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Intensification of rice-pasture rotations with annual crops reduces the stability of sustainability across productivity, economic, and environmental indicators

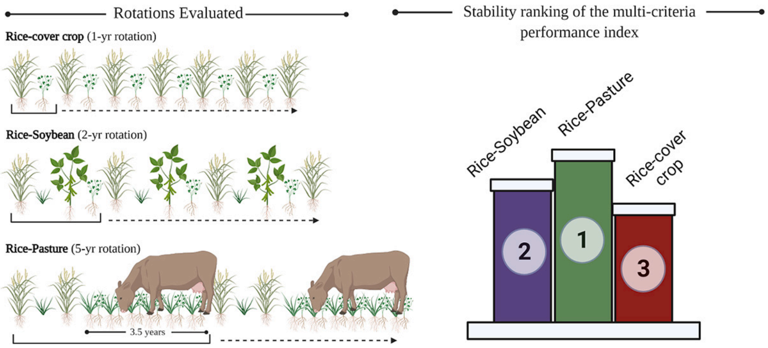
Ignacio Macedo [a,b,*], Alvaro Roel [b], José Ignacio Velazco [b], Alexander Bordagorri [b], José A. Terra [b], Cameron M. Pittelkow [a]

[a] *Department of Plant Sciences, Univ. of California, Davis, CA, USA*
[b] *Instituto Nacional de Investigación Agropecuaria, INIA-Uruguay, Ruta 8 km 281, Treinta y Tres 33000, Uruguay*

HIGHLIGHTS

- Crop-livestock systems has been intensified worldwide decoupling crops from livestock.
- We evaluated multiple indicators, an integrated index, and its stability in three rice-based rotations.
- The intensification of rice-pasture with annual crops increased system productivity but with higher inputs dependence.
- Rice-soybean rotation slightly increased the whole system performance, but rice-pasture showed the highest stability.
- This study suggests preserving the integration of rice and pasture with livestock in this region.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Integrated crop-livestock systems are facing the pressure to intensify worldwide, yet decoupling crops and livestock can lead to specialized systems relying on greater external inputs and potential negative externalities.

OBJECTIVE: Our goal was to compare rice-pasture, as the business-as-usual rotation, with two intensified systems, rice-soybean and rice-cover crop, to address the following objectives: 1) quantify partial carbon footprint (CF) including both crop and livestock, 2) develop a multi-criteria performance index based on productivity, economic, and environmental indicators at the systems-level, and 3) evaluate the stability of this index over the study period.

METHODS: To understand how increasing the frequency of annual grain crops influences whole-system sustainability, we evaluated 10 productivity, economic and environmental indicators as well as a multi-criteria performance index and its stability in three rice-based rotation systems over 7 years in Uruguay. Treatments were: (a) rice–pasture [a 5 yr rotation of rice–ryegrass (*Lolium multiflorum* Lam.)–rice, then 3.5 yr of a perennial mixture of tall fescue (*Festuca arundinacea* Schreb.), white clover (*Trifolium repens* L.), and birdsfoot trefoil (*Lotus*

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* Corresponding author at: Department of Plant Sciences, Univ. of California, Davis, CA, USA.
E-mail address: macedoyapor@gmail.com (I. Macedo).

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corniculatus L.)], (b) rice–soybean [a 2-yr rotation of rice–ryegrass–soybean (*Glycine* max [L.] Merr.)– Egyptian clover (*Trifolium alexandrinum* L.)], and (c) rice–cover crop (an annual rotation of rice–Egyptian clover).

RESULTS AND CONCLUSIONS: Rice-soybean had medium productivity and energy use, resulting in the highest nitrogen and energy use efficiency and among the lowest yield-scaled C footprint. Field greenhouse gas emissions and embodied energy in fuel and agrochemicals were similar in rice-pasture and rice-soybean, but the increase in soil organic carbon in pasture rotating with rice was able to offset this by almost 50%. Rice-cover crop had the highest economic incomes but also the highest input costs, translating into the lowest gross margin. Although the rice-soybean and rice-pasture had a similar gross margin, the variability in rice-pasture was lower and with lower input costs. Rice-soybean and rice-pasture had a multi-criteria performance index 65% higher than rice-cover crop (0.35). Rice-pasture had the highest overall stability across four different stability parameters calculated. We conclude that the intensification of rice-pasture with annual crops could reduce the stability of sustainability without increasing economic performance, even for rice-soybean that showed the best the multi-criteria performance but with less stability across indicators.

SIGNIFICANCE: The findings of this study demonstrate how the integration of rice and pastures with livestock achieves the best combination of stability across profitability and environmental performance, thus mitigating vulnerability to external stressors.

1. Introduction

Integrated crop-livestock systems are facing the pressure to intensify worldwide, thus decoupling crops from pasture and reducing the amount of time under pasture, while increasing the frequency of annual grain crops (Franzluebbers, 2007; Garrett et al., 2017; Peyraud et al., 2014). Often this intensification is occurring to meet the economic objectives of farmers who are facing higher input costs and lower prices, with decreasing margins forcing them to search for new opportunities (Peyraud et al., 2014). However, the integration of crops and livestock has long served as the backbone of sustainable agriculture, especially in terms of maintaining soil quality and effectively recycling nutrients and energy (Brewer and Gaudin, 2020; Garrett et al., 2017). Pasture-based systems provide an array of ecosystem services, not only soil organic carbon (SOC) but other regulating and provisioning services that are critical for the functioning of agricultural landscapes, such as preserving biodiversity, providing clean water, and preventing soil erosion (Jaurena et al., 2021). Given current trends in global land use, Garrett et al. (2017) highlighted knowns and unknowns related to integrated crop-livestock systems and reported that net greenhouse gas (GHG) emissions, tradeoffs between ecosystem services, and economic benefits are rarely studied, particularly using long-term experiments (LTE) to address uncertainties.

Compared to pasture-based systems, simplified cropping systems which specialize in the production of one or two grain crops can often achieve higher annual productivity, yet they also rely on greater external inputs, for example fertilizer nitrogen and energy, causing a decline in resource use efficiencies (Basso et al., 2021; Theisen et al., 2017). Both of these inputs are critical components of the overall C footprint of agricultural systems, in addition to soil GHGemissions for cropland and enteric fermentation for livestock production (Quilty et al., 2014; Selene et al., 2015). Energy inputs include direct fuel consumption for field operations and embodied energy in fertilizers and agrochemicals, which can be converted to CO_2 equivalents and compared to other sources of GHG emissions. Soil GHG emissions include N_2O and CH_4, with the latter being particularly important in flooded rice (*Oriza sativa*; L) soils (Linquist et al., 2012). When assessing C footprint, one area that has received less attention is that gains in SOCcan offset field GHG emissions and those from embodied energy inputs (Prechsl et al., 2017). Positive changes in SOC reflect the net capture of atmospheric CO_2 in croplands, with different practices such as perennial crops or changes in tillage and nutrient management capable of mitigating GHG emissions by more than 0.5 Mg CO_2 eq ha^{-1} yr^{-1} (Paustian et al., 2016). However, the extent to which the pasture phase can increase SOC and mitigate the net GHG balance of crop-pasture systems remains poorly understood, particularly because livestock are often associated with a high C footprint due to enteric CH_4 emissions (Thompson and Rowntree, 2020).

