UC Davis
UC Davis Electronic Theses and Dissertations

Title
Productivity and environmental performance in rice-based cropping systems in Uruguay

Permalink
https://escholarship.org/uc/item/9657h8ds

Author
Macedo, Ignacio

Publication Date
2023

Peer reviewed|Thesis/dissertation

eScholarship.org Powered by the California Digital Library
University of California

Productivity and Environmental Performance in Rice-Based Cropping Systems in Uruguay

By

IGNACIO MACEDO YAPOR

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Horticulture and Agronomy

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Cameron Pittelkow, Chair

Alvaro Roel

Bruce Linquist

Committee in Charge

2023

Table of Contents

Acknowledgments

I want to acknowledge several institutions that made this research possible with fellowships, data, infrastructure, and most importantly their human resources. Thank you to the University of California-Davis, Instituto Nacional de Investigación Agropecuaria-Uruguay, Fulbright Uruguay, Agencia Nacional de Investigación e Innovación-Uruguay and Sociedad Anónima Molinos Arroceros Nacionales.

Thank you to Charlie Brummer, Amélie Gaudin, Bruce Linquist, Robert Hijmans, Yufang Jin and Troy Magney for serving in different committees during my PhD.

I would like to express my sincere gratitude to my advisor, Cameron Pittelkow, and co-advisor, Alvaro Roel, for their support, flexibility, and guidance throughout my academic journey. Their invaluable advice and encouragement have helped me to excel in my studies and achieve my goals. From providing insightful feedback on my research to connecting me with relevant resources and opportunities. Thank you, Cameron and Alvaro, for being exceptional mentors.

I want to express my gratitude to Jose A. Terra for being a constant source of inspiration and for launching me into the attractive world of science. Their guidance has been instrumental in shaping my academic journey.

A big thanks to Lisa Brown, our graduate program coordinator, for her help whenever I needed it.

Thank you to all collaborators for their valuable contributions to each chapter of this dissertation.

I am grateful to my lab members, Delaney, Gina, Lindsey, Santiago, Sara, Valentina, and Zhang.

A huge thank to my friends in Davis.

Otro gracias a mis amigos en Uruguay.

Le agradezco a mi madre, mi padre y mis hermanos por siempre estar.

A Jimena, mi esposa, por el apoyo incondicional, por estar siempre dispuesta a escuchar, aconsejar y acompañar sin pedir nada a cambio, muchas gracias.

Abstract

This dissertation assesses the impact of rice-based systems on productivity and environmental sustainability in Uruguay using data from two sources. The first two chapters use data from a long-term experiment conducted in the major rice-growing region of the country, while the third chapter utilizes data from 2042 Uruguayan farmers across four seasons, accounting for 220,000 hectares. The first chapter examines the effects of different rice rotations on soil organic carbon and nitrogen as well as rice yield. The second chapter evaluates the stability of a multi-criteria performance index that considers productivity, environmental, and economic indicators. The third chapter employs geospatial machine learning models to evaluate the impact of management practices and soil features on yield and its spatial variations. The findings of this study highlight the importance of integrating rice with pastures and livestock for a balanced combination of profitability and environmental performance. Additionally, the research provides a successful example of data sharing among farmers and researchers and highlights the important role of farmers' data in guiding agronomic decisions for sustainable and yield-increasing practices, with potential implications for extension and investment in agricultural research programs.

General Introduction

Sustainable intensification calls for increasing yield in the current land while negative environmental impacts of agriculture should be minimized (Cassman & Grassini, 2020). Integrated crop-livestock systems have long served as the backbone of sustainable agriculture, especially in terms of maintaining soil quality and effectively recycling nutrients (Baethgen et al., 2021; Garrett et al., 2017). Pasture-based systems provide an array of ecosystem services, not only soil organic carbon (SOC) but other services that are critical for the functioning of agricultural landscapes (Jaurena et al., 2021). However, these systems have been and are facing 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 (Carvalho et al., 2021; Garrett et al., 2017). This decoupling can lead to a specialization of cropping systems relying on one or two-grain crops that often can 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 and negative environmental externalities (Cassman & Grassini, 2020).

Uruguay is a country in South America where agricultural products represent 75% of national exports. Rice is produced on around 200,000 ha, primarily for export (95%), with average annual yields around 8.2 Mg ha^{-1}, one of the highest worldwide. The typical crop rotation sequence is alternating rice (1-2 yr) and pasture for cattle production (3-4 yr). The inclusion of pasture, either sown or naturally regenerating, in rotation with rice provides sustainability advantages in terms of soil quality and reduced dependence on external inputs compared with other rice systems in the world (Pittelkow et al., 2016). However, soybean (Glycine max (L.) Merr.) production has continued to increase in Uruguay, following trends for much of South America and there has been an incipient process of intensification and a growing interest to intensify these systems in the last decade, for example with the inclusion of soybean or higher frequency of rice in the rotation (DIEA, 2018; Song et al., 2021).

The legacy effect of crop-pasture rotations and the previous crop on crop yields has been widely studied, highlighting the benefits of crop pastures over annual cropping rotations and the cereal-legume over cereal-cereal crops (Bullock, 1992; Ernst et al., 2018; Ribas et al., 2021). Yet, replacing pasture with annual crops may negatively influence crop productivity. Recent research in Uruguay illustrates the positive effect of crop-pasture systems on wheat, attributing this benefit to better soil quality or higher SOC content (Ernst et al., 2018; Rubio et al., 2021). However, the positive effects of pasture on yield have been shown to decline over time, meaning the more years under continuous annual crops instead of pasture, the lower the wheat yield (Ernst et al., 2018). When considering soybean or rice as an intensification option, rotating with soybean is likely to support higher rice yields relative to continuous rice. For example, rice yield improvements of 24-46% were observed after mungbean (Vigna radiata) in Vietnam (Assefa et al., 2021). Similarly, Ribas et al. (2021) found that including soybean in rotations increased rice yield by 26% compared to rice after rice in southern Brazil. Meanwhile, previous research in Uruguay indicates that rice after rice is lower yielding than rice after pasture (Méndez, 1993). However, crop yields are not only affected by the previous crop and long-term rotation history, but also by the presence of cover crops grown during the winter period. Grass and legume cover crop species are both used in Uruguay, with different C:N ratios strongly influencing decomposition patterns and soil N availability for the subsequent crop. Therefore, the immediate effect of crop (or cover crops and pastures) residues vs the long-term impact of pasture (trough soil quality) over rice yield is unclear in rice-based systems.

Soil organic carbon is a foundation of soil quality and future food security, helping regulate nutrient cycles and soil-plant-water interactions that underpin agricultural productivity (Oldfield et al., 2019). Given the mechanisms controlling SOC storage discussed below, the literature suggests that conversion of rice-pasture to rotations with a higher frequency of annual grain crops could have either positive or negative impacts on SOC. Briefly, the positive benefits of pasture for SOC are well-documented in rainfed systems (Baethgen et al., 2021), so the loss of pasture could decrease SOC. On the other hand, rice paddy soils are reported to have greater SOC sequestration and content than non-flooded (i.e. upland, aerobic, rainfed) soils due to flooded periods during irrigation that decreases residue and SOC decomposition rates (Chen et al., 2021; Sahrawat, 2012; Witt et al., 2000). Therefore, increasing the frequency of rice in the rotation could offset the loss of pasture, especially considering the high annual rice biomass production. In contrast, SOC could be reduced when a rainfed crop is included in a continuously flooded rice system (Witt et al., 2000) or sustained when soybean is included (Motschenbacher et al., 2013). The net effects of intensified rotations are therefore uncertain, specifically because the baseline system is composed of two drivers that positively affect carbon balance (pasture and flooded rice soils) and the loss of one could potentially be compensated by gains in the other (i.e. pasture being replaced by increasing frequency of flooded rice under intensification).

There are increasing calls to evaluate gains in productivity and sustainability of rice-based systems using 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 trade-offs 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 trade-offs 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). Furthermore, being "sustainable" is not enough, extreme weather variability under climate change coupled with increasing economic shocks to markets and prices requires 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 or profit of a single crop or rotation (Li et al., 2019; Riccetto et al., 2020; Sanford et al., 2021). Systems with higher perenniality (less frequency of maize and/or rotation with pastures) as well as with the integration of livestock in a soybean cropping system increased the stability of food production compared to continuous cropping systems (de Albuquerque Nunes et al., 2021; Sanford et al., 2021). But based on a review of literature, 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 including key economic and environmental indicators at the systems level would help identify rotations that exhibit both high sustainability and stability.

New agronomic research methods are needed to complement traditional experiments that can only evaluate two or three factors. Farmer-field management data with georeferenced locations that allow accounting for the weather as well as soil characteristics could contribute to a better understanding of optimum management practices affecting yield (Cassman & Grassini, 2020). Some studies have been analyzed on closing crop yield gaps using farmers' data but with less emphasis on environmental performance assessments, which is important to improving the sustainability of cropping systems (Silva et al., 2017; Yuan et al., 2021). Recent studies in Uruguay based on a dataset of rice growers and on-farm experiments found that main important management drivers explaining the yield gap were sowing date and N fertilization rate (Tseng et al., 2021). However, this study did not use a site-specific approach and did not include soil characteristics in its analysis. To my knowledge, no published work has been done that includes farmers management data and soil characteristics, and links environmental indicators with yields in a geospatial approach in Latin America.

The general goal of this work is to understand how the intensification processes of rice-based systems affects the sustainability at the rotation and farmers' field level using Uruguay as a case of study. The first two chapters are based on data from a long-term experiment initiated in 2012 in the East of Uruguay (33˚16’22.21”S; 54˚10’23.10”W, 21 masl) at the National Institute of Agricultural Research (INIA for its acronym in Spanish). The climate is mesothermic humid with a mean temperature of 22.3 ± 0.85 ˚C during summer and 11.5 ± 0.82 ˚C in winter. The annual average rainfall is 1,360 ± 315 mm, with high variation within and between years. Annual total potential evapotranspiration is 1,138 ± 177 mm from 1971 to 2016. The dominant soil at the site is classified as Argialboll according to the USDA Soil Taxonomy with a silty clay loam texture with a 0.5% slope. Treatments compared in this experiment were: 1) rice-pasture (5 yr rotation of rice - ryegrass in winter – rice, followed by 3.5 yr of a perennial pasture mixture of tall fescue, white clover, and birds foot trefoil); 2) rice-soybean (2 yr rotation of rice - ryegrass in winter – soybean - Egyptian clover in winter); and 3) rice-cover crop (annual rotation of rice - Egyptian clover in winter).

The first chapter quantifies the rice yield, biomass, and total soil organic carbon and nitrogen changes. Results showed that rice after soybean or pasture achieved the highest grain yield (9.8 Mg ha^{-1}), 9% higher than rice after rice in the rice-pasture and rice-cover crop systems. Rice-pasture showed an increase of 0.6 Mg ha^{-1} yr^{-1} of soil organic carbon, while no changes were observed in the intensified rotations which replaced pasture with additional rice or soybean crops. Soil total N was sustained in all systems. This chapter contributes with the understanding for the implementation of sustainable rice-based rotations.

The second chapter evaluates how the intensification of rice-pasture rotations with annual crops influenced multiple dimensions of sustainability and its stability. 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. 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.

The third chapter presents a successful example of data sharing among industry and researchers and conducted an exploratory geospatial data analysis using farmers' data from Uruguay accounting for approximately 220,000 ha total (~55,000 ha yr^{-1}) from 2042 field

observations. We employed geographically weighted random forest models to explore the spatial variation of the most important features across regions. Nitrogen use efficiency was quantified. Seeding date, Variety, P rate, and K rate were among the most important features explaining rice yield, and the spatial variation of the feature importance was presented in maps. Most of the rice fields did not show risk of soil N mining nor risk of potential N losses. Our research strengthens the call for the importance of farmers' data to guide agronomy decisions that sustain or increase yield while minimizing negative environmental externalities with potential future implications on extension and regional research programs as well as a guide to orient investments in agricultural research. We call for the exploration of this kind of analyses in other regions where yield variations are greater and sub-optimal management are typical which could have significant impact on food security and environmental sustainability.

References

Assefa, Y., Yadav, S., Mondal, M. K., Bhattacharya, J., Parvin, R., Sarker, S. R., Rahman, M., Sutradhar, A., Prasad, P. V. V., Bhandari, H., Shew, A. M., & Jagadish, S. V. K. (2021). Crop diversification in rice-based systems in the polders of Bangladesh: Yield stability, profitability, and associated risk. *Agricultural Systems*, *187*(October 2020). https://doi.org/10.1016/j.agsy.2020.102986

Baethgen, W. E., Parton, W. J., Rubio, V., Kelly, R. H., & M. Lutz, S. (2021). Ecosystem dynamics of crop–pasture rotations in a fifty-year field experiment in southern South America: Century model and field results. *Soil Science Society of America Journal*, *85*(2), 423–437. https://doi.org/10.1002/saj2.20204

Bullock, D. G. (1992). Crop rotation. *Critical Reviews in Plant Sciences*, *11*(4), 309–326. https://doi.org/10.1080/07352689209382349

Carvalho, P. C. de F., Savian, J. V., Della Chiesa, T., De Souza Filho, W., Terra, J. A., Pinto, P., Posselt Martins, A., Villarino, S., Da Trindade, J. K., De Albuquerque Nunes, P. A., & Piñeiro, G. (2021). Land-use intensification trends in the Rio de la Plata Region of South America: Toward specialization or recoupling crop and livestock production. *Frontiers of Agricultural Science and Engineering*, *8*(1), 97. https://doi.org/10.15302/J-FASE-2020380

Cassman, K. G., & Grassini, P. (2020). A global perspective on sustainable intensification research. *Nature Sustainability*, *3*(4), 262–268. https://doi.org/10.1038/s41893-020-0507-8

Chen, X., Hu, Y., Xia, Y., Zheng, S., Ma, C., Rui, Y., He, H., Huang, D., Zhang, Z., Ge, T., Wu, J., Guggenberger, G., Kuzyakov, Y., & Su, Y. (2021). Contrasting pathways of carbon sequestration in paddy and upland soils. *Global Change Biology*, *27*(11), 2478–2490. https://doi.org/10.1111/gcb.15595

de Albuquerque Nunes, P. A., Laca, E. A., de Faccio Carvalho, P. C., Li, M., de Souza Filho, W., Robinson Kunrath, T., Posselt Martins, A., & Gaudin, A. (2021). Livestock integration into soybean systems improves long-term system stability and profits without compromising crop yields. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-81270-z

Devkota, K. P., Pasuquin, E., Elmido-Mabilangan, A., Dikitanan, R., Singleton, G. R., Stuart, A. M., Vithoonjit, D., Vidiyangkura, L., Pustika, A. B., Afriani, R., Listyowati, C. L., Keerthisena, R. S. K., Kieu, N. T., Malabayabas, A. J., Hu, R., Pan, J., & Beebout, S. E. J. (2019). Economic and environmental indicators of sustainable rice cultivation: A comparison across intensive irrigated rice cropping systems in six Asian countries. *Ecological Indicators*, *105*(October 2018), 199–214. https://doi.org/10.1016/j.ecolind.2019.05.029

DIEA. (2018). *Anuario Estadístico Agropecuario 2018*. Ministerio de Agricultura, Ganadería y Pesca, Editorial Hemisferio Sur.

