tr><td>R-PP</td><td>Rice1</td><td>Lm</td><td>Rice2</td><td colspan="7">Perennial Pasture</td><td></td><td></td></tr>
<tr><td>R-BP</td><td>Rice</td><td colspan="3">Biannual Pasture</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R-Sy-PP</td><td>Rice1</td><td>Lm</td><td>Sy1</td><td>Lm</td><td>Sy2</td><td>Ta</td><td>Rice2</td><td colspan="5">Perennial Pasture</td></tr>
<tr><td>R-Crops</td><td>Rice1</td><td>Lm</td><td>Sy</td><td>Ta</td><td>Rice2</td><td>Ta</td><td>Sg</td><td>Ta</td><td></td><td></td><td></td><td></td></tr>
<tr><td>R-Sy</td><td>Rice</td><td>Lm</td><td>Sy</td><td>Ta</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CR</td><td>Rice</td><td>Ta</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Note: R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Lm: *Lolium multiflorum*, Ta: *Trifolium alexandrinum* L., Sy: Soybean, Sg: Sorghum, SS: Spring-Summer, AW: Autumn-Winter.

Rice was direct seeded into dry soil between October 13th and 15th, following a 4–5-week chemical fallow. The cultivar INIA Merín was used, with a target population of 200–250 plants m^{-2}. Plots were flooded within 30 days after crop emergence.

Rice nitrogen fertilization varies across rotations (Table 2). Nitrogen rates were adjusted based on soil potential mineralizable nitrogen (PMN), except in CR, where rates targeted an expected yield of 10 Mg ha^{-1} (Castillo et al., 2023). Urea was applied in two splits: 70% at early tillering initiation (V4) on dry soil and 30% at panicle initiation (R0) under flooded conditions (Counce et al., 2000). Phosphorus and potassium fertilization followed a nutrient-replacement approach in CR and R–Sy, while sufficiency-level criteria were applied in the remaining rotations.

Table 2. Average nitrogen (N) rates applied in 2022-2023 and 2023-2024 to rice crops across rotation systems in the LTE.

Rotation		N (kg ha^{-1} yr^{-1})
R-PP	Rice1	97
	Rice2	122
R-BP	Rice	97
R-Sy-PP	Rice1	98
	Rice2	112
R-Crops	Rice1	119
	Rice2	114
R-Sy	Rice	116
CR	Rice	155

Note: R: Rice, PP: Perennial Pasture, BP: Biannual Pasture, CR: Continuous Rice, Sy: Soybean.

3.4.3. Measurements

Data on NDVI, aboveground dry matter (DM, kg ha^{-1}), nitrogen concentration (%N) and grain yield (Mg ha^{-1}) were collected from 27 rice plots (1,200 m^2 each) during the 2022-2023 and 2023-2024 growing seasons. The NDVI was measured using a Trimble® GreenSeeker (GS) active sensor at five rice stages between tillering and flowering initiation, approximately every 15 days. The GreenSeeker calculates NDVI from red (660 nm) and near-infrared (780 nm) reflectance. Six measurements per plot were taken at 60 cm above the canopy, each representing an average of 10 linear meters (Figure 1). For DM and %N, six linear cuts of 50 cm at ground level were collected per plot at each measurement time. Samples were oven-dried at 55°C for 48h, ground to pass a 1 mm mesh and analyzed for N concentration using dry combustion (LECO®/Dumas combustion technique). Prior to harvest, two additional samplings were conducted: (i) six random 50 cm panicle cuts per plot for yield components and (ii) four random 1 m cuts per plot to estimate harvest index. Final rice yield was determined for each plot using a New Holland TC5070 commercial combining harvester and a digital scale (Magris MTV 206, ±10 kg) mounted on a grain cart. Grain yield was reported at 13% moisture (clean basis).

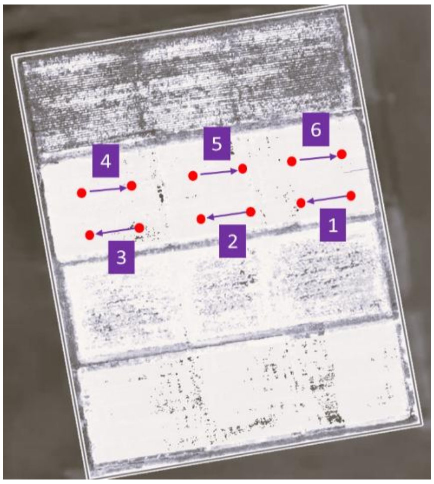

Figure 1. Schematic representation of NDVI sampling with the Trimble® GreenSeeker sensor in each rice plot at the LTE. The background image shows a cross-section of the experiment where four plots can be seen.

3.4.4. Data analysis

Grain yield was analyzed using a linear mixed model with previous crops, season and their interaction as fixed effects, and block as a random effect. Residuals were tested for normality (Shapiro–Wilk) and homogeneity of variances (Levene's test). Means were compared using Tukey's test at a 0.05 significance level.