Beyond the need to reduce GHG emissions, there are increasing calls to evaluate gains in productivity and sustainability of rice-based systems using a suite of key performance indicators (Saito et al., 2021). For example, the Sustainable Rice Platform framework has been used to detect differences between rice management practices (Stuart et al., 2018) or rice cultivation regions in Southeast Asia and Peru (Devkota et al., 2019; White et al., 2020). While these studies highlight opportunities for improvement and tradeoffs among indicators, they have neither evaluated indicators at the rotation system-level nor integrated all of them into an index. To increase sustainability, a holistic view of the performance of cropping systems is needed over the performance of individual parameters (Wittwer et al., 2021). Synergies and tradeoffs among different ecosystem services are common, thus the construction of composite indices has been reported as useful to assess how agricultural systems perform across multiple dimensions (Wittwer et al., 2021). An advantage of this approach is providing a single value for comparison and effective communication (Nardo et al., 2005; Reig Martinez et al., 2011; Tseng et al., 2021a, 2021b).

One drawback of many sustainability frameworks is they lack a measure of system stability. Extreme weather variability under climate change coupled with increasing economic shocks to markets and prices requires a high stability of yields and profitability under different conditions (Lin, 2011). Most of the research regarding stability analysis in cropping systems has focused on the yield of a single crop or rotation (Li et al., 2019; Riccetto et al., 2020; Sanford et al., 2021) or stability of income or profit (Bell et al., 2021; Harkness et al., 2021) or both (Assefa et al., 2021). Sanford et al. (2021) found that systems with higher perenniality (less frequency of maize and/or rotation with pastures) were more stable than continuous maize in terms of system productivity. Additionally, de Albuquerque Nunes et al. (2021), reported that the integration of livestock in a soybean cropping system increase the stability of food production. But to our knowledge, previous studies have not included aspects of sustainability or resource use efficiency in their definition or evaluation of stability. Developing an integrated multi-criteria performance index encompassing key economic and environmental indicators at the systems-level would help identify rotations that exhibit both high sustainability and stability in the face of uncertain weather and market conditions.

Uruguay is a small country located in South America with a rice area of approx. 160,000 ha (approx. 15% of cropping agricultural area), where most rice is rotated with pastures of diverse composition, duration and quality that are used by cattle under direct grazing (Zorrilla, 2015). Previous research suggests that improved management practices and the development of locally-adapted national cultivars have contributed to high average yields without large negative effects on environmental performance (Pittelkow et al., 2016; Tseng et al., 2021a, 2021b; Zorrilla, 2015). However, there has been an incipient process of intensification and a growing interest to produce more grain crops in these systems over the last decade, for example with the inclusion of soybean (*Glycine* max (L.) Merr.) or higher frequency of rice in the rotation (DIEA, 2018; Song et al., 2021).

In 2012 we initiated a LTE to evaluate how the intensification of rice-pasture rotations with annual crops influenced multiple dimensions of sustainability. In previous papers we have reported on individual aspects of intensification such as energy efficiency (Macedo et al., 2021) or changes in rice yield and SOC (Macedo et al., 2022). However, an important knowledge gap is how the intensification of rice-pasture rotations influences economic benefits, net GHG emissions, and tradeoffs between environmental indicators. The novelty of the current study is to evaluate new parameters (economics and C footprint) and integrate them with productivity and resource use efficiency indicators to quantify whole system sustainability and the stability of sustainability over time. We hypothesized that intensification would increase system productivity through higher input use, but this will contribute to higher environmental footprint and lower multi-criteria performance, while decreasing the stability of holistic system sustainability. Our goal was to compare a highly productive rice-pasture rotation, as the business-as-usual rotation, with two intensified systems, rice-soybean and rice-cover crop, to address the following objectives: 1) quantify partial carbon footprint (CF) including both crop and livestock activities, 2) develop a multi-criteria performance index based on productivity, economic, and environmental indicators at the systems-level, and 3) evaluate the stability of this index over the study period.

2. Methods

2.1. Study site

The LTE was initiated in 2012 in Treinta y Tres, Uruguay (33^{0}6′23′S, 54^{0}10′24′W; located 22 m above sea level) in a silty clay loam Argialboll soil according to USDA Soil Taxonomy. The climate of the site based on the Köppen-Geiger classification correspond to C: warm temperate, f: fully humid, and a: hot summer (Cfa) (Beck et al., 2018). The mean monthly temperature is 22.3 ± 0.85 °C and 11.5 ± 0.82 °C during summer and winter, respectively. Total annual rainfall at the site is 1360 ± 315 mm; annual total potential evapotranspiration is 1138 ± 177 mm.

2.2. Treatments and experimental design

The LTE design was a randomized complete block design with three replications, also known as basic design (Patterson, 1964) and with all rotation components (phases) present in time and space. A detailed description of the experimental design, as well as the agronomic management of the LTE, can be found in (Macedo et al., 2022, 2021). All rotations evaluated included irrigated rice and treatments were: 1) rice-pasture, rice-rice followed by a 3.5-year perennial pasture mix of tall fescue (*Festuca arundinacea* Schreb.), white clover (*Trifolium repens* L.), and birdsfoot trefoil (*Lotus corniculatus* L.); two intensified rotations systems, 2) rice-soybean and 3) rice-cover crop, with rotation lengths of 5, 2, and 1 years, respectively. Ryegrass (*Lolium multiflorum* Lam.) or Egyptian clover (*Trifolium alexandrinum* L.) were included as cover crops between cash crops (Fig. 1). Within each block, the number of plots per rotation varies so that every phase of every rotation is present each year, with one (rice), two (rice-soybean), and five (rice-rice- pasture yr1- pasture yr2- pasture yr3) plots per block, resulting in a total of 24 experimental units. A table with an example of one replication of the LTE was included (Table S1).