Ernst, O. R., Dogliotti, S., Cadenazzi, M., & Kemanian, A. R. (2018). Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield. *Field Crops Research*, *217*(April 2017), 180–187. https://doi.org/10.1016/j.fcr.2017.11.014

Garrett, R. D., Niles, M. T., Gil, J. D. B., Gaudin, A., Chaplin-Kramer, R., Assmann, A., Assmann, T. S., Brewer, K., de Faccio Carvalho, P. C., Cortner, O., Dynes, R., Garbach, K., Kebreab, E., Mueller, N., Peterson, C., Reis, J. C., Snow, V., & Valentim, J. (2017). Social and ecological analysis of commercial integrated crop livestock systems: Current knowledge and remaining uncertainty. *Agricultural Systems*, *155*(December 2016), 136–146. https://doi.org/10.1016/j.agsy.2017.05.003

Jaurena, M., Durante, M., Devincenzi, T., Savian, J. V., Bendersky, D., Moojen, F. G., Pereira, M., Soca, P., Quadros, F. L. F., Pizzio, R., Nabinger, C., Carvalho, P. C. F., & Lattanzi, F. A. (2021). Native Grasslands at the Core: A New Paradigm of Intensification for the Campos of Southern South America to Increase Economic and Environmental Sustainability. *Frontiers in Sustainable Food Systems*, *5*(March). https://doi.org/10.3389/fsufs.2021.547834

Li, M., Peterson, C. A., Tautges, N. E., Scow, K. M., & Gaudin, A. C. M. (2019). Yields and resilience outcomes of organic, cover crop, and conventional practices in a Mediterranean climate. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-48747-4

Lin, B. B. (2011). *Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change*. *61*(3), 183–193. https://doi.org/10.1525/bio.2011.61.3.4

Méndez, R. (1993). Rotación arroz-pasturas: Análisis físico económico del cultivo. *INIA Serie Técnica ; 38*, 21 p.

Motschenbacher, J. M., Brye, K. R., Anders, M. M., Gbur, E. E., Slaton, N. A., & Evans-White, M. A. (2013). Rice Rotation and Tillage Effects on Water-Stable Soil Macroaggregates and Their Associated Carbon and Nitrogen Contents in a Silt-Loam Soil. *Soil Science*, *178*(11), 596–611. https://doi.org/10.1097/SS.0000000000000028

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *Soil*, *5*(1), 15–32. https://doi.org/10.5194/soil-5-15-2019

Pittelkow, C. M., Zorrilla, G., Terra, J., Riccetto, S., Macedo, I., Bonilla, C., & Roel, A. (2016). Sustainability of rice intensification in Uruguay from 1993 to 2013. *Global Food Security*, *9*, 10–18. https://doi.org/10.1016/j.gfs.2016.05.003

Ribas, G. G., Zanon, A. J., Streck, N. A., Pilecco, I. B., de Souza, P. M., Heinemann, A. B., & Grassini, P. (2021). Assessing yield and economic impact of introducing soybean to the lowland rice system in southern Brazil. *Agricultural Systems*, *188*(September 2020), 103036. https://doi.org/10.1016/j.agsy.2020.103036

Riccetto, S., Davis, A. S., Guan, K., & Pittelkow, C. M. (2020). Integrated assessment of crop production and resource use efficiency indicators for the U.S. Corn Belt. *Global Food Security*, *24*(November 2019), 100339. https://doi.org/10.1016/j.gfs.2019.100339

Rubio, V., Diaz-rossello, R., Andrés, J., & Harold, M. V. E. (2021). Quantifying soil organic carbon ' s critical role in cereal productivity losses under annualized crop rotations. *Agriculture, Ecosystems and Environment 321*, *321*(October 2020). https://doi.org/10.1016/j.agee.2021.107607

Sahrawat, K. L. (2012). Soil fertility in flooded and non-flooded irrigated rice systems. *Archives of Agronomy and Soil Science*, *58*(4), 423–436. https://doi.org/10.1080/03650340.2010.522993

Saito, K., Six, J., Komatsu, S., Snapp, S., Rosenstock, T., Arouna, A., Cole, S., Taulya, G., & Vanlauwe, B. (2021). Agronomic gain: Definition, approach, and application. *Field Crops Research*, *270*(May), 108193. https://doi.org/10.1016/j.fcr.2021.108193

Sanford, G. R., Jackson, R. D., Booth, E. G., Hedtcke, J. L., & Picasso, V. (2021). Perenniality and diversity drive output stability and resilience in a 26-year cropping systems experiment. *Field Crops Research*, *263*, 108071. https://doi.org/10.1016/j.fcr.2021.108071

Silva, J. V., Reidsma, P., Laborte, A. G., & van Ittersum, M. K. (2017). Explaining rice yields and yield gaps in Central Luzon, Philippines: An application of stochastic frontier analysis and crop modelling. *European Journal of Agronomy*, *82*, 223–241. https://doi.org/10.1016/j.eja.2016.06.017

Song, X. P., Hansen, M. C., Potapov, P., Adusei, B., Pickering, J., Adami, M., Lima, A., Zalles, V., Stehman, S. V., Di Bella, C. M., Conde, M. C., Copati, E. J., Fernandes, L. B., Hernandez-Serna, A., Jantz, S. M., Pickens, A. H., Turubanova, S., & Tyukavina, A. (2021). Massive soybean expansion in South America since 2000 and implications for conservation. *Nature Sustainability*, *4*(9), 784–792. https://doi.org/10.1038/s41893-021-00729-z

Stuart, A. M., Devkota, K. P., Sato, T., Pame, A. R. P., Balingbing, C., My Phung, N. T., Kieu, N. T., Hieu, P. T. M., Long, T. H., Beebout, S., & Singleton, G. R. (2018). On-farm assessment of different rice crop management practices in the Mekong Delta, Vietnam, using sustainability performance indicators. *Field Crops Research*, *229*(October), 103–114. https://doi.org/10.1016/j.fcr.2018.10.001

Tseng, M.-C., Roel, Á., Macedo, I., Marella, M., Terra, J., Zorrilla, G., & Pittelkow, C. M. (2021). Field-level factors for closing yield gaps in high-yielding rice systems of Uruguay. *Field Crops Research*, *264*, 108097. https://doi.org/10.1016/j.fcr.2021.108097

White, M., Heros, E., Graterol, E., Chirinda, N., & Pittelkow, C. M. (2020). Balancing Economic and Environmental Performance for Small-Scale Rice Farmers in Peru. *Frontiers in Sustainable Food Systems*, *4*(October), 1–14. https://doi.org/10.3389/fsufs.2020.564418

Witt, C., Cassman, K. G., Olk, D. C., Biker, U., Liboon, S. P., Samson, M. I., & Ottow, J. C. G. (2000). Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant and Soil*, *225*(1–2), 263–278. https://doi.org/10.1023/A:1026594118145

Wittwer, R. A., Bender, S. F., Hartman, K., Hydbom, S., Lima, R. A. A., Loaiza, V., Nemecek, T., Oehl, F., Olsson, P. A., Petchey, O., Prechsl, U. E., Schlaeppi, K., Scholten, T., Seitz, S., Six, J., & Heijden, M. G. A. Van Der. (2021). Organic and conservation agriculture promote ecosystem multifunctionality. *Science Advances*, *7*(34), 1–13. https://doi.org/10.1126/sciadv.abg6995

Yuan, S., Linquist, B. A., Wilson, L. T., Cassman, K. G., Stuart, A. M., Pede, V., Miro, B., Saito, K., Agustiani, N., Aristya, V. E., Krisnadi, L. Y., Zanon, A. J., Heinemann, A. B., Carracelas, G., Subash, N., Brahmanand, P. S., Li, T., Peng, S., & Grassini, P. (2021). Sustainable intensification for a larger global rice bowl. *Nature Communications*, *12*(1), 7163. https://doi.org/10.1038/s41467-021-27424-z

Chapter 1: Irrigated rice rotations affect yield and soil organic carbon sequestration in temperate South America

Ignacio Macedo[a,b*], Alvaro Roel[b], Walter Ayala[b], M. Virginia Pravia[b], Jose A. Terra[b], Cameron M. Pittelkow[a].

[a] Department of Plant Sciences, UC Davis, USA

[b] Instituto Nacional de Investigación Agropecuaria (INIA), Treinta y Tres, Uruguay

*Author for correspondence: Ignacio Macedo (imacedo@ucdavis.edu), Graduate Student Researcher, Department of Plant Sciences, University of California, One Shields Ave, Davis, CA 95616.

Published in *Agronomy Journal*, 114(2), PP. 961-975.

ABSTRACT

Rice systems rotated with perennial pastures are being intensified in South America to increase annual grain productivity, but the effects on rice yield and soil quality remain poorly understood. We evaluated rice grain yield, crop and pasture biomass production, and soil organic carbon (SOC) and total nitrogen stocks (0-15 cm depth) in three rice-based rotations over 8 yr at the start of a long-term experiment located in Uruguay. Treatments were: 1) rice-pasture (5 yr rotation of rice - ryegrass in winter – rice, followed by 3.5 yr of a perennial pasture mixture of tall fescue, white clover, and birds foot trefoil); 2) rice-soybean (2 yr rotation of rice - ryegrass in winter – soybean - Egyptian clover in winter); and 3) rice-cover crop (annual rotation of rice - Egyptian clover in winter). Rice after soybean or pasture achieved the highest grain yield (9.8 Mg ha^{-1}), 9% higher than rice after rice in the rice-pasture and rice-cover crop systems. Estimates of belowground biomass in rice-pasture (2.7 Mg ha^{-1}) was 12 and 42% greater than rice-cover crop and rice-soybean rotations, respectively. Accordingly, rice-pasture showed an increase of 0.6 Mg ha^{-1} yr^{-1} of SOC, while no changes were observed in the intensified rotations which replaced pasture with additional rice or soybean crops. Soil total N was sustained in all systems. These results provide insights for the implementation of sustainable rice-based rotations, with rice-pasture being the only system that increased SOC while simultaneously achieving high rice yields and belowground biomass productivity.

INTRODUCTION

Uruguay is a country in South America where agricultural products represent 75% of national exports. Rice is produced on around 200,000 ha, primarily for export (95%), with average annual yields around 8.2 Mg ha^{-1}, one of the highest worldwide. The typical crop rotation sequence is alternating rice (1-2 yr) and pasture for cattle production (3-4 yr). The inclusion of pasture, either sown or naturally regenerating, in rotation with rice provides sustainability advantages in terms of soil quality and reduced dependence on external inputs compared with other rice systems in the world (Deambrosi, 2003; Pittelkow et al., 2016). For example, average fertilizer nitrogen (N) use in rice in South Asia is around 200 kg ha^{-1} while in South America it is 120 kg ha^{-1}, whereas it is only 80 kg ha^{-1} in Uruguay (Chauhan et al., 2017), owing to biological N fixation by pasture and recycling of organic N by livestock (Castillo et al., 2021). However, economic pressures are causing farmers to intensify rice-pasture rotations, specifically to reduce the pasture phase of the rotation in favor of more annual grain crops. Hereafter, intensification refers to increased cropping system intensity and the associated external inputs required for annual crop production. For example, in the last 15 years around one-third (200) of farmers abandoned the integration of pasture and livestock in their rice production systems due to lack of profit (DIEA, 2018; Molina et al., 2019). The annualization of cropping systems, decoupling crops from livestock has occurred widely over the last 20-30 years in South America, causing a decrease in pasture area and replacement of historically complex rotations with simplified crop sequences (Carvalho et al., 2021).

Two options for increasing annual grain productivity in Uruguay are substituting the pasture phase of the rotation with either soybean or rice, both of which are likely to impact yields of the following rice crop (Ribas et al., 2021; Yadvinder-Singh et al., 2008). Soybean production has continued to increase in Uruguay, following trends for much of South America in recent decades, with some farmers rotating soybean with rice in search of economic advantages (DIEA, 2018). Short-term revenue might also increase by continuously growing rice, which is common practice in many intensive rice systems worldwide but has not historically been practiced in Uruguay. Yet, replacing pasture with annual crops may negatively influence crop productivity. Recent research in Uruguay illustrates the positive effect of crop-pasture systems on wheat and barley, attributing this benefit to better soil quality or higher SOC content (Ernst et al., 2018; Rubio et al., 2021). However, the positive effects of pasture on yield have been shown to decline over time, meaning the more years under continuous annual crops instead of pasture, the lower the wheat yield (Ernst et al., 2018).