NDVI values were related to grain yield using simple linear regression. Orthogonal contrasts were performed to assess significant differences among previous crops and groups.

To analyze yield group distribution based on NDVI categories at panicle initiation (PI) for NRP and RP, the dataset was sorted by year and divided into terciles. Within each year, three categories (low, medium, high) of NDVI and yield were defined to evaluate the association between PI NDVI and final yield.

Nitrogen dilution curves were constructed to compare predecessor groups and contrasted with the critical N dilution curve for this variety ($N= 3.78*MS^{-0.435}$; $R^2= 0.71$) reported by Moreira (2024).

All statistical analyses were performed in R (version 4.2.1) (R Core Team, 2022). Mixed models were fitted using the "nlme" package, treatment mean comparisons with "multcomp" and "cld", and graphical representations with ggplot2.

3.5. Results

3.5.1. Rice yield and NDVI

The mean grain yield across both seasons (2022-2023 and 2023-2024) was 10.60 Mg ha^{-1}, with a coefficient of variation of 13%, consistent with historical yield levels and variability of the LTE. Mean yield in 2022-2023 (10.74 Mg ha^{-1}) was 4% higher than in 2023-2024 (Table 3). The largest yield differences were associated with previous summer crop. In 2022-2023, rice following soybean achieved the highest yield (12.16 Mg ha^{-1}), 6% greater than rice after perennial pasture or sorghum, and 33% higher than rice after rice. In 2023-2024, yields after perennial pasture, soybean and sorghum did not differ significantly and averaged 16% higher than those after rice. Plant stands at emergence did not differ among previous crops; however, at harvest, rice after rice had 7% fewer panicles m^{-2} and 13% fewer grains per panicle compared with other previous crops (Supplementary Table I).

Table 3. Adjusted mean and standard errors for grain yield by previous summer crops across two seasons in the LTE in Uruguay. Different letters indicate significant differences at $p < 0.05$.

Previous crop	Season 2022-2023	Season 2023-2024
	Mg ha^{-1}	
Soybean	12.16 ± 0.19 a	10.75 ± 0.19 a
Perennial Pasture	11.44 ± 0.20 b	11.05 ± 0.20 a
Sorghum	11.47 ± 0.23 b	10.52 ± 0.23 ab
Biannual Pasture	10.52 ± 0.23 c	9.83 ± 0.23 bc
Rice	8.09 ± 0.20 d	9.28 ± 0.20 c
Mean	10.74 ± 0.17	10.30 ± 0.17

The NDVI dynamics during the rice growing cycle was similar across seasons, with values increasing from tillering initiation ($\bar{x}$= 0.34) to panicle initiation ($\bar{x}$= 0.60), followed by a plateau or slight increase until flowering initiation ($\bar{x}$= 0.66) (Figure 2A). Nevertheless, high variability was observed at each stage, partly associated by the season and the previous crop (Figure 2B).

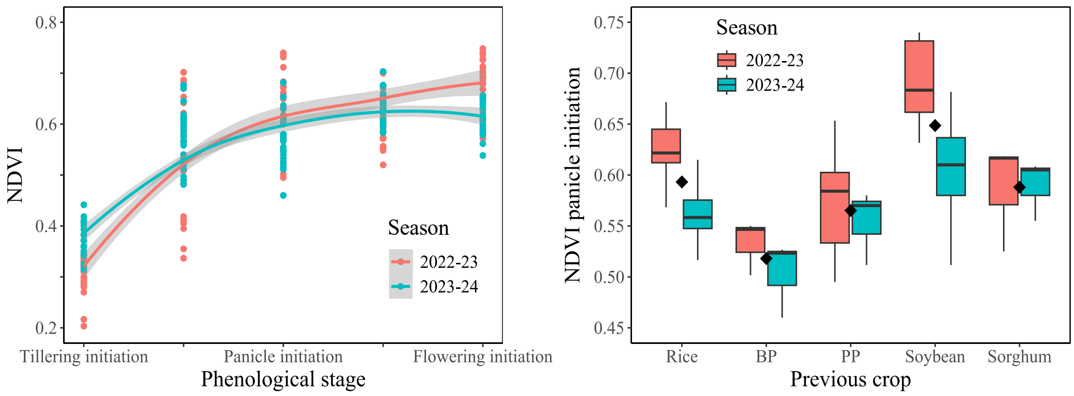

Figure 2. NDVI dynamics from rice tillering initiation to flowering initiation (A) and variability of NDVI at panicle initiation across previous summer crops (B) in 2022-2023 and 2023-2024. BP: Biannual pasture, PP: Perennial pasture. Black diamonds: mean NDVI of each previous crop across seasons.

3.5.2. Relationship between NDVI dynamics and grain yield

Across all data, the relationship between NDVI and grain yield was generally weak at all growth stages (Figure 3). The strongest association was observed at panicle initiation, showing a positive and significant relationship (R^2= 0.16). At flowering initiation, the relationship was also positive and significant but explained only 9% of yield variation. No association was found between NDVI at tillering initiation and yield. Thus, subsequent analyses focused on NDVI measured at panicle initiation.