2.3. Agronomic and environmental indicators evaluated

Ten indicators covering productivity, environmental footprint, and economics were calculated at the systems-level over 7 years (2012–2018). Indicators were selected based on the linkage with impact areas, such as nutrient, health and food security or climate adaptation and GHG reduction, as proposed by Saito et al., (2021) (Table 1). Detailed crop management information included agronomic inputs

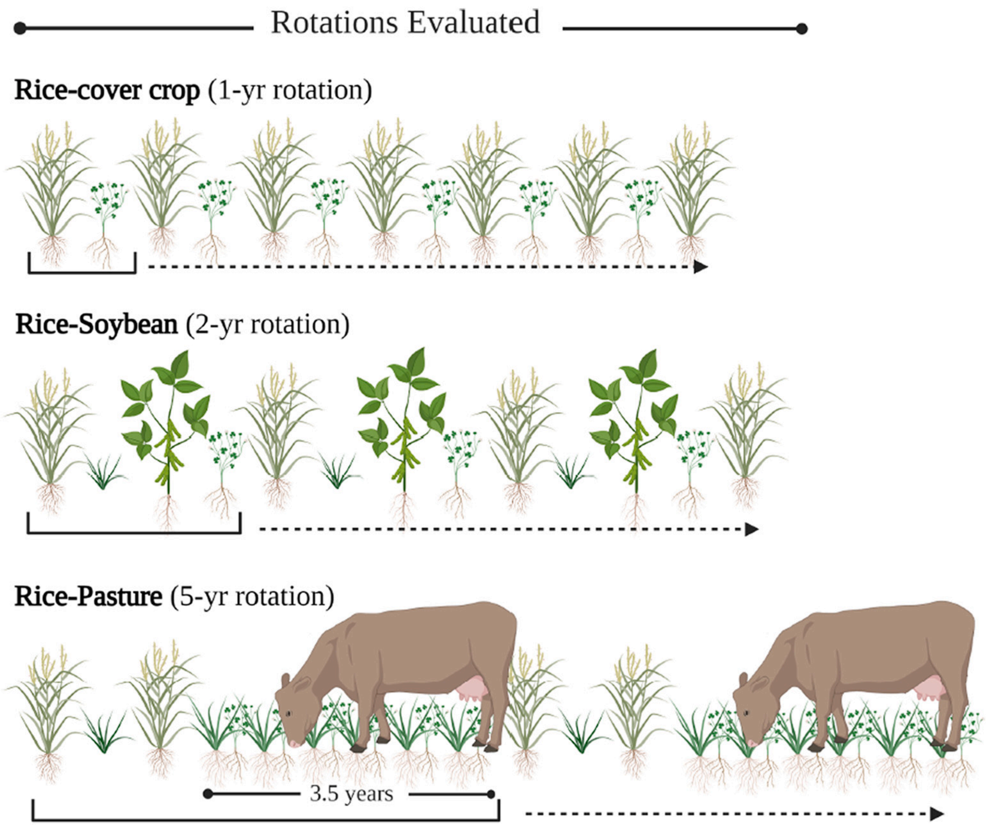

Fig. 1. Rice-based rotations evaluated and sequence length for each crop during the 7-yr study period. Rice-cover crop: rice during spring-summer rotating with Egyptian clover winter cover crop. Rice-Soybean: rice and soybean (cash crops during spring-summer) in rotation with ryegrass and Egyptian clover (winter cover crops). Rice-Pasture: two year rice during spring-summer (with ryegrass cover crop in winter) followed by a perennial pasture mix of tall fescue, white clover, and birdsfoot trefoil.

Table 1
Indicators, units, and descriptions included in the study. All indicators were calculated at the systems-level.

Indicator	Unit	Description
Productivity	GJ ha^{-1} yr^{-1}	Includes total grain and beef production depending on the rotation
Energy Use	GJ ha^{-1} yr^{-1}	Energy used in field management activities and embodied inputs
Nitrogen Use	kg N ha^{-1} yr^{-1}	Nitrogen from synthetic fertilizer
Partial carbon footprint (CF)	kg CO_2eq ha^{-1} yr^{-1}	Emissions from field management activities and field (CH_4 and N_2O emissions) based on IPPC, 2006
Energy Use Efficiency (EUE)	GJ GJ^{-1}	Productivity per unit energy input
Nitrogen Use Efficiency (NUE)	GJ kg N^{-1}	Productivity per unit N input
Yield Scaled Partial CF	kg CO_2eq GJ^{-1}	Partial CF per unit productivity
Income	USD ha^{-1} yr^{-1}	Income from outputs produced in the system (grain and/or beef)
Costs	USD ha^{-1} yr^{-1}	Input, post-harvest, and administrative costs were included
Gross margin	USD ha^{-1} yr^{-1}	Net difference between Income and Costs

(seed, fertilizers, and pesticides, diesel consumption of machinery activities (e.g. planting, harvest, sprays), electricity use for irrigation, and cropping system outputs (grain yield and beef production). As described below, to standardize units across systems for energy efficiency and partial CF calculations all input variables were converted to energy and CO_2 equivalent units and all output variables were converted to energy units. Additionally, all inputs and outputs were converted to USD to perform an economic analysis.

Productivity was estimated by the aggregation of grain production (rice or soybean) and beef production based on the rotation outputs multiplied by energy conversion factors (Table S2). Energy use refers to all inputs used in each rotation (diesel, seeds, fertilizers, pesticides, electricity for irrigation) expressed in GJ. Nitrogen use is the nitrogen from synthetic fertilizer used in each rotation. Partial CF involves GHG emissions from fuel consumption and embodied energy in external inputs calculated as CO2 equivalents (Table S2) and field GHG emissions as explained below. Three indicators that address resource use efficiency were evaluated. Energy use efficiency and nitrogen use efficiency were calculated as the ratio of energy outputs (GJ ha^{-1} yr^{-1}) per unit of energy use and nitrogen use, respectively, at the rotation level. Yield-scaled partial CF reflects the emissions intensity, or GHG emitted per unit of productivity. The economic analysis included the estimation of income, costs, and gross margin. The income was computed using the outputs of the systems multiplied by the sale price of each output. The costs calculation comprised: diesel, seeds, fertilizers, pesticides, transport of products, rent, labor, crop advice, taxes, irrigation water and polypipes, grain drying, soybean sales commission, administration, veterinary inputs, and services. The price of each input was estimated for each year as the average price across different commercial representatives of inputs and their suppliers. The price of products such as grain, beef, as well as some inputs were obtained from DIEA (2018) for each year.

Field emissions included in the partial CF estimation were based on IPCC guidelines (IPCC, 2019). Methane from rice crops was estimated based on the Tier 2 method with field-specific scaling factors represented in the following Eq. (1):

$$CH_4 = EF^{*}t \tag{1}$$

Where: EF represents the daily emission factor and t the irrigation period.

The EF was scaled based on the water regimen in the cultivation period (SFw = 1) as well as in the pre-season before the cultivation period (SFp = 0.68) and the type and amount of organic amendment applied (SFo), which in our case represented crop residues from the previous crop in the rotation. Average EF for all rice observations was 1.64 kg CH_4 per day (std. dev +/− 0.36) and average irrigation period was 103.5 days (std. dev +/− 13 days). Methane emission from enteric fermentation was also estimated based on the Tier 2 method, including the number of animals ha^{-1} yr^{-1} in the pasture phase of the rice-pasture system, multiplied by the EF. The EF was scaled based on the gross energy intake (MJ $head^{-1}$ day^{-1}).