When considering soybean or rice as an intensification option, rotating with soybean is likely to support higher rice yields relative to continuous rice. Crop yield benefits are particularly noteworthy when cereal and legume crops are alternated (Crookston et al., 1991; Stanger et al., 2008). For example, rice yield improvements of 24-46% were observed after mungbean (*Vigna radiata*) in Vietnam. Similarly, Ribas et al. (2021) found that including soybean in rotations increased rice yield by 26% compared to rice after rice in southern Brazil. Meanwhile, previous research in Uruguay indicates that rice after rice is lower yielding than rice after pasture (Méndez, 1993). However, crop yields are not only affected by the previous crop and long-term rotation history, but also the presence of cover crops grown during the winter period. Grass and legume cover crop species are both used in Uruguay, with different C:N ratios strongly influencing decomposition patterns and soil N availability for the subsequent crop.

Soil organic carbon is a foundation of soil quality and future food security (Amelung et al., 2020; Bünemann et al., 2018), helping regulate nutrient cycles and soil-plant-water interactions that underpin agricultural productivity (Oldfield et al., 2019). Given the mechanisms controlling SOC storage discussed below, the literature suggests that conversion of rice-pasture to rotations with higher frequency of annual grain crops could have either positive or negative impacts on SOC. Briefly, the positive benefits of pasture for SOC are well-documented in rainfed systems (Baethgen et al., 2021), so the loss of pasture could decrease SOC. However, rice is grown under flooded soil conditions which benefits SOC, thus increasing the frequency of rice in rotation could offset the loss of pasture, especially considering high annual rice biomass production (Witt et al., 2000). In contrast, SOC could be reduced when a rainfed crop is included in a continuously flooded rice system (Witt et al., 2000) or sustained when soybean is included (Motschenbacher et al., 2013). The net effects of intensified rotations are therefore uncertain, specifically because the baseline system is composed of two drivers that positively affect carbon (C) balance (pasture and flooded rice soils) and the loss of one could potentially by compensated by gains in the other (i.e. pasture being replaced by increasing frequency of flooded rice under intensification).

Rice paddy soils are reported to have greater SOC sequestration and content than non-flooded (i.e. upland, aerobic, rainfed) soils due to flooded periods during irrigation (lower redox potential) that decreases residue and SOC decomposition rates (Chen et al., 2021; Pan et al., 2010; Sahrawat, 2012). As a result, continuous rice tends to have higher SOC compared to rice-based cropping systems which include rainfed crops such as maize in rotation (Yadvinder-Singh et al., 2008; Dobermann & Witt, 2000; Witt et al., 2000). While perennial pastures supporting livestock production are also grown under aerobic conditions, it is widely accepted that the integration of livestock and crops in rotation enhances SOC sequestration and tightens nutrient cycles (Brewer & Gaudin, 2020). This is because perennial pastures are often associated with greater C inputs and reduced soil disturbance compared to annual crops (Ernst & Siri-Prieto, 2009; Franzluebbers et al., 2014; Terra et al., 2006). Previous work suggests that rice-pasture systems could increase soil quality compared to continuous rice, despite pastures being grown under rainfed conditions. For example, integrated rice-pasture systems improved rice yield and nutrient use efficiency compared to a monocropping rice system with winter fallow in the south of Brazil (Denardin et al., 2020).

Another important driver of SOC is above and belowground biomass production (Fujisaki et al., 2018). The crop rotation sequence determines the amount of biomass produced in the system, thus affecting C inputs and soil N supply (Cassman et al., 1996; Witt et al., 2000). A study in rice paddy soils in subtropical China showed a positive relationship between changes in SOC and C inputs (A. Chen et al., 2016), whereas for double-cropped rice in a subtropical climate, approximately 4% of residue C inputs were transformed to stabilized SOC (Mandal et al., 2008). Recent literature indicates a higher efficiency of belowground biomass contribution to SOC (Mazzilli et al., 2015; Sokol & Bradford, 2019). For example, C humification rate into particulate soil organic matter in a no-till corn-soybean (*Glycine max* (L.) Merr.) rotation was significantly greater for belowground residues (10-24%) compared to aboveground residues (0.5-1%) (Mazzilli et al., 2015). To identify biomass thresholds for maintaining soil quality, several studies in the U.S. Corn Belt have quantified the C inputs needed in a corn-soybean rotation to sustain SOC. Using simulation models, Huggins et al. (1998) and Gollany et al. (2019) estimated that 5.6 C ha^{-1} yr^{-1} (from aboveground biomass and roots under tillage) or 3.8 Mg C ha^{-1} yr^{-1} (aboveground biomass under no-tillage), respectively, was required to sustain SOC in the 0-30 cm soil depth. However, the impact of biomass on SOC sequestration and required C inputs under different rice-based rotations including pasture and annual crops in temperate regions has not been quantified.

In this study, we addressed this important knowledge gap for integrated crop-livestock systems with long pasture phases which are facing pressures to intensify worldwide (Carvalho et al., 2021; Lemaire et al., 2014). Three contrasting rice-based rotations were evaluated after 34 years of previous soil use under a rice-pasture rotation: rice-pasture as the current paradigm in Uruguay, rice-soybean as the first step of intensification, already practiced in Uruguay and a common system in southern Brazil, and rice-cover crop as an extreme intensification system closer to what could be continuous rice. We hypothesized that rice-soybean and rice-cover crop systems will have a negative effect on SOC due to the loss of perennial pastures and lower belowground biomass inputs, consequently reducing rice yield. The objectives of this study were to: 1) evaluate rice grain yield during the first 8 years of a long-term experiment; 2) quantify the evolution of SOC stocks and total N (TN), and 3) assess biomass production and its relationship with SOC changes across rotation systems. Insights from this research can inform about the implementation of rice-based rotations that can sustain high productivity and soil quality through SOC storage.

MATERIALS AND METHODS

Site description and the long-term experiment

The study site is in the East of Uruguay (33° 16 ' 22.21'' S; 54° 10 ' 23.10 W''; 21 masl) (Figure 1), located in the Temperate Grassland terrestrial ecoregion (Olson et al., 2001). The climate is mesothermic humid with a mean temperature of 22.3 ± 0.85 °C during summer and 11.5 ± 0.82 °C in winter. Annual average rainfall is 1360 ± 315 mm, with high variation within and between years. Annual total potential evapotranspiration is 1138 ± 177 mm for the period of 1971 to 2016.

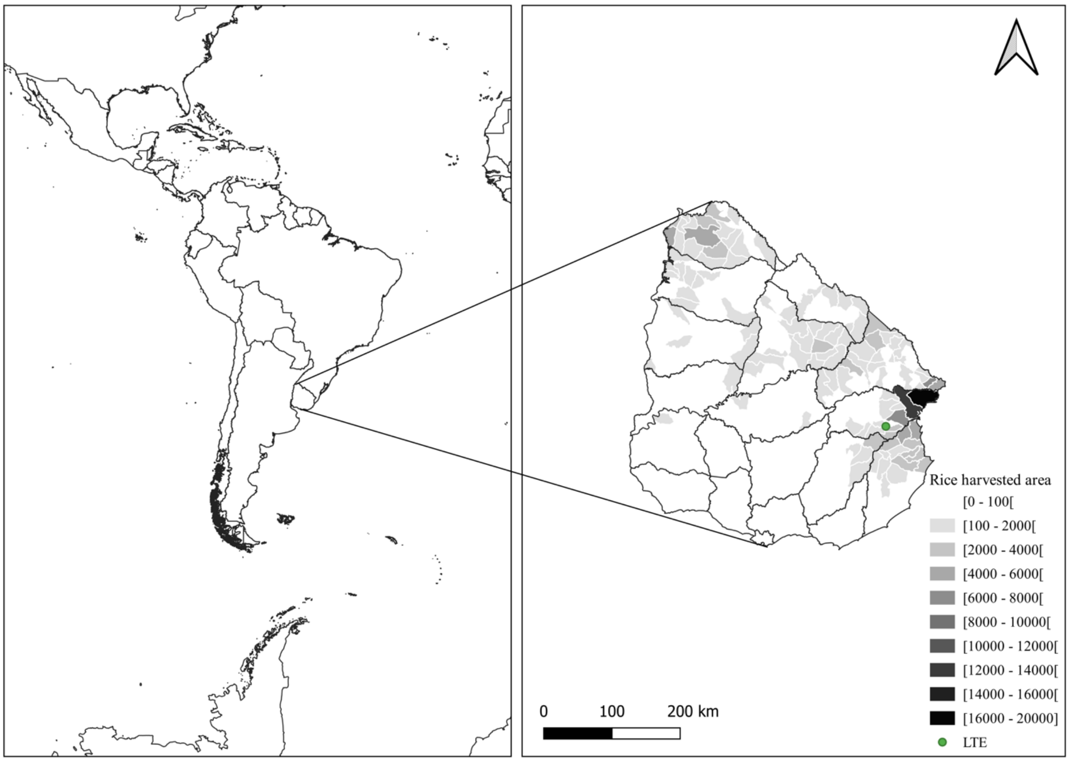

Figure 1. Map of South America and Uruguay with the spatial distribution of rice harvested area (ha) (MGAP, Census 2011). The location of the long-term experiment is the green symbol.

Dominant soils at the site are classified as Argialbolls according to USDA Soil Taxonomy with 0.5% slopes. Soil properties at the beginning of the experiment are presented in Table 1.

Table 1. Initial surface soil (0–15 cm) characteristics of the experimental site where rice-based systems were evaluated in Treinta y Tres, Uruguay starting in 2012.

Classification	Argialboll
Texture	Silty clay loam
Clay (g kg^{-1})	300
Silt (g kg^{-1})	510
Sand (g kg^{-1})	190
Bulk density (g cm^{-3})	1.25
Soil organic carbon (g kg^{-1})	14.2
Total nitrogen (g kg^{-1})	1.4
pH	5.7
P content (mg kg^{-1})*	10.3
Ca content (cmol kg^{-1})	7
Mg content (cmol kg^{-1})	2.8
K content (cmol kg^{-1})	0.25
Na content (cmol kg^{-1})	0.35

* Method of extraction: Bray 1

The long-term experiment was initiated in 2012 on a field previously in a rice-pasture rotation for 34 years. One disk harrow and two landplane operations were made before the beginning of the experiment. The experiment was laid out in a randomized complete block design with all phases of the rotations present in time and space. It included three replications with plot sizes of 1200 m^2 (60 by 20 m). Although the full experiment was composed of six different rice rotation systems, for this study three systems were evaluated which represented the extremes in the length of pasture vs. the frequency of rice (rice-pasture, rice-soybean, and rice-cover crop, with winter cover crops grown in all systems) since the other treatments fall in between these ones. Treatments were: 1) rice (*Oriza sativa* L.) - ryegrass (*Lolium multiflorum* Lam.) in winter – rice, followed by 3 yr of perennial pasture of tall fescue (*Festuca arundinacea* Schreb.), white clover (*Trifolium repens* L.), and birdsfoot trefoil (*Lotus coriculatus* L.) (rice-pasture, 5 yr); 2) rice - ryegrass in winter - soybean (*Glycine max* (L.) Merr.) – Egyptian clover (*Trifolium alexandrinum* L.) in winter (rice-soybean, 2 yr); and 3) rice – Egyptian clover in winter (rice-cover crop, 1 yr.) (Figure 2). Rice-pasture, rice-soybean and rice-cover crop included 15, 6 and 3 experimental units respectively. One replicate as an example is included in Supplemental table S1.

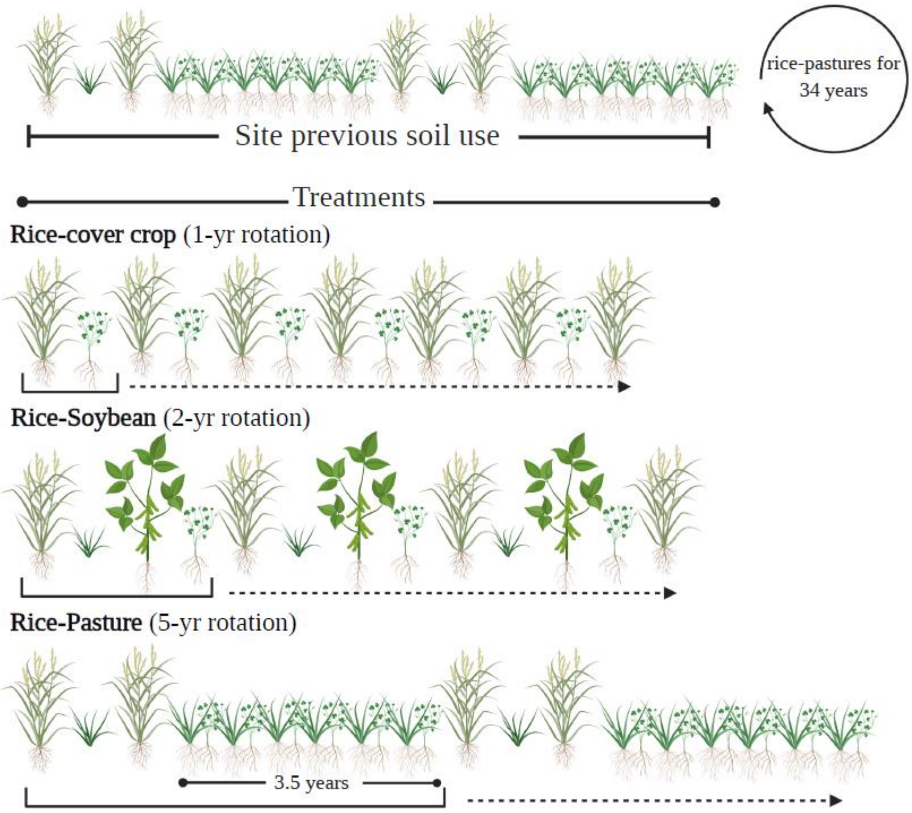

Figure 2. Rice-based rotations evaluated and sequence length for each crop during the 8 yr study period. The experiment was initiated in a field previously in a rice-pasture rotation for 34 years.