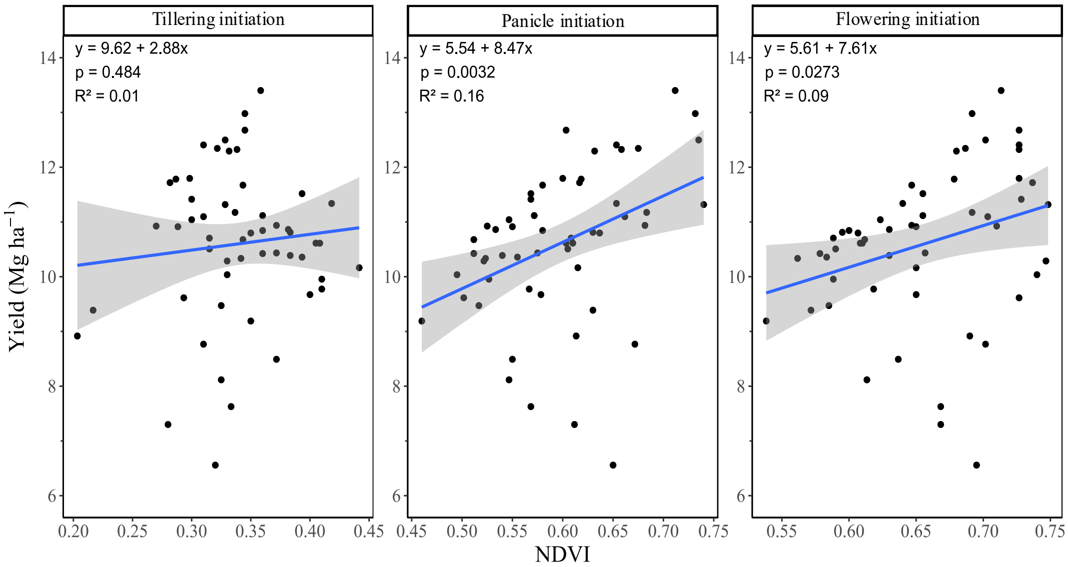

Figure 3. Relationship between NDVI at tillering, panicle initiation and flowering initiation with rice yield (Mg ha^{-1}) in an LTE in Uruguay. Regression equations, p-values and coefficients of determination (R^2) are shown for each stage.

<u>3.5.3. Relationship between NDVI at panicle initiation and grain yield by season</u>

The relationship between NDVI at panicle initiation and rice yield was consistent across seasons (Figure 4). Despite apparent differences in slope and fit, orthogonal contrast analysis confirmed no significant differences between regression lines. Both seasons showed positive trends, with yield increases of 757 kg ha^{-1} and 864 kg ha^{-1} for every 0.1 increase in NDVI in 2023-2024 and 2022-2023, respectively. Nevertheless, yield variability explained by NDVI remained modest (R^2= 0.11 and R^2= 0.21 for 2022-2023 and 2023-2024 seasons, respectively). Given the poor fit and evidence of clustering by previous crop, further analysis was conducted by cropping sequence.

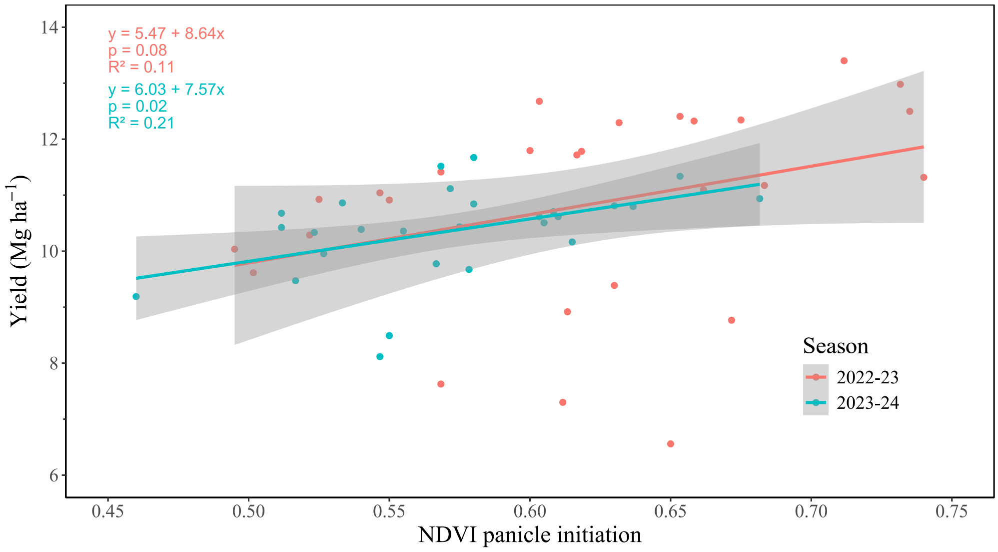

Figure 4. Relationship between NDVI at panicle initiation and rice yield (Mg ha^{-1}) in 2022-2023 and 2023-2024 in an LTE in Uruguay. Regression equations, p-values, and R^2 values are shown for each season.