Direct N_2O emissions were estimated with the Tier 1 method for all systems. Nitrous oxide emission from inorganic and organic N inputs in the case of rice-soybean and rice-cover crop were considered, while N_2O emissions from both N inputs and urine and dung (N_2O $_{PRP}$) were included for rice-pasture rotation. Nitrous oxide emissions from inputs in this study included N from synthetic fertilizers (Fsn) and N in crop residues (Fcr). Emission factors of 0.01, 0.003, and 0.02 kg N_2O–N ha^{-1} were used for N additions (synthetic and crop residues) in rainfed conditions, flooded rice, and cattle, respectively. Indirect N_2O emissions were not estimated with the goal of not introducing more assumptions into our analysis. For indirect emissions, a large portion of N loss is predicted to occur via leaching and volatilization pathways, but there is no empirical evidence to support this assumption for our study conditions consisting of a flooded rice system with relatively low drainage and low slopes. In addition, the IPCC methodology for direct N_2O emissions distinguishes between flooded rice soils and non-flooded conditions, with a lower fraction of N inputs converted to N_2O under flooded soil conditions. However, the fraction of N leaching and volatilization does not change depending on flooded or non-flooded soils, supporting our decision to be conservative. Direct field emissions were converted to CO_2 equivalents to standardize units and added to emissions from activities associated with fertilizers, seeds, and diesel consumption to compute the partial CF and make comparisons between rotations, with 30 and 298 CO_2 equivalents used to covert CH_4 and N_2O, respectively. Fuel consumption of each machinery activity is detailed in supplemental Table S3. All equations used to estimate CH_4 and N_2O can be found in the supplemental material S1.

2.4. Multi-criteria performance index and stability analysis

A multi-criteria performance index was developed to obtain a holistic comparison between rotations in terms of sustainability. The number of variables researchers can measure to include in such an index is always limited and represents a fraction of the true system performance (Manning et al., 2018). Similar to Wittwer et al., (2021) we did not assume independence between the indicators since different indicators in cropping systems are often correlated. This was done because we were interested in individual understanding of the indicators and to capture synergies and trade-offs among different indicators in the multi-criteria index. To build the performance index which included different indicators with different units and levels of variation, the re-scaling to min-max normalization approach was used based on the following equations (Mutyasira et al., 2018; Nardo et al., 2005):

$$I_{ijkl} = \frac{\left(Y_{ijkl} - Y_{jmin}\right)}{\left(Y_{jmax} - Y_{jmin}\right)} \tag{2}$$

$$I_{ijkl} = \frac{\left(Y_{jmax} - Y_{ijkl}\right)}{\left(Y_{jmax} - Y_{jmin}\right)} \tag{3}$$

Where: I_{ijkl} is the normalized value of the indicator j for the rotation i for the replication k and the year l. Y_{ijkl} is the original value (raw data) of the indicator j for rotation i for the replication k and the year l. Y_{jmax} and Y_{jmin} represent the maximum and minimum of the original observed value (across years, replications and rotations), respectively. Briefly, when higher values of the indicator are better, Eq. (2) was used and when lower values of the indicator are better, Eq. (3) was used. In this way, the values of the normalized indicators were between 0 and 1, with values closer to 1 having better performance. The multi-criteria performance index was calculated as the average of 9 of the normalized indicators. The synthetic N use was not included in the multi-criteria index because a low use of N could imply that the system does not need synthetic N because nitrogen biological fixation and soil N cycling or could imply soil N mining.

To evaluate the sensitivity/robustness of the multi-criteria performance index the inclusion/exclusion method was used (Nardo et al., 2005). The composite index should not be heavily influenced by a single indicator. For that, we evaluated how the multi-criteria performance index changes when one of the indicators was not included to compute the index (Fig. S1). The coefficient of variation (CV) between the indices was calculated.

The stability of the multi-criteria performance index was evaluated across the rotations following the approach proposed by Li et al. (2019) for yield stability analysis. Briefly, this stability analysis evaluates four parameters: 1) the range of the variable, 2) the CV, 3) the temporal variance, and 4) the Finlay-Wilkinson (FW) regression slopes (Finlay and Wilkinson, 1963). In the FW regression, the multi-criteria performance index was regressed against an environmental index, defined by the average index of the three rotations in each year and then ranked from low to high years. Rotations with the smaller multi-criteria performance index range, CV, variance, and FW regression slope indicate higher stability. Because each of these parameters provides different information, the overall stability was obtained through a rank based on the mean of the four parameters. The same procedure explained before was applied to each of the indicators included in the multi-criteria index with the aim to explore the stability of each indicator across rotations.

2.5. Data analysis

All analyses were performed in R (4.0.5) (R Core Team, 2021). Linear mixed-effects models were performed using the function ‘lmer’ from the R package ‘lme4’ (Bates et al., 2015). All indicators and the multi-criteria performance index were evaluated by analysis of variance (ANOVA) using mixed models, where replication and years were considered as random effects and rotation was a fixed effect. The function ‘cld’ from the R package ‘multcomp’ was used to conduct a post-hoc means comparison (Hothorn et al., 2008). Normality and homogeneity of variance assumptions were tested following standard protocols via the Shapiro–Wilk and Levene tests, respectively. When appropriate, mean values were compared using the Tukey test for all indicators and the multi-criteria performance index across the rotations at the 0.05 significance level. Linear regressions were performed with the OLS method for the stability analysis (Finlay and Wilkinson, 1963) and *t*-tests were applied to evaluate differences between slopes. The ‘ggplot2’ R package was used for graphical purposes (Wickham, 2016).

3. Results

3.1. Productivity, nitrogen use, and energy use

With an annual rice grain harvest, the highest mean system productivity was achieved in rice-cover crop (162 GJ ha^{-1} yr^{-1}), being 1.4 and 2.4 times greater than the total energy outputs in grain and meat products in rice-soybean and rice-pasture, respectively (Table 2). On the other hand, the two intensified systems (rice-soybean and rice-cover crop) required 63 and 279% more energy inputs than rice-pasture (9.3 GJ ha^{-1} yr^{-1}), respectively. In addition to increased fuel use and mechanization on an annual basis, N fertilizer use in rice-cover crop was 3.7 times greater than in rice-pasture and rice-soybean systems (both approximately 40 kg N ha^{-1} yr^{-1}).

Table 2
Mean Productivity (GJ ha^{-1} yr^{-1}), Energy Use (GJ ha^{-1} yr^{-1}), and Nitrogen use (kg ha^{-1} yr^{-1}) and (standard deviation) in three rice-based systems across the study period.

Rotation	Productivity	Energy use	Nitrogen use
	GJ ha^{-1} yr^{-1}	GJ ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}
Rice-cover crop	162 (18.2)^{a}	25.90 (1.70)^{a}	148 (30.2)^{a}
Rice-Soybean	117 (13.7)^{b}	15.10 (0.71)^{b}	40.3 (5.19)^{b}
Rice-Pasture	66.4 (5.41)^{c}	9.27 (0.56)^{c}	38.9 (6.87)^{b}

Different letters indicate differences between treatments ($p < .05$).