Agronomic management

All crops in the field experiment were produced under no-till management. For all rotations, rice was planted in October and harvested in March-April. Irrigation was under continuous flooding from 25-30 days after crop emergence to 25 days after flowering. For the rice-soybean rotation, soybean (V-VI maturity groups) was planted in November and harvested in April-May. Perennial pasture in the rice-pasture rotation, and the cover crops in all rotations, were broadcast immediately after harvest of row crops. The seeding rates of each species were: rice, 130-150 kg ha^{-1}; soybean, 70-80 kg ha^{-1}, tall fescue 15-17 kg ha^{-1}; white clover 2-3 kg ha^{-1}; birdsfoot trefoil, 6-8 kg ha^{-1}; ryegrass, 18-20 kg ha^{-1} and *Trifolium alexandrinum* L., 18-20 kg ha^{-1}. The management of N-P-K fertilization follows guidelines developed nationally (J. Castillo et al., 2015; Enrique Deambrosi et al., 2015; Hernández et al., 2013). Rice N fertilization was urea split in two applications, the first one at mid-tillering (V4-V6) immediately before flooding, and the second one at panicle initiation (R0) (Counce et al., 2000). Phosphorus (P_2O_5) and potash (K_2O) fertilization for row crops and perennial pasture was performed at planting. Pasture also received phosphorus fertilizer at the end of the first and second year. Cover crops were not fertilized. Total annual average N-P-K fertilization applied per rotation is presented in Table 2. Crop and pasture management for weeds, diseases, and pests followed INIA Rice Program recommendations. All operations (seeding, fertilization, pesticide application, and harvesting) were managed with machinery like that used by farmers and perennial pastures of rice-pasture were under direct rotational grazing with sheep during the 3 years. Detailed crop management information and input use can be found in the following study (Macedo et al., 2021).

Table 2. Average annual fertilizer nutrient additions by rotation.

Treatment	Nutrient		
	N	P_2O_5	K_2O
	kg ha^{-1} yr^{-1}		
Rice-pasture	39	36	18
Rice-soybean	40	61	65
Rice-cover crop	148	70	51

Soil and Plant Sampling

Rice grain yield was obtained from the whole plot using a combine harvester. Grain was weighed in a wagon with a digital balance (10 kg precision). Moisture content was measured at harvest and rice yield is reported at a standard moisture content of 13%.

For the baseline soil analysis conducted in 2012 (Table 1), five composite samples (12 cores per sample) were collected in each replication at 0-15 cm depth. For soil chemical analysis in subsequent years, surface samples were collected manually from each plot using the same methodology in 2016, 2017, 2018, 2019 and 2020 before planting the rice crop.

The samples were air-dried and sieved through a 2 mm mesh, then dried at 45 °C for 48 h. The SOC and total N content was measured by dry combustion at 900 °C (LECO Truespec; Wright and Bailey, 2001).

For bulk density (BD), samples were collected with a hydraulic jig with a core diameter of 38 mm and a volume of 170.1 cm^3 (0-15 cm depth). Samples were composited and dried at 105 °C to a constant weight. Bulk density measurements were made in 2016 and 2019. For 2017, 2018, and 2020 BD values from 2016, 2019 and 2019 were used, respectively. Due to a lack of BD measurements at the beginning of the experiment, recent measurements were made from a field with similar rotation history and soil conditions (one disk harrow and two landplanes) directly next to the long-term experiment. As this field had the same rice-pasture sequence for many decades, this value was used as an estimate of initial BD for all rotations. We acknowledge this is a limitation in our study, as only SOC and total N concentrations were measured directly at the start of the experiment. It should be noted that the starting bulk density would have been the same for all rotations, thus our assumption might impact absolute changes in SOC and total N, but not relative differences between treatments. To explore the implications of this assumption, all regressions below for SOC and total N were also performed with concentrations alone and the results and conclusions did not change.

Total SOC and N stocks were expressed on a fixed depth (0-15 cm) and calculated as follows:

$$SOC\ or\ TN = c\ \times d\ \times BD\ \times 10^{-1}$$

where SOC or TN represents the stocks, c is the concentration of SOC or N in g kg^{-1}, d is the depth of soil sampling in cm, and BD is the bulk density in g cm^{-3}.

Four plant samples of 0.34 m^2 were composited from each plot to determine rice harvest index (shoot/grain partitioning) each year. With the value of rice grain yield on a dry basis of the whole plot (60 by 20 m), total aboveground biomass was estimated using this harvest index. Aboveground biomass in soybean was estimated using a harvest index of 0.4 (Bolinder et al., 2007) combined with measured grain yield. Three samples of 0.1 m^2 were made for cover crops to calculate aboveground biomass 1-2 d before termination with herbicides. To estimate aboveground biomass in the perennial pasture of the rice-pasture system, 3 samples of 0.1 m^2 were obtained immediately before and after grazing periods (7-10 per year). After 3 yr of pasture, biomass was also collected prior to termination with an herbicide application. All plant samples were composited and dried at 60 °C for 48 h to a constant weight.

Different shoot/root ratios from the literature were used to estimate belowground biomass. A value of 7 was used for rice based on a previous measurements of shoot/root ratio in Uruguay (Deambrosi y Mendez personal communication), similar to those values reported by Ju et al. (2015) under different N rates and varieties. Shoot/root ratios of cover crops used were those reported by (Pinto et al., 2021), 8 and 6 for ryegrass and Egyptian clover, respectively. Shoot/root ratios for soybean (5) as well as the perennial pasture (2) were based on (Bolinder et al., 2007).

Statistical analysis

Linear regression models were used to evaluate changes in SOC and TN stocks in each treatment. The estimation method was restricted maximum likelihood (REML). Linear and quadratic models were both evaluated and the best fit model was selected based on log likelihood ratio tests. To evaluate differences between slopes (the rate of SOC change) between treatments, T-tests were applied. Biomass variables and rice yield 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. Considering that rotation effects on crop productivity tend to accumulate with time, rice yields were also evaluated separately for the most recent two years of the experiment. Pearson correlation analysis between aboveground biomass, belowground biomass, total residues, total biomass and SOC annual changes (slopes) were performed. Additionally, ANOVA was conducted for SOC and N concentration across all sampling years, and for BD in 2016 and 2019. When appropriate, means were separated using Fisher's least significant difference (LSD) at the 0.05 level. Normality and homogeneity of variance assumptions were tested following standard protocols using the Shapiro-Wilk and Levene test, respectively. All statistical analysis were conducted with Infostat (Di Rienzo et al., 2017). The ggplot2 package (R statistical software) was used for graphical purposes (Wickham, 2016).

RESULTS

Rice yield

Mean rice yield across all treatments and years was 9.4 Mg ha^{-1}. All rice phases of each rotation were present every year (Figure 3). Rice immediately after soybean or pasture (i.e. rice-soybean and the first rice in rice-pasture) achieved the highest grain yield (9.8 Mg ha^{-1}), with rice after soybean also showing the lowest variation in yield (7.6% CV). Rice grown in consecutive summers, either after winter legume or a ryegrass cover crop (i.e. rice-cover crop and the second rice in rice-pasture) had the lowest yields, but with differences between them. Rice-cover crop yields were 5.6% greater than the second rice of rice-pasture (8.7 Mg ha^{-1}), with rice-cover crop also showing the highest variation (11.2% CV). Similar trends were found when only the most recent two years were analyzed (Figure 3), with the exception that yields in the rice-cover crop rotation were not different from the other rice crops.

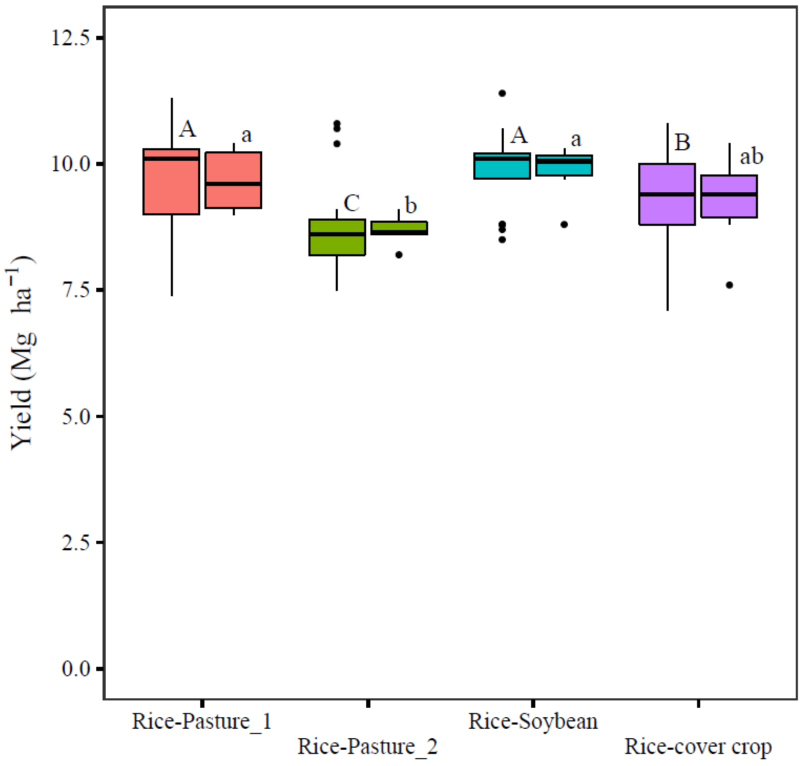

Figure 3. Boxplot of rice grain yield (13% moisture content) under different rice rotations. The first and second rice crops in the rice-pasture rotation are reported separately as Rice_pasture1 and Rice_Pasture2. Horizontal black lines illustrate the median. Black circles are outliers. Different uppercase letters indicate significant differences between treatments for all years and lowercase letter for the last two years (2017-2018) ($p < .05$).

SOC and TN

During the first stage of this long-term experiment, SOC stocks in rice-pasture increased 0.6 Mg ha^{-1} yr^{-1} ($R^2 = 0.55$) in topsoil (Figure 4A). Meanwhile, SOC stocks were maintained in the two intensified cropping systems (rice-soybean and rice-cover crop) (Figure 4B and C). Similar to SOC, there was a trend of increasing TN in rice-pasture at a rate of 0.05 Mg ha^{-1} yr^{-1} ($p = 0.057$) (Figure 4D). In rice-soybean and rice-cover crop, no change in TN was observed (Figure 4 E and F). Between linear and quadratic models, model fit always improved using linear models (except for TN in rice-soybean and rice-cover crop) based on log likelihood tests. No differences between rice-soybean and rice-cover crop slopes were found for the rate of SOC change, however the slope for rice-pasture was statistically greater than rice-soybean and rice-cover crop.

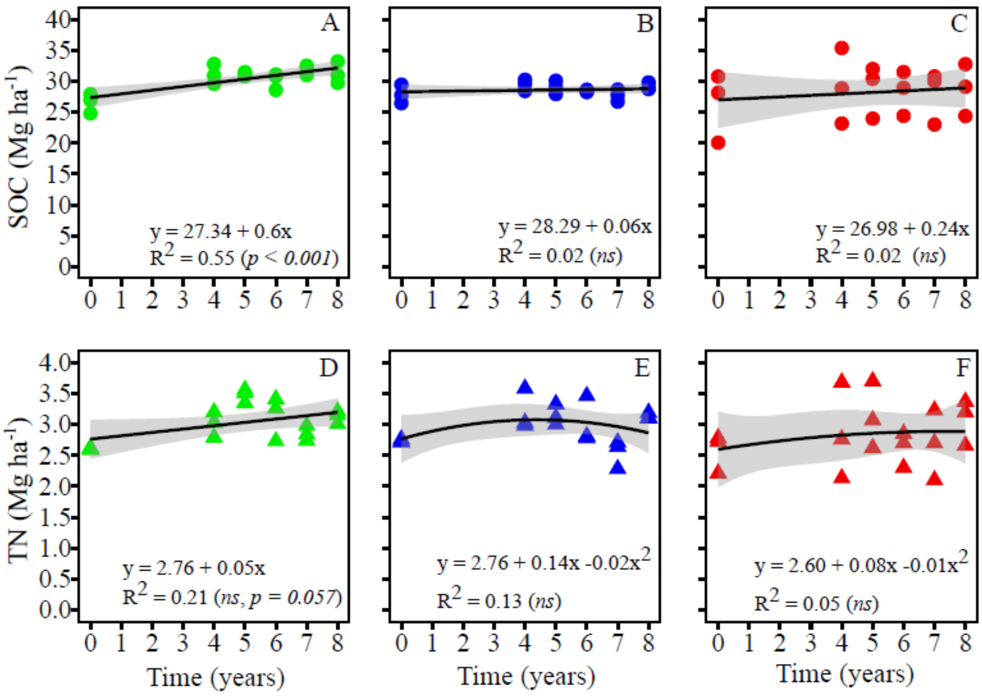

Figure 4. Soil organic carbon (SOC) and total nitrogen (TN) stocks in the top 0-15 cm soil depth over 8 yr in three rice-based systems: rice-pasture (A and D), rice-soybean (B and E), and rice-cover crop (C and F).

When considering concentrations instead of stocks, average SOC concentration was 9.6 % and 12.7 % greater in rice-pasture compared to rice-soybean and rice-cover crop, respectively (Table 3). A similar hierarchy was found in TN concentrations, where rice-pasture achieved the highest value while rice-cover crop the lowest, and rice-soybean had an intermediate value. The BD of rice-soybean and rice-cover crop was 4 and 7% greater than rice-pasture (1.28 g kg^{-1}), respectively, in 2016 but no differences were found in 2019.