<u>3.5.4. Relationship between NDVI at panicle initiation and grain yield by previous crop</u>

The relationship between NDVI at panicle initiation and grain yield improved when previous crops were grouped, resulting in two distinct groups (Figure 5A and 5B). On group included the previous crops for which the NDVI–yield relationship was significant—both those explaining a large proportion of the variability (Biannual pasture, R^2= 0.87; Perennial pasture, R^2= 0.73) and those with a more modest contribution (Soybean, R^2= 0.48; Sorghum, R^2= 0.22). In contrast, no significant relationship between NDVI and yield was observed for rice seeded after rice. Orthogonal contrasts showed no differences among soybean, pastures and sorghum, which were therefore grouped as NRP (non-rice predecessor). In this group, the NDVI–yield relationship was positive and significant (R^2= 0.54), with grain yield increasing by 957 kg ha^{-1} per 0.1 increase in NDVI at panicle initiation.

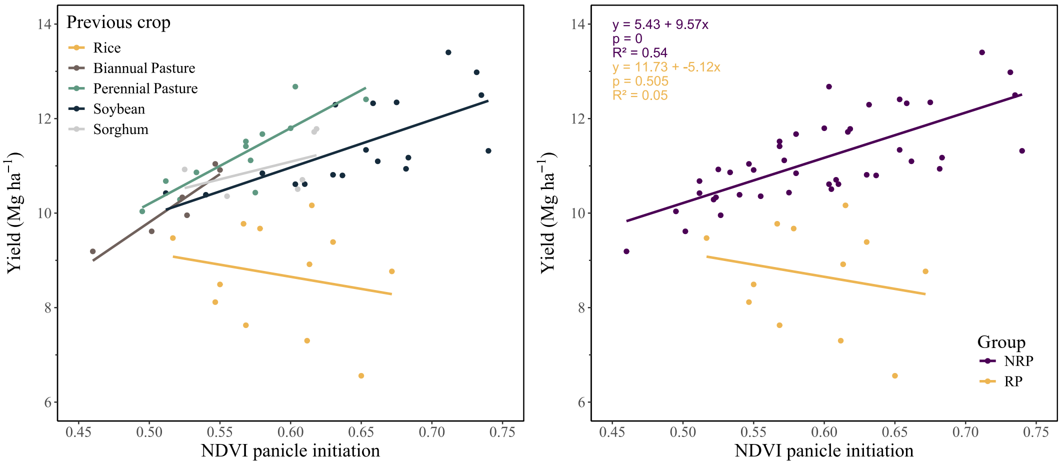

Figure 5. Relationship between NDVI at panicle initiation and rice yield (Mg ha^{-1}) by previous summer crop (A) and by grouped categories (B) in an LTE in Uruguay. Regression equations, p-values and R^2 values are shown for each group. NRP: non-rice predecessor; RP: rice predecessor.

3.5.5. Yield distribution according to NDVI categories at panicle initiation by previous crops groups

Clear differences were observed between NRP and RP in yield distribution by NDVI categories at panicle initiation across both seasons (Figure 6). In NRP, medium and high NDVI values corresponded to high yield in >60% of cases, with no low-yield cases. Conversely, low NDVI values corresponded to low yield in 40% of cases and high yield in only 10%. In RP, regardless of NDVI value, 100% of cases corresponded to low yield.