3.2. Partial carbon footprint

Rice-cover crop had the highest partial CF (GHG from field emissions and crop production practices) (8110 kg CO_2 eq ha^{-1} yr^{-1}), 1.9 and 2.3 times greater than rice-pasture and rice-soybean, respectively. Field GHG emissions represent between 76 and 86% of partial CF in the systems evaluated (Fig. 2). Compared to rice-pasture, rice-cover crop increased field GHG emissions by 75% while rice-soybean decreased by 28%. Emissions from agricultural inputs (fuel and agrochemicals) followed the same hierarchy as energy use, with higher values for intensified systems. However, soil organic carbon sequestration during the study period only occurred in rice-pasture, while other systems experienced no change in soil organic carbon (Macedo et al., 2022). The SOC increase in rice-pasture offset nearly 50% of the partial CF in this system (− 2202 kg CO_2 eq ha^{-1} yr^{-1}, 0.6 Mg ha^{-1} yr^{-1} of SOC). Considering this offset, net emissions of rice-pasture were 1690 kg CO_2 eq ha^{-1} yr^{-1}, translating to a partial CF that was 2.1 and 4.8 times lower than rice-soybean and rice-cover crop, respectively.

3.3. Systems-level efficiencies

Accounting for both inputs and outputs at the systems-level, rice-pasture had a 14% increase and 8% decrease in EUE compared to rice-cover crop and rice-soybean, respectively (Fig. 3). Rice-soybean rotation improved NUE by 68% compared to rice-pasture (1.74 GJ kg N^{-1}) while rice-cover crop had 34% lower NUE. Similar values of yield-scaled

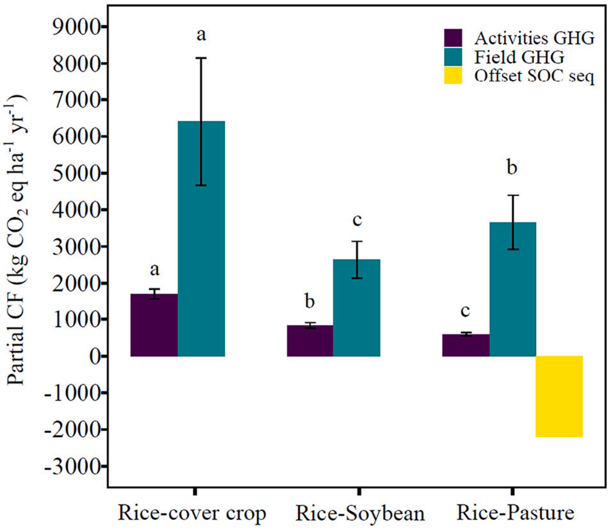

Fig. 2. Partial carbon footprint (CF) (kg CO_2 eq ha^{-1} year^{-1}) from field management activities (fuel consumption and embodied energy in external inputs) and field GHG emissions (estimated CH_4 and N_2O emissions) in three rice-based systems. The yellow bar represents soil organic sequestration reported (Macedo et al., 2022), offsetting partial CF by nearly 50% (− 2202 kg CO_2 eq ha^{-1} yr^{-1}). Different letters indicate differences between treatments ($p < .05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

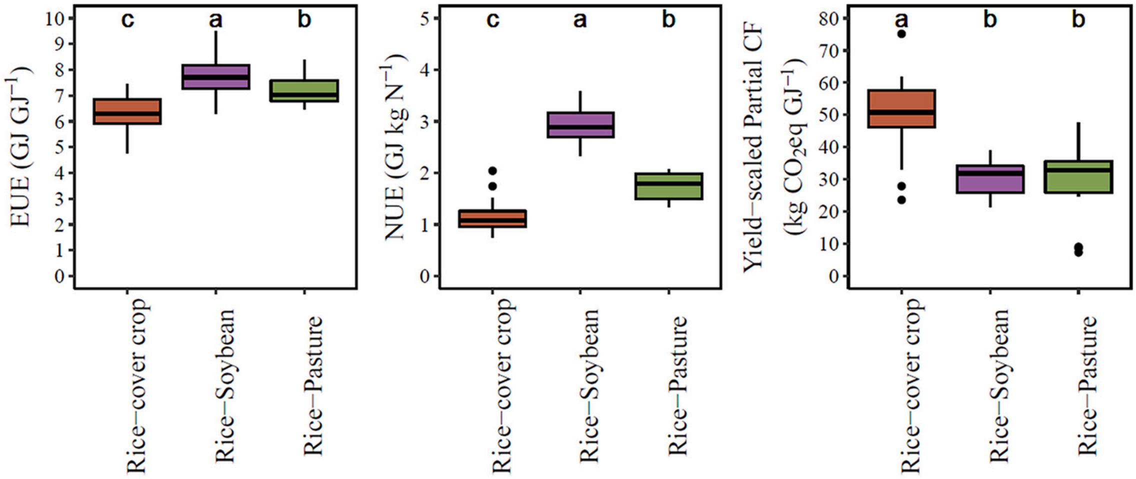

Fig. 3. Boxplots for energy use efficiency (EUE) (GJ GJ^{-1}), nitrogen use efficiency (NUE) (GJ kg N^{-1}), and yield-scaled partial carbon footprint (kg CO$_2$ eq. GJ^{-1}) in three rice-based systems. Different letters indicate differences between treatments ($p < .05$).

partial CF were observed in rice-pasture and rice-soybean systems, while rice-cover crop was 66% higher (an additional 19.6 kg CO$_2$ eq per unit of productivity (GJ) than the average of rice-soybean and rice-pasture, 30.43 kg CO$_2$ eq. GJ^{-1}).

3.4. *Economics*

The intensified systems showed an increase in both, costs and income compared with rice-pasture rotation (Fig. 4). While income was increased by 11 and 44%, costs were increased by 16 and 42% for rice-soybean and rice-cover crop, respectively. As a result, the gross margin was similar in rice-soybean and rice-pasture, but with a lower variability in the rice-pasture rotation. Rice-cover crop showed a reduction of 134 USD ha^{-1} yr^{-1} in the gross margin compared to the average of rice-soybean and rice pasture (212.5 USD ha^{-1} yr^{-1}).

3.5. *Multi-criteria performance index and stability*

When integrating all indicators into one multi-criteria performance index, rice-soybean showed the highest value (0.6), slightly higher than rice-pasture system (0.56). The lowest multi-criteria performance index was rice-cover crop (0.35), 41.7 and 37.5% lower than rice-soybean and rice-pasture, respectively (Fig. 5 A). The normalized indicators illustrated in the heatmap showed that rice-cover crop maximized productivity and income, while rice-pasture had the best costs and energy use, and rice-soybean showed better performance in NUE and EUE (Fig. 5 B).

The sensitivity of the multi-criteria performance index was similar between rice-based rotations when one indicator at a time was excluded from calculations (Fig. S1). Density plots for the multi-criteria performance index did not differ much from the original one (all indicators, pink color), with an average CV between indices of 7.8, 3, and 6.6% with the rice-cover crop, rice-soybean, and rice-pasture systems, respectively. The fact that no single indicator had a disproportionate effect on the index indicates the robustness of this method.