Table 3. Bulk density (g cm^{-3}) measured in 2016 and 2019, and soil organic carbon and nitrogen concentrations (g kg^{-1}) for all years in three rice-based rotation systems. Values represent means ± standard deviation. Different letters indicate significant differences between treatments ($p < .05$).

Treatment	BD_2016				BD_2019			
	g cm^{-3}							
Rice-pasture	1.28	±	0.03	b	1.26	±	0.02	a
Rice-soybean	1.33	±	0.05	ab	1.32	±	0.05	a
Rice-cover crop	1.37	±	0.08	a	1.35	±	0.1	a
	SOC				N			
	g kg^{-1}							
Rice-pasture	16.1	±	1.1	a	1.6	±	0.2	a
Rice-soybean	14.6	±	0.6	b	1.5	±	0.1	ab
Rice-cover crop	14.1	±	2.6	b	1.4	±	0.3	b

Biomass

Rice-cover crop produced 35 and 48% more total biomass (aboveground residues plus belowground biomass and grain yield) on an average annual basis compared to rice-soybean and rice-pasture, respectively (Table 4). Similarly, aboveground residues were 1.8 Mg ha^{-1} yr^{-1} higher for rice-cover crop than the mean of rice-soybean and rice-pasture (7 Mg ha^{-1} yr^{-1}). In contrast, estimates of belowground biomass in rice-pasture (2.7 Mg ha^{-1} yr^{-1}) were 12 and 42% greater than rice-cover crop and rice-soybean, respectively. Total residue production (aboveground residues + belowground biomass, without grain) in rice-pasture (9.8 Mg ha^{-1} yr^{-1}) was 0.9 Mg ha^{-1} yr^{-1} greater than rice-soybean and 1.5 Mg ha^{-1} yr^{-1} lower than rice-cover crop. The relative contribution of aboveground residues by rice crops was higher compared to the other rotation phases in all treatments. However, while rice contributed the higher belowground biomass in rice-soybean and rice-cover crop the pasture phase produced more belowground biomass compared to the other components in the rice-pasture system (Supplemental table S2).

Table 4. Mean aboveground residues (without grain) and belowground biomass, total residues (aboveground residues + belowground biomass), and total biomass production (Mg ha^{-1} yr^{-1}) ± standard deviation in three rice-based systems across the study period. Different letters indicate differences between treatments ($p < .05$).

Treatment	Aboveground residues	Belowground biomass	Total residues	Total biomass
	Mg ha^{-1} yr^{-1}			
Rice-pasture	7.0 ± 0.8 b	2.7 ± 0.4 a	9.8 ± 1.2 b	13 ± 1.3 c
Rice-soybean	7.0 ± 1.2 b	1.9 ± 0.3 c	8.9 ± 1.5 c	14.3 ± 2.0 b
Rice-cover crop	8.8 ± 1.8 a	2.4 ± 0.4 b	11.2 ± 2.2 a	19.3 ± 2.7 a

Of the different biomass indices, only belowground biomass showed a significative correlation with annual change in SOC during the study period (r = 0.92, p-value= 0.0005). A quadratic regression was fit between these two variables. Based on the linear relationship of these variables, it was estimated that an annual production of 1.9 Mg ha^{-1} yr^{-1} of belowground biomass is needed to maintain SOC (Figure 5).

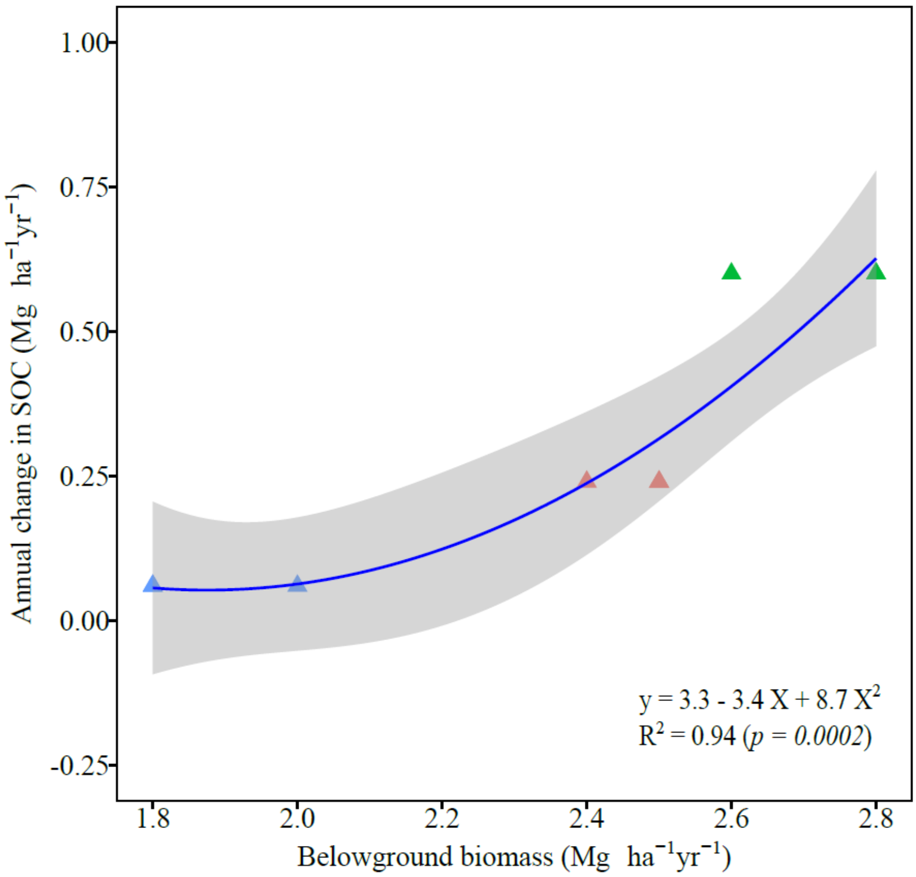

Figure 5. Relationship between soil organic carbon annual change in the top 0-15 cm soil depth and estimated mean annual total belowground biomass in three rice-based systems. Triangle colors represent rotations, green: rice-pasture, blue: rice-soybean and red: rice-cover crop.

DISCUSSION

Rice grain yields

We found that rice crops following soybean or pasture the previous summer had higher grain yield than those following rice, with yields being more stable in the case of rice following soybean (Figure 3). Considering soils in this experiment may have accumulated SOC after decades of rice-pasture rotation in a temperate climate (Deambrosi, 2009), we are unaware of other experimental evidence addressing changes in rice yield and SOC following intensification with annual grain crops. Even though there is less frequency of rice in the rice-pasture than rice-cover crop or rice-soybean systems, in this study we do not focus on the annualized grain yield of each system because it is not relevant in Uruguay. At the system-level, considering that all rice yields ranged from approximately 8-10 Mg ha^{-1}, any system with more years of rice would have higher total rice productivity. Instead, we focus on field-level yields of each rice crop under different rotations because total rice area in Uruguay is limited by irrigation water availability to around 200,000 ha per year. Thus, even if a certain rotation produces more rice or is more profitable, total rice area is relatively static and cannot expand beyond this limit. Accordingly, the intensification of rice-pasture with annual crops does not necessarily mean an increase in yield per unit of area and time for rice. Rather, intensification with annual crops would replace pasture area, leading to the decoupling of rice and pasture systems which currently cover around 1M ha annually. We recognize that in other regions where land is the main limitation, the conversion of continuous rice to a rice-pasture system would represent a reduction in system-level grain yields, causing agricultural expansion to maintain current rice production levels.

We did not find that replacing pasture with annual crops necessarily decreased rice productivity, with both rice-soybean (full 8 yr) and rice-cover crop (last 2 yr) achieving similar yields as the first year of rice in rice-pasture (Figure 3). This finding does not agree with recent work for rainfed crops in Uruguay, where changes in soil quality or SOC may have a stronger impact on soil chemical and physical properties and decreased productivity compared to flooded rice systems (Ernst et al., 2018; Rubio et al., 2021). However, we observed that rice following soybean had higher yields than rice following rice for the two intensification options, as predicted. It is well-known that cereal yields tend to be higher in cereal-legume rotations compared to cereal monoculture (Crookston et al., 1991; Stanger et al., 2008). Farmaha et al. (2016) reported that both corn and soybeans improved their grain yield when they alternated crops (maize-soy or soy-maize). In rice systems, Xuan et al. (2012) found yield improvements between 24-46% when rice alternates with mungbean, and 26% after soybean in southern Brazil (Ribas et al., 2021).

While it is logical to expect long-term rotations with pasture are better for rice yield, our results indicate this only applies to the first year of rice after pastures. In contrast, the second year of rice in the rice-pasture system had lower yields than rice following either rice or soybean in the two intensified continuous cropping systems running for 8 years, which is opposed to the conclusions of Ernst et al. (2018). These results suggest that the previous crop effect can be strong, potentially masking the benefit of pasture in the rotation since the second rice of rice-pasture showed the worst performance. However, a closer examination of the two instances of rice following rice indicates other reasons may explain these yield differences. It was unexpected that rice-cover crop had a higher yield compared to the second rice of rice-pasture (Figure 3), but this could be due to several factors. First, the winter cover crop was a legume (*Trifolium alexandrinum* L.) in the rice-cover crop system, while it was annual ryegrass between the two rice crops of the rice-pasture rotation. Therefore, some combination of biological N fixation associated with the legumes, or allelopathy for the grass cover crop preceding rice (Li et al., 2008) could have contributed to higher rice yields following a legume cover crop. Two other factors could be a higher C:N ratio of ryegrass residue, thus increasing N immobilization in the second rice of rice-pasture, and a higher N fertilization rate for rice-cover crop than the rice-pasture rotation. From a practical perspective, around 40% of national rice area is rice following rice, hence these results suggest the inclusion of annual legume cover crops could help maintain high yields in the second year, especially compared to a preceding ryegrass cover crop under no-till. Rice straw management practices that maintain soil cover and contribute to long-term SOC while minimizing negative yield impacts on a second rice crop should be included in future research.

Impact of rotations on SOC and TN stocks

Rice-pasture was the only system with a positive SOC sequestration rate during the study period (Figure 4). Similarly, Benintende et al. (2008) found after 4 years that SOC concentrations in the first 0-15 cm depth in rice-pasture systems were higher (30.6 g kg^{-1}) than continuous rice systems (26.1 g kg^{-1}). The rice-pasture system combines the benefits of both crops for SOC: pasture was in place for 70% of the rotation sequence (3.5 of 5 yr) and flooded rice soils help slow microbial respiration of C due to anaerobic conditions (Chen et al., 2021; Sahrawat, 2012). The fact that the other two systems maintained, but did not increase SOC, suggests that the benefits of pasture cannot be compensated by an increased frequency of flooded rice crops (every year in rice-cover crop and every other year in rice-soybean). The lack of effect for these systems was despite high C inputs through total annual biomass production and winter cover crops (discussed further below). Previous studies focusing on the conversion of continuous rice to rotations including rainfed (non-flooded) crops show that SOC generally decreases due to increased microbial respiration under aerobic soil conditions (Dobermann & Witt, 2000; Witt et al. 2000). However, for rice-soybean compared to the rice-cover crop system, we did not observe differences in SOC concentration or sequestration rates (Table 3, Figure 4). This may be due to rice-pasture being the starting point of the experiment rather than continuous rice.

A new insight from this work is that despite starting with a 1.42% SOC, the rice-pasture treatment further increased SOC by 0.6 Mg ha^{-1} yr^{-1} during the study period (Figure 4). This experiment was initiated in a rice-pasture rotation under conventional management for 34 years, with an average rice grain yield of 4300 kg ha^{-1} during the 1983-1987 period, 5700 kg ha^{-1} between 1987-1991, and 6700 kg ha^{-1} during 1999-2009 (Deambrosi, 2009; Méndez, 1993). This positive change in SOC likely occurred for three reasons: higher rice productivity in the current experiment compared to the previous period (9.4 vs 6.7 Mg ha^{-1}), the conversion to no-till in all experimental rotations compared to conventional tillage practices previously used, and the inclusion of tall fescue mixed with legumes in the pasture phase which increases belowground C inputs (discussed below) compared to an annual grass in pastures grown during the previous period. The reason for higher rice productivity is because our experimental management was consistent with optimal practices for closing yield gaps in Uruguay such as planting date and nitrogen fertilization (Tseng et al., 2021). No-till also promotes SOC in surface layers. Given that rice-pasture is the dominant rotation currently practiced in Uruguay, this finding holds broad relevance for improving soil quality through better management and higher cropping system productivity. Importantly, both of these are aligned with farmers' production goals.

While rotations with pastures can provide important ecosystem services, such as climate regulation, nutrient cycling, and food production (Carvalho et al., 2021; Franzluebbers et al., 2014), there is increasing pressure to intensify systems to help overcome some of the economic challenges related to land leasing arrangements and thin margins for rice in South America (high production costs and low prices). In this context, an important result is that the intensified systems did not decrease SOC in the top 15 cm soil depth during our midterm experiment. Preserving soil quality can be critical in countries that like Uruguay attempt to make sustainability a pillar of an export-oriented agricultural economy. In recent years, national regulations have been enacted to restrict some rainfed crop sequences to prevent soil erosion and degradation (Pérez Bidegain et al., 2018). More broadly, accounting for potential negative impacts on SOC due to increasing frequency of annual crops in rotation is particularly important given recent declines in pasture-based systems in Argentina, Uruguay, and southern Brazil (Modernel et al., 2016). For Uruguay, recent estimates suggest that 70% of the increase in crop area is by substitution of crop-pasture with crop-crop sequences, while 30% is by agricultural expansion into natural grasslands (DIEA, 2018; Ernst et al., 2018).