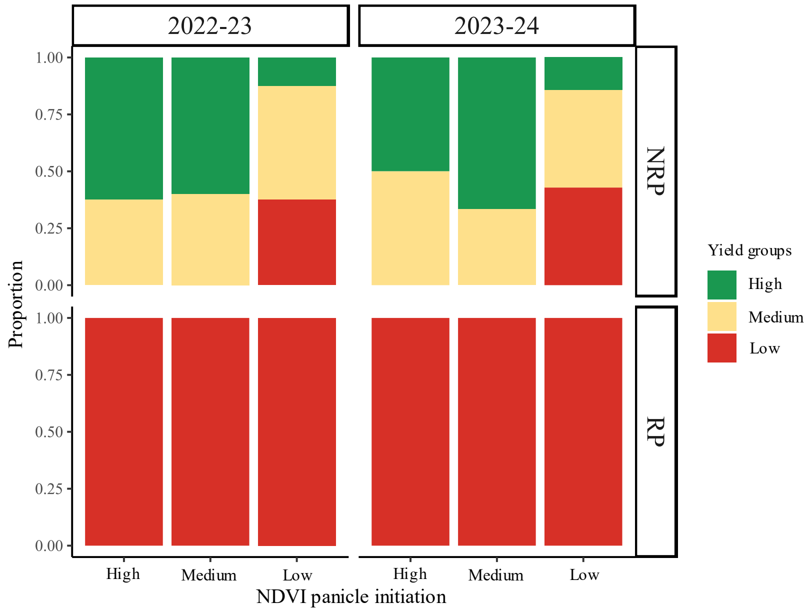

Figure 6. Yield group distribution by NDVI categories at panicle initiation for NRP and RP across both seasons in an LTE in Uruguay. NRP: non-rice predecessor; RP: rice predecessor. 2022-2023: Low yield <10.92 Mg ha^{-1}, medium 10.92-11.32 Mg ha^{-1}, high >11.32 Mg ha^{-1}; NDVI low <0.60, medium 0.60-0.65, high >0.65. 2023-2024: Low yield <10.42 Mg ha^{-1}, medium 10.42-10.60 Mg ha^{-1}, high >10.60 Mg ha^{-1}; NDVI low <0.55, medium 0.55-0.60, high >0.60.

3.5.6. Nitrogen uptake and dilution curves by previous crop groups

Both groups showed positive relationships between nitrogen uptake and NDVI dynamics during the growing cycle (NRP: R^2= 0.83; RP: R^2= 0.81), with no significant differences between curves (Figure 7A). On average, NDVI reached a plateau ($\bar{x}$= 0.64) at 44-54 kg N ha^{-1} uptake, which was close to the mean uptake of 57 kg N ha^{-1} measured at panicle initiation (Supplementary Table II).

On the other hand, nitrogen dilution effects were observed in both predecessor groups, reflecting greater biomass accumulation relative to nitrogen uptake as the crop cycle advanced (Figure 7B). Dilution curves were significant and differed between both groups. The NRP group (N= 2.44*MS$^{-0.28}$; R^2= 0.81) showed higher dilution compared with RP (N= 2.41*MS$^{-0.24}$; R^2= 0.75). Differences were most evident beyond 5 Mg ha^{-1} of dry matter, where NRP values fell below and RP values were above the critical nitrogen dilution curve for this variety (N= 3.78*$MS^{-0.435}$; R^2= 0.71).

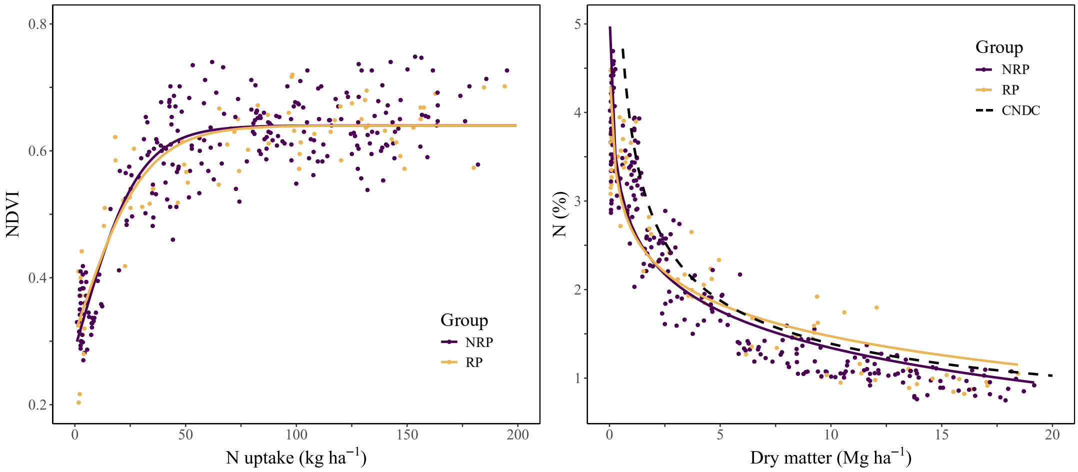

Figure 7. Rice nitrogen uptake curve and NDVI (A) and nitrogen dilution curve (B) for previous crop groups in an LTE in Uruguay. NRP: non-rice predecessor; RP: rice predecessor; CNDC: Critical nitrogen dilution curve. The dashed black line represents the critical N dilution curve for this variety (N= 3.78*$MS^{-0.435}$; R^2= 0.71) (Moreira, 2024).

3.6. Discussion

Our study aimed to establish the relationship between NDVI dynamics and rice grain yield under contrasting crop rotations in an LTE. Several studies reported the effectiveness of NDVI to estimate active biomass, nutritional status and rice productivity (Ali et al., 2015; Cao et al., 2015; Fita et al., 2024; Harrell et al., 2011; Rehman et al., 2019). There is strong evidence that production system design and crop sequences influence nitrogen dynamics in the soil–plant system and ultimately rice productivity (Carlos et al., 2020; Castillo et al., 2023; Denardin et al., 2025; Macedo et al., 2022; Ribas et al., 2021). However, to our knowledge, no studies have examined how rotation systems or cropping sequences affect the relationship between NDVI and grain yield. Considering these relationships will allow optimization of crop management and improve yield estimation in diverse rice production systems. In this context, we found that grouping by previous summer crops improved the relationship between NDVI at panicle initiation and crop performance.