The rice-pasture rotation had the highest stability, showing the lowest values in all the stability parameters included in the analysis, while rice-cover crop had the highest values which corresponded with the lowest stability across all parameters (Table 3). The range was 3.5 and 2.2 times higher in rice-cover crop and rice-soybean, respectively compared to rice-pasture. The CV showed a similar trend as the range, and the temporal variance was 4 times higher in rice-cover crop and 3.3 times higher in rice-soybean than in rice-pasture. For the FW regression, the response of multi-criteria performance index to increasing environmental index (representing average multi-criteria performance index ranked from low to high years) showed that rice-soybean and rice-cover

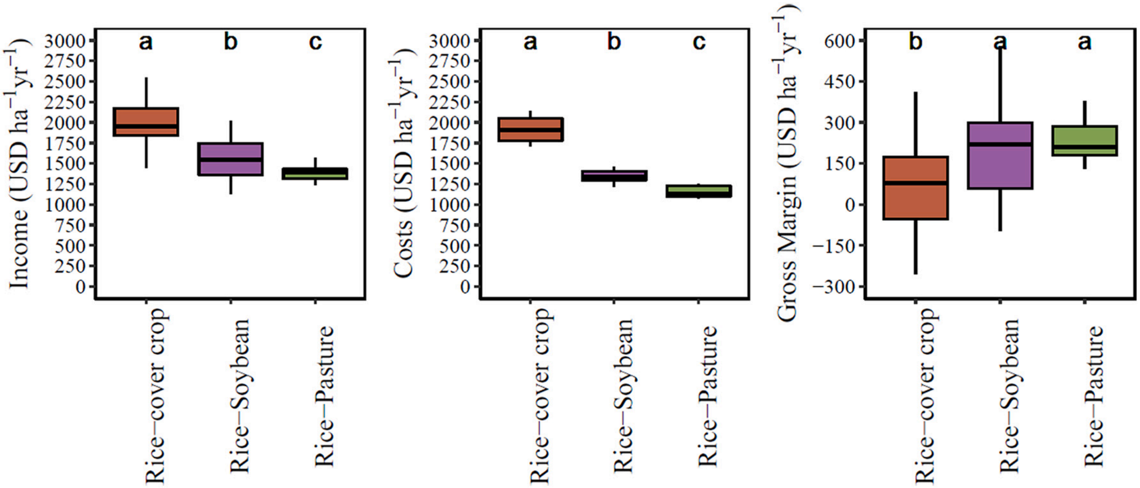

Fig. 4. Boxplots for income, costs, and gross margin (USD ha^{-1} yr^{-1}GJ GJ^{-1}) in three rice-based systems. Different letters indicate differences between treatments ($p < .05$).

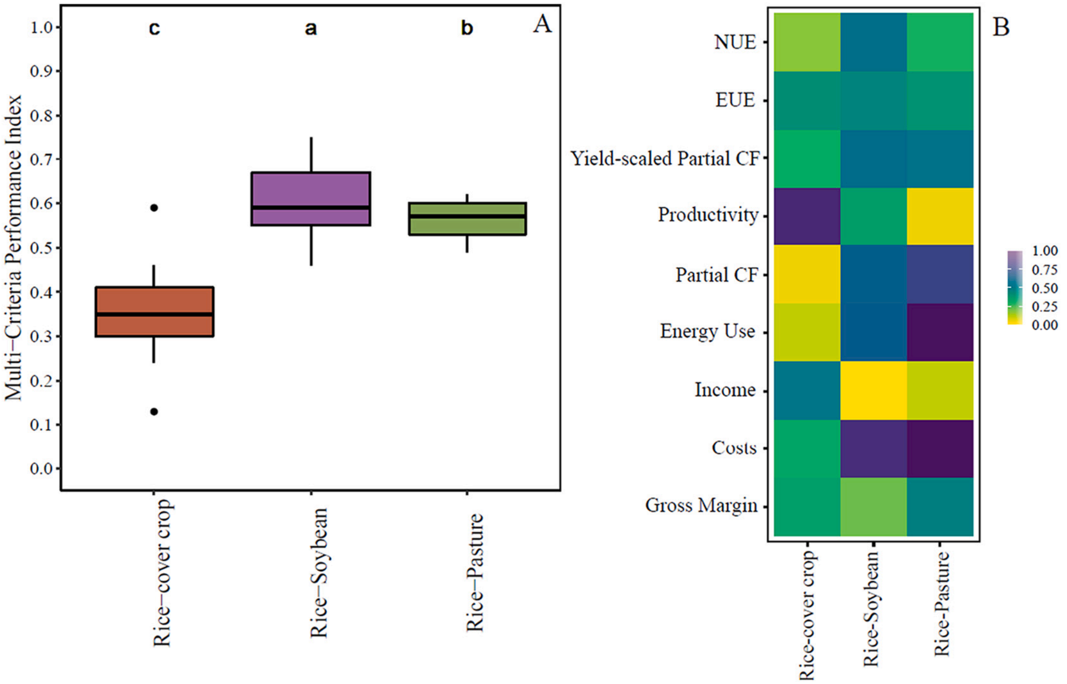

Fig. 5. Boxplots for multi-criteria performance index (0–1) (A) and heatmap plot for normalized variables included in the multi-criteria performance index (0–1) (the closer to 1 the better) (B) in three rice-based systems. Different letters indicate differences between treatments ($p < .05$).

Table 3
Multi-criteria performance index stability parameters and rank for three rice-based rotation systems.

Rotation	Multi-criteria performance index stability parameters				Rank
	Range	CV (%)	Temporal Variance	FW slope	
Rice-cover-crop	0.46 (3)	27.50 (3)	0.12 (3)	1.33 a (3)	3
Rice-Soybean	0.29 (2)	13.45 (2)	0.10 (2)	1.28 a (2)	2
Rice-Pasture	0.13 (1)	6.99 (1)	0.03 (1)	0.39 b (1)	1

crop had a similar positive slope but different intercepts (Fig. 6). This means both systems increased performance in better conditions, but on an absolute basis rice-soybean had an intercept nearly double that of rice-cover crop in poor-yielding environments. On the other hand, the rice-pasture rotation had the lowest FW slope (ranging between 0.5 and 0.6), indicating the most stable performance across all environments. When all the parameters were aggregated in a rank, rice-pasture showed the most stable multi-criteria performance index followed by rice-soybean and rice-cover crop. The stability performance of each of the indicators included in the multi-criteria index followed the same pattern as the stability of the multi-criteria index with rice-pasture achieving the highest stability in 7 out of 9 indicators (Table S4).