Research like the present study is necessary to understand the effects of substituting pasture with annual crops, both in terms of short-term crop productivity and long-term changes in soil quality. It is important to note that SOC gains in rice-pasture will not continue indefinitely, and likewise, the potential effects of intensified systems may take more time to appear. Limited studies have evaluated SOC following the conversion of rice-pasture to more intensive alternatives over 8 yr. According to IPCC (Tier 1), 20 yr is an adequate time frame to report changes in SOC stocks, which assumes that a new equilibrium is reached (IPCC, 2006). However, many reports also show changes in SOC in the midterm (around 3-10 yr) (Ladha et al., 2011), although the rate of change is higher during the initial years (Fujisaki et al., 2018).

Unlike changes in SOC, there was only a trend of increasing TN in rice-pasture (p value = 0.057) (Figure 4). Soil C and N biogeochemistry are tightly linked, thus benefits for SOC are likely to become evident and translate into higher soil N supplying capacity (Dobermann and Witt, 2000; Sahrawat, 2012). Research has demonstrated that pasture including legumes supports biological N fixation (Labandera et al., 1988), thus a rice-pasture rotation not only helps maintain TN but supports lower long-term use of external N fertilizer inputs in rice compared to other regions (Castillo et al., 2021; Chauhan et al., 2017). Total N also did not change for rice-cover crop, which has been reported in other studies (Witt et al., 2000), likely owing to submerged soils as well as biological N fixation by free-living microorganisms in floodwater (Ladha & Reddy, 2003). Additionally, the annual legume cover crop included during winter in this treatment, as well as the N fertilization rate (148 kg N ha^{-1}) could be help sustain TN (Zhang et al., 2017).

Rice-soybean and rice-cover crop systems sustained TN, which could suggest substantial N contributions through biological N fixation by the annual legume cover crop and the soybean included in these systems. For example, *T. alexandrinum* L. is reported to be one of the top-ranked species in terms of biological N fixation (Pinto et al., 2021). Additionally, it is possible that the relatively low soybean grain yield (2.5 Mg ha^{-1}), which means a low N removal by this crop and a relative high contribution through biological N fixation, resulted in a slightly negative or neutral apparent N balance (Salvagiotti et al., 2008; Santachiara et al., 2017). In a high grain price scenario, results for rice-soybean and rice-cover crop imply that intensification of the cropping system through increased frequency of annual grain crops could allow rice farmers to improve profit without sacrificing SOC in the midterm relative to the baseline rice-pasture system of 34 years. However, we stress that these results were only achieved in combination with other important soil conservation practices in both intensification options, such as no-till and winter cover crops. Future research over the long-term is still needed to understand how the combination of different pasture species, their management, and soil tillage practices can be optimized, in addition to livestock management practices during the pasture phase, to positively affect SOC sequestration and N dynamics in rice-based systems.

Biomass production and animal effect on SOC

It is often thought that increasing C inputs is the most effective way to build SOC (Amelung et al., 2020; Fujisaki et al., 2018), for example through increased biomass production. However, our analysis emphasizes the need to focus on the source of C (e.g. root vs. shoot biomass) and the quality of C inputs from different phases of the cropping system (e.g. rice vs. pasture) to prioritize opportunities for increasing SOC. The three systems produced between 8.8-11.2 Mg ha^{-1} yr^{-1} of residues, with different amounts in above and belowground fractions (Table 4). Similar values have been reported for other high-intensity rice-rice systems (Witt et al., 2000), which also maintained or gained SOC during the study period.

While the rice-cover crop system had the highest total annual biomass productivity which in theory would help build SOC, we found that only belowground biomass from the different treatments showed a relationship with the rate of SOC sequestration (Figure 5). Rice-pasture had the greatest belowground biomass production (2.7 Mg ha^{-1} yr^{-1}), representing 28% of total residues, while in the other systems belowground biomass represented 21% of total residues (Table 4). Root systems and rhizodeposition are increasingly recognized to play an important role in SOC sequestration (Liang et al., 2002; Mazzilli et al., 2015; Villarino et al., 2021). In a 13C tracer study, Mazzilli et al. (2015) found that the humification coefficient of belowground C inputs into particulate organic C was 24% and 10% for soybean and corn, respectively, while that of aboveground C inputs was only 0.5% and 1.0%. Thus, higher belowground biomass as well the sustained contribution of biological N fixation through legumes in rice-pasture could explain why this system showed both the greatest SOC sequestration rate and SOC concentration.

The result that total biomass input was greater in the two intensified systems but this did not reflect in SOC sequestration could also be related to the animal effect in crop-livestock rotations. Direct grazing on pasture has been shown to improve soil fertility in rice-based systems (Denardin et al., 2020), leading to a greater potential to sequester SOC than continuous cropping systems (Johnson et al., 2007). The integration of livestock in rice systems benefits the subsequent rice crop, improving nutrient use efficiency and rice yield (Castillo et al., 2021; Denardin et al., 2020). The positive effect of rice-pasture in this study suggests that these integrated crop-livestock systems could be improved locally and further adopted in this ecoregion, considering that in Argentina, Paraguay, and southern Brazil, continuous rice cropping systems prevail.

Limitations

There are several limitations of this study. One is that we only evaluated surface soil depth (0-15 cm) when considering changes in SOC or TN, while some studies suggest including deeper layers, specifically in no-till systems where SOC could decrease in sub-surface layers (Olson et al., 2014). Additionally, the detection of SOC changes is most appropriate over long-term timescales (Paustian et al., 2016; Smith et al., 2020), but herein we evaluate SOC and TN over 8 years during the first stage of this long-term experiment. Nevertheless, many studies report short or mid-term differences of SOC and TN with the aim to detect initial changes due to management.

A related limitation is that SOC sequestration rates are not constant over time, and eventually reach a plateau or saturation (Hassink & Whitmore, 1997; Pravia et al., 2019), with initial changes often being greater than later ones (Fujisaki et al., 2018). For this reason, the reported SOC sequestration rate reported here for rice-pasture should be considered with caution. Based on equations in Hassink and Whitmore (1997), there is still room for SOC retention in the mineral fraction of soil in this experiment (3.2% of C for saturation for a 30% clay soil). Additionally, other research in a rice-rice system after 31 years found that total SOC increased with greater C inputs at 0-15 cm depth, with the stable fraction of SOC showing saturation while the labile soil fraction did not (Sun et al., 2013).

Finally, there is a tradeoff between SOC sequestration, which is often achieved through C inputs such as residue retention and flooded soils, and methane emissions which represent the primary field greenhouse gas (GHG) associated with rice production (Bhattacharyya et al., 2014). Currently, SOC is promoted as a climate change mitigation strategy for agriculture, but this does not necessarily apply to flooded rice like it does to crops grown under aerobic soils. While sequestering SOC in rice soils could partially mitigate the negative impacts of high methane emissions, relatively little research has explored this area. Assuming an average global warming potential of 3.8 Mg CO_2 eq ha^{-1} for field GHG emissions from rice systems (Linquist et al., 2012), the SOC sequestration rate reported here (0.6 Mg C ha^{-1} yr^{-1} for rice-pasture) could offset this by close to 60%. Therefore, future monitoring of this long-term experiment is necessary account for methane emissions as part of the total C balance and identify tradeoffs associated with different rotations. This could be combined with simulation modeling to understand the potential for SOC saturation in the future, which could result in lower sequestration rates than the present study.

CONCLUSIONS

The design of cropping systems that increase SOC while maintaining or increasing yields is a key step in the transition to sustainable agriculture. With the aim to evaluate potential outcomes of intensifying rice-pasture systems, we assessed three rotations: 1) the business-as-usual system in Uruguay (rice-pasture), 2) an emerging cropping system that is already practiced in southern Brazil and by some farmers in Uruguay (rice-soybean), and 3) one that is not currently practiced in Uruguay but has the highest frequency of rice, similar to most of the rice grown in the world (rice-cover crop). Rice yield, SOC and TN sequestration rates, and biomass production were assessed after 34 yr of rice-pasture prior to the experiment. We found that intensified systems including rice-soybean and rice-cover crop were able to maintain SOC stocks over 8 years. In contrast, the rice-pasture system (with increased rice productivity compared to before the experiment) showed an opportunity for SOC sequestration. Belowground biomass estimates were the main factor explaining SOC changes in these systems, with approximately 1.9 Mg ha^{-1} yr^{-1} of belowground biomass inputs required to maintain SOC stocks. Our results indicate there is still a challenge to further increase yield in the second year of rice of different rotations, which was 12% lower than rice after soybean or a perennial pasture, highlighting the short-term agronomic effect of rotations (previous crop, cover crop, and fertilizer management) on crop yields. Although not investigated here, a possible option based on our results could be integrating soybeans into the rice-pasture rotation, for example, by including one soybean crop between two rice crops, allowing for benefits to SOC and simultaneously increasing rice yield for the second rice in the rotation.

The findings of this study suggest that for Argialbolls soils in a temperate region of South America under no-till, the inclusion of a perennial grass in the rotation and high belowground residue production sequesters SOC and sustains high productivity of rice. Intensification of the sequence by replacing perennial pastures with soybeans and more rice improves rice yield, but does not increase SOC. On the other hand, intensification through rice each year with a winter cover crop maintains SOC, but ended to slightly reduced productivity compared to the rice-pasture or rice-soybean rotations.

ACKNOWLEDGEMENTS

We thank the National Institute of Agricultural Research (INIA) of Uruguay and the National Research and Innovation Agency (ANII-Uy, FSA_PP_2018_1_148336) to partially support this research. We are grateful for the invaluable help provided by Alexander Bordagorri, Irma Furtado, Matias Oxley and Adan Rodriguez in laboratory and field work. We thank the Department of Plant Sciences, UC Davis and Fulbright Uruguay-ANII for supporting I. Macedo with graduate fellowships.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-18887-7

Baethgen, W. E., Parton, W. J., Rubio, V., Kelly, R. H., & M. Lutz, S. (2021). Ecosystem dynamics of crop–pasture rotations in a fifty-year field experiment in southern South America: Century model and field results. *Soil Science Society of America Journal*, *85*(2), 423–437. https://doi.org/10.1002/saj2.20204

Benintende, S. M., Benintende, M. C., Sterren, M. A., & De Battista, J. J. (2008). Soil microbiological indicators of soil quality in four rice rotations systems. *Ecological Indicators*, *8*(5), 704–708. https://doi.org/10.1016/j.ecolind.2007.12.004

Bhattacharyya, P., Neogi, S., Roy, K. S., Dash, P. K., Nayak, A. K., & Mohapatra, T. (2014). Tropical low land rice ecosystem is a net carbon sink. *Agriculture, Ecosystems and Environment*, *189*, 127–135. https://doi.org/10.1016/j.agee.2014.03.013

Bolinder, M. A., Janzen, H. H., Gregorich, E. G., Angers, D. A., & VandenBygaart, A. J. (2007). An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems and Environment*, *118*(1–4), 29–42. https://doi.org/10.1016/j.agee.2006.05.013

Brewer, K. M., & Gaudin, A. C. M. (2020). Potential of crop-livestock integration to enhance carbon sequestration and agroecosystem functioning in semi-arid croplands. *Soil Biology and Biochemistry*, *149*(September). https://doi.org/10.1016/j.soilbio.2020.107936

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*(February), 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Carvalho, P. C. de F., Savian, J. V., Della Chiesa, T., De Souza Filho, W., Terra, J. A., Pinto, P., Posselt Martins, A., Villarino, S., Da Trindade, J. K., De Albuquerque Nunes, P. A., & Piñeiro, G. (2021). Land-use intensification trends in the Rio de la Plata Region of South America: toward specialization or recoupling crop and livestock production. *Frontiers of Agricultural Science and Engineering*, *8*(1), 97. https://doi.org/10.15302/J-FASE-2020380

Cassman, K. G., Dobermann, A., Sta Cruz, P. C., Gines, G. G., Samson, M. I., Descalsota, J. P., Alcantara, J. M., Dizon, M. A., & Olk, D. C. (1996). Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics. *Plant and Soil*, *182*(2), 267–278. https://doi.org/10.1007/BF00029058

Castillo, J., Terra, J. ., & Méndez, R. (2015). Indicadores objetivos para la recomendación de fertilización N en arroz. *XII Conferência Internacional de Arroz Para América Latina e Caribe*, 1.

Castillo, Jesús, Kirk, G. J. D., Rivero, M. J., Dobermann, A., & Haefele, S. M. (2021). The nitrogen economy of rice-livestock systems in Uruguay. *Global Food Security*, *30*(August), 100566. https://doi.org/10.1016/j.gfs.2021.100566

Chauhan, B. S., Jabran, K., & Mahajan, G. (2017). Rice Production Worldwide. In B. S. Chauhan, K. Jabran, & G. Mahajan (Eds.), *Rice Production Worldwide*. Springer International Publishing. https://doi.org/10.1007/978-3-319-47516-5

Chen, A., Xie, X., Dorodnikov, M., Wang, W., Ge, T., Shibistova, O., Wei, W., & Guggenberger, G. (2016). Response of paddy soil organic carbon accumulation to changes in long-term yield-driven carbon inputs in subtropical China. *Agriculture, Ecosystems and Environment*, *232*, 302–311. https://doi.org/10.1016/j.agee.2016.08.018

Chen, X., Hu, Y., Xia, Y., Zheng, S., Ma, C., Rui, Y., He, H., Huang, D., Zhang, Z., Ge, T., Wu, J., Guggenberger, G., Kuzyakov, Y., & Su, Y. (2021). Contrasting pathways of carbon sequestration in paddy and upland soils. *Global Change Biology*, *27*(11), 2478–2490. https://doi.org/10.1111/gcb.15595

Counce, P. A., Keisling, T. C., & Mitchell, A. J. (2000). A uniform, objectives, and adaptive system for expressing rice development. *Crop Science*, *40*(2), 436–443. https://doi.org/10.2135/cropsci2000.402436x

Crookston, R. K., Kurle, J. E., Copeland, P. J., Ford, J. H., & Lueschen, W. E. (1991). Rotational Cropping Sequence Affects Yield of Corn and Soybean. *Agronomy Journal*, *83*(1), 108–113. https://doi.org/10.2134/agronj1991.00021962008300010026x

Deambrosi, E. (2009). Importancia de la investigación integrada a escala semi-comercial. In *10 años de la Unidad de Producción Arroz-Ganadería* (pp. 79–86). https://www.researchgate.net/profile/Fabio_Montossi/publication/273129760_UPAG_2009/links/54f860970cf210398e96520b.pdf

Deambrosi, Enrique. (2003). Rice production system in Uruguay and its sustainability. *Proceedings of the III International Conference of Temperate Rice, Punta Del Este, Uruguay, INIA*.