Although grain yields differed significantly among previous crops, consistent with other studies (Carmona et al., 2018; Macedo et al., 2022; Ribas et al., 2021), NDVI dynamics showed limited ability to reflect these differences. We observed that grain yield estimation based on NDVI at panicle initiation improved when differentiating rice from non-rice predecessors. These differences may be attributed to canopy structure, nitrogen dynamics and yield-limiting and reducing factors occurring after panicle initiation, which affect productivity and weaken the relationship. Such factors include diseases, nutrient imbalances and weeds (Van Ittersum et al., 2013). Rice following rice is particularly prone to a higher incidence of weeds and diseases, which may be exacerbated by the increased N fertilization required to compensate for lower soil nitrogen mineralization potential, ultimately resulting in grain yield reductions (Filizadeh et al., 2007; Keim and Webster, 1973; Konthoujam et al., 2007; Litzenberger, 1974). In the same LTE, Martinez (2023) and Martinez and Escalante (2021) reported higher incidence of stem and sheath diseases in rice after rice compared with other previous crops, attributable to higher inoculum buildup and nitrogen application. In our study, RP received on average 31 kg N ha^{-1} more than NRP and also showed higher tissue N concentration (lower dilution) than the critical curve for this variety (Figure 7B), consistent with luxury consumption (Moreira, 2024). Fita et al. (2024) and Fu et al. (2019) reported that high nitrogen concentrations after panicle initiation tend to be less efficiently used for grain production. By contrast, rice after pastures received less nitrogen fertilizer (see Table 2) yet showed the strongest relationship between NDVI at panicle initiation and yield (Figure 5A). Therefore, high NDVI values may sometimes reflect excess nitrogen and prolonged green biomass rather than actual grain yield gains (Cabrera-Bosquet et al., 2011; Maresma et al., 2016).

The strongest relationship between NDVI and grain yield was found at panicle initiation, consistent with previous studies (Moreno-García et al., 2013; Rehman et al., 2019; Tubaña et al., 2012). However, while those studies reported R^2 values between 0.57 and 0.74, our overall relationship—without differentiation by predecessor—was much weaker (R^2= 0.16). Rotation system design, cultivar and structural and biological characteristics of rice may explain these discrepancies. At early growth stages, canopy cover is minimal, so soil, water and suspended sediments interfere with the spectral signal acquired by the sensor (Martin and Heilman, 1986). As plants grow, leaves and stems increasingly contribute to reflectance until saturation occurs (Dela Torre et al., 2021). Thus, NDVI captures differences in biomass and vigor that influence grain yield, as it is strongly related to photosynthetically active biomass, chlorophyll abundance and energy absorption (Myneni et al., 1995).

The NDVI evolution throughout the growing cycle aligned with previous reports that identified saturation values (Cao et al., 2015; Chang et al., 2005; Fita et al., 2024; Gu et al., 2013; Rehman et al., 2019). NDVI saturation typically occurs at full canopy cover, even though biomass and leaf area index continue to increase (Gitelson, 2004). At this point, near-infrared reflectance continues to rise, while red reflectance declines only slightly, resulting in minor changes in the ratio (Thenkabail et al., 2000). In our study, NDVI saturated at ~0.60-0.64, corresponding to an uptake of 44-54 kg N ha^{-1}, similar to the 0.6 NDVI and 52 kg N ha^{-1} reported by Ali et al. (2015), and to the 47-52 kg N ha^{-1} reported by Moreira (2024) at panicle initiation. By contrast, Rehman et al. (2019) and Yao et al. (2014) found NDVI saturation at 0.76-0.78, associated with uptakes of 100-180 kg N ha^{-1}, values higher than those in our study and likely attributable to differences in nitrogen management and more favorable climatic conditions. Notably, despite lower NDVI and nitrogen uptake at panicle initiation, high grain yield levels were achieved in our study.

This study has certain limitations, including tits reliance on only two growing seasons, the variability in nitrogen rates applied to the different systems —adjusted according to the PMN— and the absence of fungicide treatments. Nonetheless, it provides an initial approximation that lays the groundwork for future research to refine early-season grain yield estimation. Validation using field data and yield monitor information will be critical to strengthen applicability.

Overall, this work improves the use of NDVI as a tool for estimating rice grain yield potential under contrasting crop sequences. While the general predictive capacity was modest, differentiating by the previous summer crop and excluding rice predecessors from the analysis substantially improved the fit, explaining up to 54% of grain yield variability. These findings highlight the importance of developing robust vegetation index–yield relationships within each rotation system to enhance estimation reliability, optimize management and support yield mapping (Chang et al., 2005; Harrell et al., 2011). Moreover, nitrogen uptake and NDVI thresholds were identified, beyond which the probability of achieving high grain yields increased and the risk of low grain yields was minimized. In a highly productive region with diverse rotations, this approach enhances the effectiveness of remote sensing tools for rice management (Dela Torre et al., 2021; Zsebó et al., 2024), while highlighting the need to better understand rice-on-rice sequences where yield-limiting and reduction factors confound NDVI-based relationships.