4. Discussion

4.1. Impacts of rotations on productivity, environment, and economics

Our findings contribute to the understanding of the intensification of agriculture via increased frequency of annual grain crops and its influence on agronomic, economic, and environmental performance, specifically in rice-pasture systems in the southern cone of South America. Widespread conversion of pasture to cropland is occurring in this region (Jaurena et al., 2021; Song et al., 2021), but our findings indicate this may come with hidden costs in terms of negative environmental externalities. We found total cropping system productivity was driven by higher frequency of rice or soybean in the rotation but replacing the pasture and livestock phase of the business-as-usual system also translated into significantly higher external inputs (Table 2). A key message is that despite rice-cover crop having the highest productivity, it also had the highest energy and nitrogen fertilizer use, which corresponded with the lowest NUE and EUE and highest yield-scaled C footprint. This is

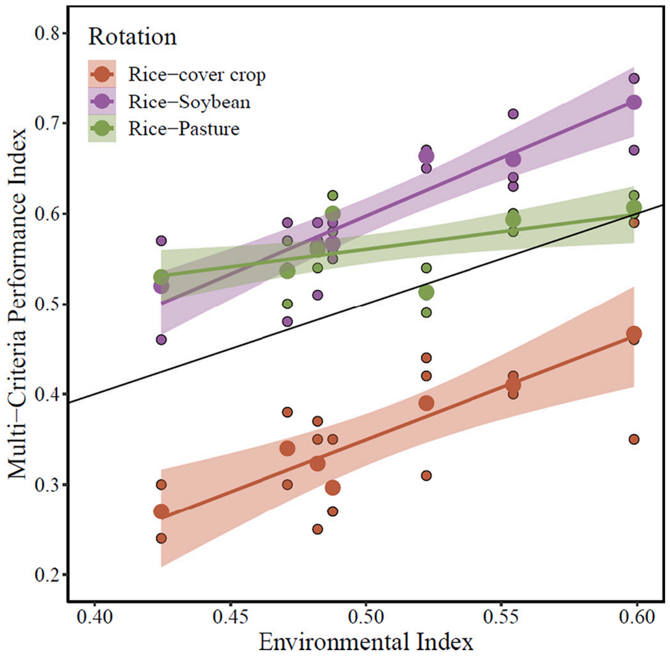

Fig. 6. Stability of three rice-based systems as determined by the slope of FW regressions for multi-criteria performance index against environmental index. Black line illustrates the 1:1 line, big circles indicates the mean across the three observations and small circles represent individual observations.

because it not only had higher field GHG emissions but also embodied energy in inputs (Fig. 2), yet the higher system productivity of producing an annual rice crop did not make up for these increased sources of emissions. These results partially confirm our hypothesis that intensification of rice-pasture systems with rice-cover crop increases environmental footprint regarding the indicators studied here.

In contrast, rice-soybean had medium productivity and energy use and lower field GHG emissions due to fewer seasons of rice, resulting in the highest NUE and EUE and among the lowest yield-scaled C footprint (Table 2, Fig. 3). Previous research illustrates similar findings where the inclusion of soybean in the rotation improved the performance of the system compared to a rice-fallow system (Theisen et al., 2017; Vogel et al., 2021). Contrary to our hypothesis, these results illustrate that replacing pasture with annual crops can have different impacts on sustainability depending on the type of crop (e.g. rice or soybean) and corresponding production practices and GHG emissions. Continued research on the environmental consequences of rapid land use in this region is necessary, particularly comparing soybean to pasture-based systems integrated with rice at different scales to resolve potential tradeoffs between agricultural production and ecological conservation (Carvalho et al., 2021; Song et al., 2021).

There is an urgent need to link CF, which contributes to climate change at a global scale, with the economic decision-making of individual farmers weighing different aspects of cost, revenue, and profitability in short- vs. long-term rotations. Regarding the CF of different systems, while field GHG emissions and embodied energy in fuel and agrochemicals were similar in rice-pasture and rice-soybean, a new insight from our analysis is that the increase in SOC with rice-pasture was able to offset this by almost 50% (Fig. 2). This is despite rice-pasture having the animal component of direct livestock grazing for several years, which is often considered a key source of GHG emissions (Thompson and Rowntree, 2020), although comparisons with rice which also have high CH_4 emissions are rare. To our knowledge, this finding in rice-based systems is unique and strengthens the concept of mitigating net GHG emissions through soil C sequestration in crop-pasture systems and its viability (Franzluebbers et al., 2014; Garrett et al., 2017). Since the other two systems (rice-cover crop and rice soybean) were able to sustain SOC, at least in the midterm (Macedo et al., 2022), efforts should be focused on ways to reduce CH_4 and N_2O emissions, which represented the vast majority of CF, through improved water and N fertilizer management without compromising productivity to develop economically viable, environmentally friendly, and socially acceptable cropping systems. It is known that SOC sequestration has limits and reaches a plateau (Hassink and Whitmore, 1997) which could suggest in the long-term (e.g., 20 yr. period after SOC has reached a new equilibrium) that the system with the lowest field GHG emissions will be the best no matter the SOC content. However, it is still critical to value the benefits of SOC sequestration, specifically if SOC content at “the end” is expected to be different among systems like the current study, because if one system with higher SOC is replaced by another with lower SOC (e.g., rice-pasture by rice-soybean), the SOC that was stored before could be lost, thereby increasing the CF of the system.

In addition to aspects of resource use efficiency and CF, our assessment illustrates the better economic performance of integrated crop-pasture systems compared to the intensified systems. Similar to the energy cost-benefits of achieving higher productivity at the systems-level, rice-cover crop had the highest economic returns but also the highest input costs, translating into the lowest gross margin. These results are consistent with our hypothesis and underscore the need to not only view grain crops as potentially increasing annual revenues compared to pasture, but to account for the higher investment requirements. Although the rice-soybean and rice-pasture had a similar gross margin, the variability in rice-pasture was lower with the additional benefit of having lower input costs (Fig. 4). These results imply that integrated crop-pasture systems can reduce the economic risks of production due to weather variability and fluctuation in commodity and input prices that are beyond their control. Similar results were found by Bell et al. (2021) in Australia or Vogel et al. (2021) in rice-based systems in Brazil, showing an increase of 2.8 times in profit for improved rice-livestock systems compared to a baseline system. Conversely, Poffenbarger et al. (2017) found similar returns between integrated crop-livestock systems and cash crop systems with higher costs in crop-livestock systems in Iowa, United States. Future research that addresses economics beyond profit, for example by considering the environmental and social value of these systems in terms of positive or negative externalities, could advance our understanding of how to optimize agricultural systems across competing objectives.

4.2. *Systems-level performance*

Our multi-criteria analysis highlights the importance of integrating several dimensions of sustainability using a holistic view of system performance over multiple crop cycles (Kumar et al., 2018). If performance was only based one or two indicators such as yield and profitability, the intensification of crop-pasture rotations with rice or soybean would show increased annual productivity, as expected, yet this neglects environmental tradeoffs that may be occurring (Wittwer et al., 2021). Instead, the multi-criteria performance index reflects both benefits and disadvantages at the rotation systems-level, such as high inputs and production costs in rice-cover crop which caused low efficiencies, high C footprint, and low economic returns, together resulting in the lowest performance index. In contrast, rice-soybean had the highest performance index because it was often in the middle and achieved the best balance of productivity, resource use efficiencies, and profitability (Fig. 5). Rice-pasture also had a similar performance index (a small but statistically significant decrease of 6.7%), but with key benefits related to lower economic risk (decreased variability in profitability) and greater stability of performance (further explored in the next section). To our knowledge a composite index has been used to integrate several indicators for a single crop (Nardo et al., 2005; Tseng et al., 2021a, 2021b) but there are few precedents in the literature for the whole system or rotation (Emran et al., 2021; Wittwer et al., 2021). This framework advances knowledge by simultaneously quantifying multiple indicators for each system, which can be coupled with tradeoff analysis among individual (Kumar et al., 2018) or multiple variables (Devkota et al., 2019) to increase cropping systems sustainability. By default, this approach also requires monitoring individual indicators for different systems which is necessary to understand tradeoffs between indicators and track changes in performance over time.