Deambrosi, Enrique, Méndez, R., & Castillo, J. (2015). Elementos a considerar en la inclusión de potasio en la fertilización del arroz. *Inia*, 1–10.

Denardin, L. G. de O., Martins, A. P., Carmona, F. de C., Veloso, M. G., Carmona, G. I., Carvalho, P. C. de F., & Anghinoni, I. (2020). Integrated crop-livestock systems in paddy fields: New strategies for flooded rice nutrition. *Agronomy Journal*. https://doi.org/10.1002/agj2.20148

Di Rienzo, J. A., Casanoves, F., Balzarini, M. G., Gonzalez, L., Tablada, M., & Robledo, C. W. (2017). *InfoStat software estadístico: versión 2017* (No. 2017). Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. http://www.infostat.com.ar

DIEA. (2018). *Anuario Estadístico Agropecuario 2018*. Ministerio de Agricultura, Ganadería y Pesca, Editorial Hemisferio Sur. https://descargas.mgap.gub.uy/DIEA/Anuarios/Anuario2018/ Anuario_2018.pdf

Dobermann, A., & Witt, C. (2000). *The potential impact of crop intensification on carbon and nitrogen cycling in intensive rice systems.* (G. J. D. Kirk & D. C. Olk (eds.); pp. 1–25). International Rice Research Institute (IRRI).

Ernst, O. R., Dogliotti, S., Cadenazzi, M., & Kemanian, A. R. (2018). Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield. *Field Crops Research*, *217*(April 2017), 180–187. https://doi.org/10.1016/j.fcr.2017.11.014

Ernst, O., & Siri-Prieto, G. (2009). Impact of perennial pasture and tillage systems on carbon input and soil quality indicators. *Soil and Tillage Research*, *105*(2), 260–268. https://doi.org/10.1016/j.still.2009.08.001

Farmaha, B. S., Eskridge, K. M., Cassman, K. G., Specht, J. E., Yang, H., & Grassini, P. (2016). Rotation impact on on-farm yield and input-use efficiency in high-yield irrigated maize–soybean systems. *Agronomy Journal*, *108*(6), 2313–2321. https://doi.org/10.2134/agronj2016.01.0046

Franzluebbers, A. J., Sawchik, J., & Taboada, M. A. (2014). Agronomic and environmental impacts of pasture-crop rotations in temperate North and South America. *Agriculture, Ecosystems and Environment*, *190*, 18–26. https://doi.org/10.1016/j.agee.2013.09.017

Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y. B., & Chotte, J. L. (2018). Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. *Agriculture, Ecosystems and Environment*, *259*(August 2017), 147–158. https://doi.org/10.1016/j.agee.2017.12.008

Hassink, J., & Whitmore, A. P. (1997). A Model of the Physical Protection of Organic Matter in Soils. *Soil Science Society of America Journal*, *61*(1), 131–139. https://doi.org/10.2136/sssaj1997.03615995006100010020x

Hernández, J., Berger, A., Deambrosi, E., & Lavecchia, A. (2013). Soil Phosphorus Tests for Flooded Rice Grown in Contrasting Soils and Cropping History. *Communications in Soil Science and Plant Analysis*, *44*(7), 1193–1210. https://doi.org/10.1080/00103624.2012.756000

Huggins, D. R., Clapp, C. E., Allmaras, R. R., Lamb, J. A., & Layese, M. F. (1998). Carbon Dynamics in Corn-Soybean Sequences as Estimated from Natural Carbon-13 Abundance. *Soil Science Society of America Journal*, *62*(1), 195–203. https://doi.org/10.2136/sssaj1998.03615995006200010026x

IPCC. (2006). Cropland. In K. T. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara (Ed.), *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Vol. IV* (pp. 1–66). https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_1_Overview.pdf

Johnson, J. M. F., Franzluebbers, A. J., Weyers, S. L., & Reicosky, D. C. (2007). Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental Pollution*, *150*(1), 107–124. https://doi.org/10.1016/j.envpol.2007.06.030

Ju, C., Buresh, R. J., Wang, Z., Zhang, H., Liu, L., Yang, J., & Zhang, J. (2015). Root and shoot traits for rice varieties with higher grain yield and higher nitrogen use efficiency at lower nitrogen rates application. *Field Crops Research*, *175*, 47–55. https://doi.org/10.1016/j.fcr.2015.02.007

Labandera, C., Danso, S. K. A., Pastorini, D., Curbelo, S., & Martin, V. (1988). Nitrogen Fixation in a White Clover-Fescue Pasture Using Three Methods of Nitrogen-15 Application and Residual Nitrogen-15 Uptake. *Agronomy Journal*, *80*(2), 265–268. https://doi.org/10.2134/agronj1988.00021962008000020022x

Ladha, J. K., & Reddy, P. M. (2003). Nitrogen fixation in rice systems: State of knowledge and future prospects. *Plant and Soil*, *252*(1), 151–167. https://doi.org/10.1023/A:1024175307238

Ladha, Jagdish K., Reddy, C. K., Padre, A. T., & van Kessel, C. (2011). Role of Nitrogen Fertilization in Sustaining Organic Matter in Cultivated Soils. *Journal of Environmental Quality*, *40*(6), 1756–1766. https://doi.org/10.2134/jeq2011.0064

Lemaire, G., Franzluebbers, A., Carvalho, P. C. de F., & Dedieu, B. (2014). Integrated crop-livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agriculture, Ecosystems and Environment*, *190*, 4–8. https://doi.org/10.1016/j.agee.2013.08.009

Li, G., Zeng, R. Sen, Li, H., Yang, Z., Xin, G., Yuan, J., & Luo, Y. (2008). Allelopathic effects of decaying Italian ryegrass (Lolium mutiflorum Lam.) residues on rice. *Allelopathy Journal*, *22*(1), 15–23.

Liang, B. C., Wang, X. L., & Ma, B. L. (2002). Maize root-induced change in soil organic carbon pools. *Soil Science Society of America Journal*, *66*(3), 845–847. https://doi.org/10.2136/sssaj2002.8450

Linquist, B., Van Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & Van Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, *18*(1), 194–209. https://doi.org/10.1111/j.1365-2486.2011.02502.x

Macedo, I., Terra, J. A., Siri-Prieto, G., Velazco, J. I., & Carrasco-Letelier, L. (2021). Rice-pasture agroecosystem intensification affects energy use efficiency. *Journal of Cleaner Production*, *278*, 123771. https://doi.org/10.1016/j.jclepro.2020.123771

Mandal, B., Majumder, B., Adhya, T. K., Bandyopadhyay, P. K., Gangopadhyay, A., Sarkar, D., Kundu, M. C., Choudhury, S. G., Hazra, G. C., Kundu, S., Samantaray, R. N., & Misra, A. K. (2008). Potential of double-cropped rice ecology to conserve organic carbon under subtropical climate. *Global Change Biology*, *14*(9), 2139–2151. https://doi.org/10.1111/j.1365-2486.2008.01627.x

Mazzilli, S. R., Kemanian, A. R., Ernst, O. R., Jackson, R. B., & Piñeiro, G. (2015). Greater humification of belowground than aboveground biomass carbon into particulate soil organic matter in no-till corn and soybean crops. *Soil Biology and Biochemistry*, *85*, 22–30. https://doi.org/10.1016/j.soilbio.2015.02.014

Méndez, R. (1993). Rotación arroz-pasturas: análisis físico económico del cultivo. *INIA Serie Técnica ; 38*, 21 p. http://www.ainfo.inia.uy/digital/bitstream/item/2942/1/111219220807121346.pdf

Modernel, P., Rossing, W. A. H., Corbeels, M., Dogliotti, S., Picasso, V., & Tittonell, P. (2016). Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America. *Environmental Research Letters*, *11*(11). https://doi.org/10.1088/1748-9326/11/11/113002

Molina, F., Terra, J., & Roel, A. (2019). Evolución de algunas variables tecnológicas en el cultivo de arroz en Uruguay. *Serie Técnica N°250 Arroz 2018*, 1–4. https://doi.org/http://doi.org/10.35676/INIA/ST.250

Motschenbacher, J. M., Brye, K. R., Anders, M. M., Gbur, E. E., Slaton, N. A., & Evans-White, M. A. (2013). Rice Rotation and Tillage Effects on Water-Stable Soil Macroaggregates and Their Associated Carbon and Nitrogen Contents in a Silt-Loam Soil. *Soil Science*, *178*(11), 596–611. https://doi.org/10.1097/SS.0000000000000028

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *Soil*, *5*(1), 15–32. https://doi.org/10.5194/soil-5-15-2019

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'Amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., & Kassem, K. R. (2001). Terrestrial ecoregions of the world: A new map of life on Earth. *BioScience*, *51*(11), 933–938. https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2

Olson, K. R., Al-Kaisi, M. M., Lal, R., & Lowery, B. (2014). Experimental Consideration, Treatments, and Methods in Determining Soil Organic Carbon Sequestration Rates. *Soil Science Society of America Journal*, *78*(2), 348–360. https://doi.org/10.2136/sssaj2013.09.0412

Pan, G., Xu, X., Smith, P., Pan, W., & Lal, R. (2010). An increase in topsoil SOC stock of China's croplands between 1985 and 2006 revealed by soil monitoring. *Agriculture, Ecosystems and Environment*, *136*(1–2), 133–138. https://doi.org/10.1016/j.agee.2009.12.011

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Pérez Bidegain, M., Hill, M., Clérici, C., Terra, J., Sawchik, J., & Garc\'\ia-Préchac, F. (2018). Regulatory utilization of USLE/RUSLE erosion rate estimates in Uruguay: a policy coincident with the UN Sustainable Development Goals. *Soil and Sustainable Development Goals. Stuttgart: Catena-Schweizerbart*, 82–91.

Pinto, P., Rubio, G., Gutiérrez, F., Sawchik, J., Arana, S., & Piñeiro, G. (2021). Variable root:shoot ratios and plant nitrogen concentrations discourage using just aboveground biomass to select legume service crops. *Plant and Soil*. https://doi.org/10.1007/s11104-021-04916-x

Pittelkow, C. M., Zorrilla, G., Terra, J., Riccetto, S., Macedo, I., Bonilla, C., & Roel, A. (2016). Sustainability of rice intensification in Uruguay from 1993 to 2013. *Global Food Security*, *9*, 10–18. https://doi.org/10.1016/j.gfs.2016.05.003

Pravia, M. V., Kemanian, A. R., Terra, J. A., Shi, Y., Macedo, I., & Goslee, S. (2019). Soil carbon saturation, productivity, and carbon and nitrogen cycling in crop-pasture rotations. *Agricultural Systems*, *171*(December 2017), 13–22. https://doi.org/10.1016/j.agsy.2018.11.001

Ribas, G. G., Zanon, A. J., Streck, N. A., Pilecco, I. B., de Souza, P. M., Heinemann, A. B., & Grassini, P. (2021). Assessing yield and economic impact of introducing soybean to the lowland rice system in southern Brazil. *Agricultural Systems*, *188*(September 2020), 103036. https://doi.org/10.1016/j.agsy.2020.103036

Rubio, V., Diaz-rossello, R., Andrés, J., & Harold, M. V. E. (2021). Quantifying soil organic carbon ' s critical role in cereal productivity losses under annualized crop rotations. *Agriculture, Ecosystems and Environment 321*, *321*(October 2020). https://doi.org/10.1016/j.agee.2021.107607

Sahrawat, K. L. (2012). Soil fertility in flooded and non-flooded irrigated rice systems. *Archives of Agronomy and Soil Science*, *58*(4), 423–436. https://doi.org/10.1080/03650340.2010.522993

Salvagiotti, F., Cassman, K. G., Specht, J. E., Walters, D. T., Weiss, A., & Dobermann, A. (2008). Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. *Field Crops Research*, *108*(1), 1–13. https://doi.org/10.1016/j.fcr.2008.03.001

Santachiara, G., Borrás, L., Salvagiotti, F., Gerde, J. A., & Rotundo, J. L. (2017). Relative importance of biological nitrogen fixation and mineral uptake in high yielding soybean cultivars. *Plant and Soil*, *418*(1–2), 191–203. https://doi.org/10.1007/s11104-017-3279-9

Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N. H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J. E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, *26*(1), 219–241. https://doi.org/10.1111/gcb.14815

Sokol, N. W., & Bradford, M. A. (2019). Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. *Nature Geoscience*, *12*(1), 46–53. https://doi.org/10.1038/s41561-018-0258-6

Stanger, T. F., Lauer, J. G., & Chavas, J. P. (2008). The profitability and risk of long-term cropping systems featuring different rotations and nitrogen rates. *Agronomy Journal*, *100*(1), 105–113. https://doi.org/10.2134/agronj2006.0322

Sun, Y., Huang, S., Yu, X., & Zhang, W. (2013). Stability and saturation of soil organic carbon in rice fields: evidence from a long-term fertilization experiment in subtropical China. *Journal of Soils and Sediments*, *13*(8), 1327–1334. https://doi.org/10.1007/s11368-013-0741-z

Terra, J. a, García Préchac, F., Salvo, L., & Hernández, J. (2006). Soil use intensity impact on total and particulate soil organic matter in no till crop-pasture rotations under direct grazing. *Advances in GeoEcology*, *38*(APRIL), 233–241. https://www.researchgate.net/publication/260676077_Soil_use_intensity_impacts_on_total_and_particulate_soil_organic_matter_in_no-till_crop-pasture_rotations_under_direct_grazing

Tseng, M. C., Roel, A., Macedo, I., Marella, M., Terra, J. A., Zorrilla, G., & Pittelkow, C. M. (2021). Field-level Factors for Closing Yield Gaps in High-Yielding Rice Systems of Uruguay. *Field Crops Research*, *264*. https://doi.org/10.1016/j.fcr.2021.108097

Villarino, S. H., Pinto, P., Jackson, R. B., & Piñeiro, G. (2021). *Plant rhizodeposition : A key factor for soil organic matter formation in stable fractions*. *April*, 1–14.