3.7. Conclusions

Cropping sequence, particularly the previous summer crop, affects both grain yield and NDVI dynamics. However, when considering all sequences together, NDVI showed only a modest relationship with productivity and failed to differentiate among predecessors based on yield. In contrast, when discriminating by previous summer crops and excluding rice-on-rice sequences, the relationship between NDVI at panicle initiation and crop performance improved. In sequences following pastures, soybean or sorghum, NDVI values above ~0.65 and nitrogen uptake higher than ~50 kg ha^{-1} at panicle initiation increased the probability of achieving high yields while reducing the likelihood of low grain yields, while also providing a basis for management adjustments when necessary.

In temperate–subtropical regions, these findings highlight that NDVI at panicle initiation, interpreted in the context of previous crop and nitrogen nutrition, constitutes a valuable tool for agronomic management and early diagnosis of grain yield potential in indica-type rice.

3.8. References

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3.9. Supplementary material

Table I. Yield components and harvest index (HI) for the differentiated groups.

Group	Grains panicle^{-1}	Panicle m^{-2}	1000-grain weight (g)	HI
RP	84	556	26.3	0.56
NRP	97	600	26.7	0.57
Difference$_{RPvsNRP}$ (%)	-13	-7	-2	-2

Table II. Plant stands at emergence (Pl m^{-2} E); aboveground biomass at panicle initiation (DM PI, kg ha^{-1}); nitrogen uptake at panicle initiation (N Upt PI, kg ha^{-1}); and nitrogen uptake in grain (N Upt G, kg ha^{-1}) and straw (N Upt P, kg ha^{-1}) at harvest for the differentiated groups.

Group	Pl m^{-2} E	DM PI	N Upt PI	N Upt G	N Upt P
RP	259	3108	69	83	38
NRP	266	2265	53	102	44
$Difference_{RPvsNRP}$ (%)	-3	+37	+30	-19	-14

4. Discusión y conclusiones generales

Teniendo en cuenta los desafíos actuales de la producción agrícola, surge la necesidad de desarrollar prácticas de manejo que permitan aumentar la producción y mantener la productividad a largo plazo en las tierras agrícolas existentes sin comprometer el desempeño ambiental (Cassman y Grassini, 2020; Ghosh et al., 2019). En este marco, el presente trabajo integró dos enfoques complementarios orientados a comprender y optimizar la productividad del cultivo de arroz dentro de los sistemas de rotaciones predominantes en Uruguay.

El área potencial de arroz en Uruguay está en torno al millón de hectáreas anuales, pero está limitada por la disponibilidad de agua a alrededor de 200.000 ha por año. La superficie total de arroz es relativamente estática y no puede expandirse más allá de este límite (Macedo et al., 2022). En la última década, la producción arrocera en el país ha experimentado importantes transformaciones con la intensificación y diversificación de los sistemas productivos. El área de arroz sobre soja ha aumentado un 25 %, mientras que la superficie de arroz sobre arroz ha disminuido un 22 %. En contraste, el área de arroz sobre pasturas se ha mantenido estable (Molina, 2025). De acuerdo con las diferencias de productividad observadas entre rotaciones o antecesores en este estudio, y considerando las 149.000 ha sembradas en el año agrícola 2023-2024 (MGAP-DIEA, 2024), si se eliminara la siembra de arroz sobre rastrojos de arroz, la producción nacional aumentaría entre 51.000 y 84.000 toneladas anuales, lo que equivaldría a un 4-6 % adicional de la producción total. Ahora bien, al centrar el análisis en los años de alto potencial productivo —en lugar de considerar el promedio general— el incremento podría llegar a las 105.000 toneladas anuales, lo que representaría un aumento del 8% en la producción total, generando un ingreso adicional superior a 70 millones de dólares por la exportación de arroz, tomando como referencia el precio FOB de 2024.

Por otro lado, los resultados de este trabajo evidencian una clara relación entre el rendimiento del arroz y el NDVI medido al inicio de primordio en todos los sistemas analizados, excepto cuando el arroz fue antecedido por otro arroz. Esto abre la posibilidad de tener una estimación de la productividad de arroz anticipada, siendo una herramienta valiosa y de alta aplicabilidad para optimizar el manejo, la planificación y la toma de decisiones acerca de potenciales estrategias de los sistemas. Una estimación a campo del potencial de rendimiento del arroz utilizando tecnología de teledetección puede emplearse, por ejemplo, para generar mapas de potencial productivo, así como para proporcionar prescripciones de aplicación de fertilizante nitrogenado, sentando las bases para realizar un manejo por ambientes o sitio-específico (Bonilla et al., 2015; Chang et al., 2005; Harrell et al., 2011). Este hallazgo también adquiere especial relevancia, ya que permitiría contar con proyecciones de los potenciales productivos nacionales, lo cual sería determinante para la gestión y el manejo de los recursos, al tiempo que aportaría información estratégica para una posible proyección del comercio exterior (De la Casa y Ovando, 2007; Jiang et al., 1999; Marshall et al., 2018). Esta importancia se magnifica si se considera que Uruguay está entre los diez principales exportadores mundiales de arroz y es el único país que se enfrenta al desafío de tener que exportar el 95 % del arroz que se produce, ya que solamente un 5 % se consume internamente.