From an extension or decision-making standpoint, these results imply that the use of a composite index is a good tool for efficient communication and rotation systems comparison. However, there are some constraints to this study. First, despite including several key performance indicators related to economics, productivity, and environmental aspects (Saito et al., 2021), there were a number of other indicators that were not included. We acknowledge that any multi-criteria analysis will always contain a subset of all possible indicators and so will capture only a fraction of the holistic system performance, which makes it difficult for comparing results among studies (Manning et al., 2018). Second, we expressed productivity in terms of energy and did not include the potential human nutritional value that can be produced in each system which can make results different from what we obtain here. Further research is needed to know not only how much energy is produced but the quality of food to reflect how these systems might influence human health as proposed by McAuliffe et al. (2019). We did not measure nutrient losses and only estimated rather than measured field GHG emissions, similar to other life cycle analysis studies. We did not include pesticides in our analysis as a potential contamination risk indicator, which could cause negative environmental impacts on soil and water quality and biodiversity loss (Chivenge et al., 2020). Further research that quantifies water use and its efficiency at the system level is needed to expand these types of analysis. Additionally, not all possible crop sequences were included in the field study. Given the positive outcomes of both rice-pasture and rice-soybean, it is possible that soybean could be included as a third crop in rotation with rice and pasture to enhance system performance. Future work that explore different scenarios of rice-soybean-pasture combinations are needed to better understand the performance of these systems. Finally, interpretation of results and comparison with other values in the literature should be taken with caution since studies often rely on different systems boundaries and conversion factors for estimating indicators.

4.3. *Stability of systems-level performance*

Our analysis is distinctive in the way that we quantified stability, moving beyond crop yields or profits in previous work. When evaluating the stability of a composite multi-criteria performance index at the rotation system level, we found that simpler systems (rice-cover crop and rice-soybean) had lower stability, thus indicating that integrated crop-pasture systems could be more resilient since stability has been described as one potential parameter of resilience (Peterson et al., 2018). Consistent with our hypothesis, this implies that the intensification of rice-pasture systems with annual grain crops such as rice or soybean could make the system more vulnerable to external conditions. A strength of this study is accounting for changes in input costs and grain and beef prices each year as well as weather variation over the 7 years, as these represent external factors beyond farmer control that fluctuate widely in Uruguay. More broadly this approach could be used to account for the stability of agricultural systems to different stressors such as drought, floods, pandemics, political conflicts, and unstable food or inputs prices. The highest overall stability was observed in the rice-pasture system, which ranked first across all four stability parameters included in this analysis (Table 3). Similar results (based on yield and income/profit) were reported when comparing diversified systems, such as rice-maize, rice-sunflower, or rice-mungbean against rice-fallow in Bangladesh (Assefa et al., 2021) or when livestock was included in a soybean-grazed cover crop system vs. no grazing in Brazil (de Albuquerque Nunes et al., 2021).

This novel framework allowed for differentiating rice-soybean and rice-cover crop (the 2nd and 3rd, respectively) in the rank, illustrating the benefit of assessing multiple parameters of stability together (Table 3). If stability had only been evaluated using the FW slope analysis approach which is commonly employed in genotype by environment studies (Finlay and Wilkinson, 1963), rice-soybean and rice-cover crop would have shown the same stability across different environments, yet rice-soybean also had a smaller range, CV, and temporal variance. Additionally, and similar as was discussed in the previous section, if the stability of one or two indicators had been evaluated, such as productivity or profit, this would have neglected the stability of costs or energy use and underlying relationships among indicators (e.g., more stable in productivity but less stable in energy use) which is captured in the stability of the multi-criteria performance index used here. Supporting the results obtained from the stability of the multi-criteria index, when analyzing the stability of each indicator, rice-pasture showed the highest stability in 7 out of 9 indicators. Hence, this new approach allowed us to contemplate tradeoffs among indicators and quantify a holistic measure of the stability of sustainability in the different systems and recreate alternative scenarios of production systems that might be useful for policymakers and the private sector. Future research that explores the stability of the phases that integrate each rotation as well as the drivers explaining stability is needed to implement sustainable and stable rotations systems.

5. Conclusions

How the intensification of crop-pasture systems will influence agricultural sustainability remains a key question, with a particular emphasis on understanding tradeoffs between economic and environmental indicators under different intensification scenarios. The use of LTE is useful to implement these types of assessments. Our study evaluated the intensification of a rice-pasture rotation (2 rice crops in 5 years) with a higher frequency of annual crops with similar crop intensity; rice-soybean (1 rice crop every other year) and rice-cover crop (1 rice crop every year). System productivity, energy use, nitrogen use, partial CF and corresponding efficiencies (NUE, EUE, yield-scaled partial CF) and economics (income, costs, and gross margin) were assessed for 7 years. We found that the intensification of rice-pasture increased system productivity by 50–100 GJ ha^{-1} yr^{-1} but this required more inputs which reduced the efficiencies of the system. As we hypothesized, the intensification with rice-cover crop and rice-soybean increased the partial CF of the system, while also increasing income and costs of the rotation but not necessarily the economic result. The rice-cover crop system decreased the gross margin while only rice-soybean achieved a similar gross margin to rice pasture, with lower variability in the latter. The multi-criteria performance index as a proxy of system sustainability was slightly higher for rice-soybean but 37.5% lower for rice-cover crop, highlighting the potential for different outcomes depending on crop type. However, both intensified systems decreased the stability of the sustainability since rice-pasture showed the best score in all four parameters that evaluated stability. The findings of this study caution against the intensification of rice-pasture systems due to higher environmental footprint, similar or lower profitability, and higher economic risk. Although we found replacing perennial pastures with annual crops could increase system productivity, the required increase in inputs and field GHG emissions reduced efficiencies, increased partial CF, and reduced the stability of whole system performance, thus making intensified systems more vulnerable to external and unpredictable conditions. In contrast, multiple benefits from the integration of rice and pastures with livestock across environmental and economic indicators suggest a strong need to preserve this system in a region experiencing rapid land use change and decreasing pasture area in favor of annual grain crops. However, preserving rice-pasture systems without policy intervention or incentives could be difficult due to market dynamics and/or land lease contracts. Therefore, research should also focus on improvements within the rotation (i.e., how to improve within rice-soybean) through soil and crop management.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103488.

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