Entonces del análisis surge una pregunta: ¿por qué se sigue sembrando 30 % del área del país de arroz sobre rastrojos de arroz? En primer lugar, la tenencia de la tierra, donde el arroz compite positivamente con la ganadería, y el productor arrocero actúa principalmente como arrendatario, mientras que el propietario de la tierra suele ser el productor ganadero (Tommasino y Hernandez, 2003). En segundo lugar, la rotación de soja y arroz no puede ser implementada por todos los agricultores, ya que la producción de soja en tierras bajas es riesgosa debido a la alta probabilidad de exceso de agua, especialmente al inicio de la temporada y en campos ubicados en posiciones más bajas del paisaje o en las proximidades de arroyos y ríos (Ribas, Zanon et al., 2021). En tercer lugar, la variabilidad errática de las precipitaciones estacionales a lo largo de los años provoca fluctuaciones impredecibles en los rendimientos de la soja, mientras que el riesgo en arroz irrigado es menor (Ribas, Zanon et al., 2021). Hace varias décadas, Gamarra (1996) ya señalaba que la condición de arrendatarios de la mayoría de los productores de arroz constituía una de las principales limitantes para la inversión en tecnología, especialmente en lo referente al mejoramiento de las condiciones de nivelación y drenaje de las chacras, así como en la posibilidad de implementar rotaciones que contribuyan a mejorar la calidad del suelo y los rendimientos. Si bien consideramos que estos factores son los más limitantes, también deben tenerse en cuenta otras restricciones sociales y económicas (Goulart et al., 2020; Rosenberg et al., 2022). En este marco, la diversificación de los sistemas de arroz es un tema complejo (Rosenberg et al., 2022), pero gran parte del éxito —o de las dificultades— en la integración de cultivos como la soja dentro de las rotaciones arroceras dependerá de la capacidad de los productores para rediseñar adecuadamente sus sistemas y manejarlos considerando las particularidades de los suelos (Castillo et al., 2013).

En síntesis, los resultados demuestran que avanzar hacia sistemas arroceros más integrados y diversos es posible, ya que estos permiten mantener altos niveles de productividad incluso en ambientes de máximo potencial. Las condiciones favorables de las regiones templado-subtropicales de Sudamérica brindan una oportunidad concreta para consolidar este modelo. No obstante, aún queda camino por recorrer para avanzar en esta dirección, tanto en los aspectos ya mencionados como en otros igualmente relevantes, orientados a reducir las siembras de arroz sobre rastrojos de arroz o mejorar las condiciones en estos. Este cambio no solo permitiría incrementar la producción nacional, sino también mejorar la rentabilidad por hectárea, dado que está demostrado que un aumento en el rendimiento de los cultivos repercute directamente en mayores márgenes brutos y en la viabilidad económica de las explotaciones (Palosuo et al., 2021). Además, alcanzar altos rendimientos contribuye a un uso más eficiente de la tierra, lo que no solo reduciría la carga de trabajo, sino que también ofrecería alternativas relevantes para mitigar el cambio climático (Lamb et al., 2016), al tiempo que generaría beneficios ambientales adicionales, como mayores oportunidades para la conservación de la biodiversidad (Ekroos et al., 2016).

En perspectiva, este trabajo establece un punto de partida hacia sistemas arroceros más integrados, eficientes y basados en evidencia, donde la sinergia entre el diseño de las rotaciones y herramientas de agricultura de precisión —como el monitoreo remoto y el manejo por ambientes— permita optimizar la productividad dentro de los límites de superficie y disponibilidad de agua. En este sentido, los resultados obtenidos aportan elementos objetivos para interpretar los patrones productivos observados y respaldan la adopción de estrategias de manejo más ajustadas a la heterogeneidad de los sistemas arroceros. No obstante, se destaca la necesidad de ampliar la base de información y validar estos resultados en un mayor número de zafras, ambientes productivos y condiciones de manejo, con el fin de fortalecer la robustez y la aplicabilidad de los enfoques propuestos. A futuro, este enfoque abre la posibilidad de profundizar en el uso de series temporales de información satelital para la estimación temprana del rendimiento, la delimitación dinámica de ambientes productivos y la integración de estas herramientas en la toma de decisiones agronómicas, contribuyendo a consolidar un modelo de crecimiento sostenible y tecnológicamente avanzado para el arroz uruguayo.

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