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

Witt, C., Cassman, K. G., Olk, D. C., Biker, U., Liboon, S. P., Samson, M. I., & Ottow, J. C. G. (2000). Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant and Soil*, *225*(1–2), 263–278. https://doi.org/10.1023/A:1026594118145

Xuan, D. T., Guong, V. T., Rosling, A., Alström, S., Chai, B., & Högberg, N. (2012). Different crop rotation systems as drivers of change in soil bacterial community structure and yield of rice, Oryza sativa. *Biology and Fertility of Soils*, *48*(2), 217–225. https://doi.org/10.1007/s00374-011-0618-5

Yadvinder-Singh, Bijay-Singh, & Timsina, J. (2008). Crop Residue Management for Nutrient Cycling and Improving Soil Productivity in Rice-Based Cropping Systems in the Tropics. In *Advances in Agronomy* (Vol. 85). https://doi.org/10.1016/S0065-2113(04)85006-5

Zhang, T., Chen, A., Liu, J., Liu, H., Lei, B., Zhai, L., Zhang, D., & Wang, H. (2017). Cropping systems affect paddy soil organic carbon and total nitrogen stocks (in rice-garlic and rice-fava systems) in temperate region of southern China. *Science of the Total Environment*, *609*, 1640–1649. https://doi.org/10.1016/j.scitotenv.2017.06.226

SUPPLEMENTAL MATERIAL

Supplemental table S1. One replicate of the long-term experiment.

			Rotations							
			Rice-cover crop	**Rice-soybean**		**Rice-pasture**				
			Plots							
			1	2	3	4	5	6	7	8
Block	Calendar year	Year								
1	2012	0	Rice	Rice	Soybean	Rice	Rice	Pasture	Pasture	Pasture
1	2013	1	Rice	Soybean	Rice	Rice	Pasture	Pasture	Pasture	Rice
1	2014	2	Rice	Rice	Soybean	Pasture	Pasture	Pasture	Rice	Rice
1	2015	3	Rice	Soybean	Rice	Pasture	Pasture	Rice	Rice	Pasture
1	2016	4	Rice	Rice	Soybean	Pasture	Rice	Rice	Pasture	Pasture
1	2017	5	Rice	Soybean	Rice	Rice	Rice	Pasture	Pasture	Pasture
1	2018	6	Rice	Rice	Soybean	Rice	Pasture	Pasture	Pasture	Rice
1	2019	7	Rice	Soybean	Rice	Pasture	Pasture	Pasture	Rice	Rice
1	2020	8	Rice	Rice	Soybean	Pasture	Pasture	Rice	Rice	Pasture

Supplemental table S2. Mean aboveground residues (without grain) and belowground biomass, total residues (aboveground residues + belowground biomass), and total biomass production (Mg ha^{-1}) ± standard deviation in three rice-based systems disaggregated by rotation component across the study period.

Treatment	Aboveground residues				Belowground biomass				Total residues[a]				Total biomass			
	Mg ha^{-1}															
Rice-pasture	**7.07**	**±**	**0.78**	**b**	**2.72**	**±**	**0.38**	**a**	**9.79**	**±**	**1.16**	**b**	**12.98**	**±**	**1.25**	**c**
Rice1	7.95	±	2.03		2.34	±	0.29		10.28	±	1.67		18.69	±	2.32	
Ryegrass	1.39	±	2.06		0.17	±	0.09		1.56	±	0.83		1.56	±	0.83	
Rice2	7.26	±	0.75		2.12	±	0.29		9.38	±	1.80		16.97	±	2.35	
Pasture yr. 1	6.70	±	2.00		2.93	±	0.98		9.63	±	2.95		9.63	±	2.95	
Pasture yr. 2	6.49	±	1.65		3.25	±	0.83		9.74	±	2.49		9.74	±	2.49	
Pasture yr. 3	5.52	±	1.84		2.76	±	0.92		8.29	±	2.76		8.29	±	2.76	
Rice-soybean	**6.97**	**±**	**1.21**	**b**	**1.91**	**±**	**0.29**	**c**	**8.88**	**±**	**1.45**	**c**	**14.29**	**±**	**2.01**	**b**
Rice	8.07	±	1.04		2.38	±	0.19		10.45	±	1.15		19.03	±	1.55	
Ryegrass	1.42	±	0.82		0.18	±	0.10		1.60	±	0.90		1.60	±	0.90	
Soybean	3.36	±	1.61		1.08	±	0.38		4.44	±	1.55		6.68	±	2.34	
T. alexandrinum	1.09	±	1.02		0.18	±	0.17		1.27	±	1.16		1.27	±	1.16	
Rice-cover crop	**8.81**	**±**	**1.81**	**a**	**2.43**	**±**	**0.35**	**b**	**11.24**	**±**	**2.15**	**a**	**19.27**	**±**	**2.70**	**a**
Rice	7.54	±	1.81		2.22	±	0.29		9.77	±	1.63		17.80	±	2.30	
T. alexandrinum	1.27	±	1.24		0.21	±	0.21		1.48	±	1.41		1.48	±	1.41	

Chapter 2: 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.

*Author for correspondence: Ignacio Macedo (imacedo@ucdavis.edu), Graduate Student Researcher, Department of Plant Sciences, University of California, One Shields Ave, Davis, CA 95616.

Published in *Agricultural Systems,* vol. 202, p. 103488.

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.

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 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).

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.

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 returns 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.

Keywords: multidimensionality; sustainability; paddy soils; crop-livestock; resilience; carbon footprint

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 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 greenhouse gases (GHG) emissions 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 soil organic carbon (SOC) can 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., 2021).

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). Sandford 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., 2021; 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 or higher frequency of rice (*Glycine max* (L.) Merr.) 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.

METHODS

Study site

The LTE was initiated in 2012 in Treinta y Tres, Uruguay (33^{o}6´23´´ S, 54^{o}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 ^{o}C and 11.5 ± 0.82 ^{o}C during summer and winter, respectively. Total annual rainfall at the site is 1360 ± 315 mm; annual total potential evapotranspiration is 1138 ± 177 mm.

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 (Figure 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).

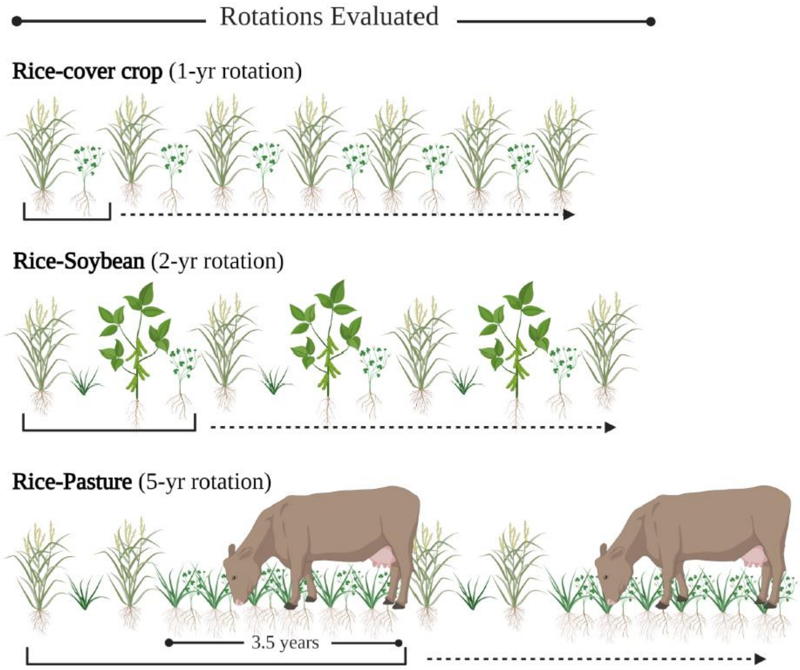

Figure 1. Rice-based rotations evaluated and sequence length for each crop during the 7-yr study period. Rice-cover crop: rice during spring-summer rotating with Egyptian clover winter cover crop. Rice-Soybean: rice and soybean (cash crops during spring-summer) in rotation with ryegrass and Egyptian 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.

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 (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.

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

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:

$$CH_4 = EF * t \qquad (1)$$

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.

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):

$$I_{ijkl} = \frac{(Y_{ijkl} - Y_{jmin})}{(Y_{jmax} - Y_{jmin})} \quad (2)$$

$$I_{ijkl} = \frac{(Y_{jmax} - Y_{ijkl})}{(Y_{jmax} - Y_{jmin})} \quad (3)$$

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 0-1, 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 (Figure 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.

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).

RESULTS

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 ($p < .05$).

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 (Figure 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.

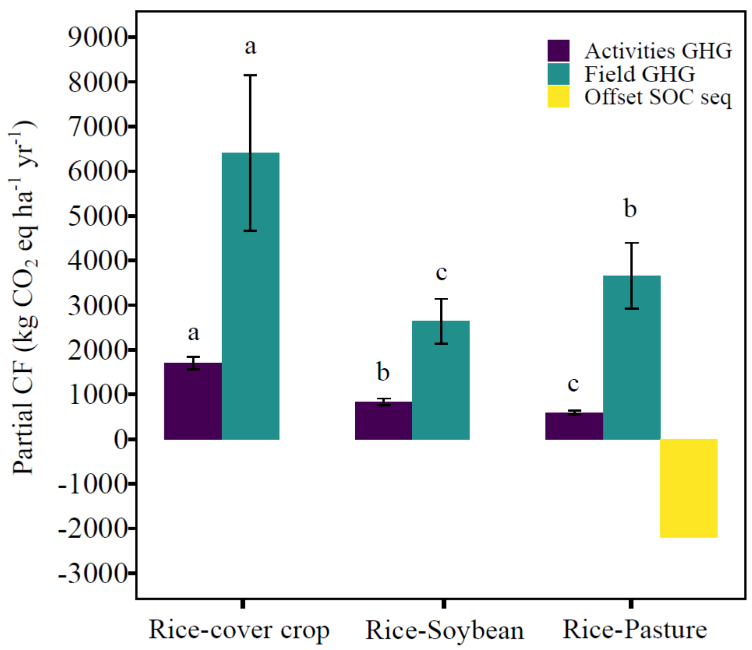

Figure 2. Partial carbon footprint (CF) (kg CO_2 eq ha^{-1} $year^{-1}$) from field management activities (fuel consumption and embodied energy in external inputs) and field GHG emissions (estimated CH_4 and N_2O emissions) in three rice-based systems. The yellow bar represents soil organic sequestration 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 ($p < .05$).

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 (Figure 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 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}).

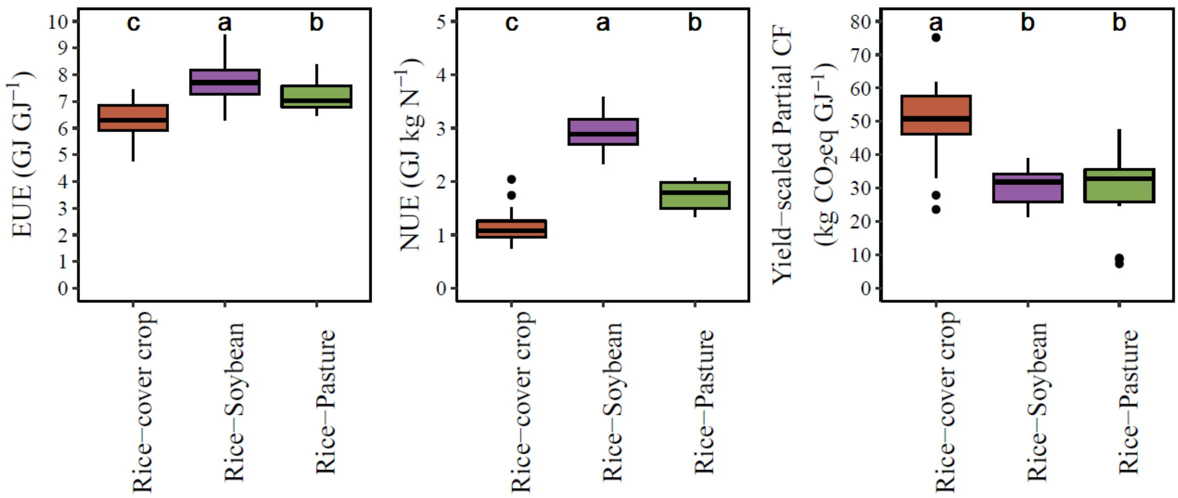

Figure 3. Boxplots for energy use efficiency (EUE) (GJ GJ^{-1}), nitrogen use efficiency (NUE) (GJ kg N^{-1}), and yield-scaled partial carbon footprint (kg CO_2 eq GJ^{-1}) in three rice-based systems. Different letters indicate differences between treatments ($p < .05$).

Economics

The intensified systems showed an increase in both, costs and income compared with rice-pasture rotation (Figure 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}).

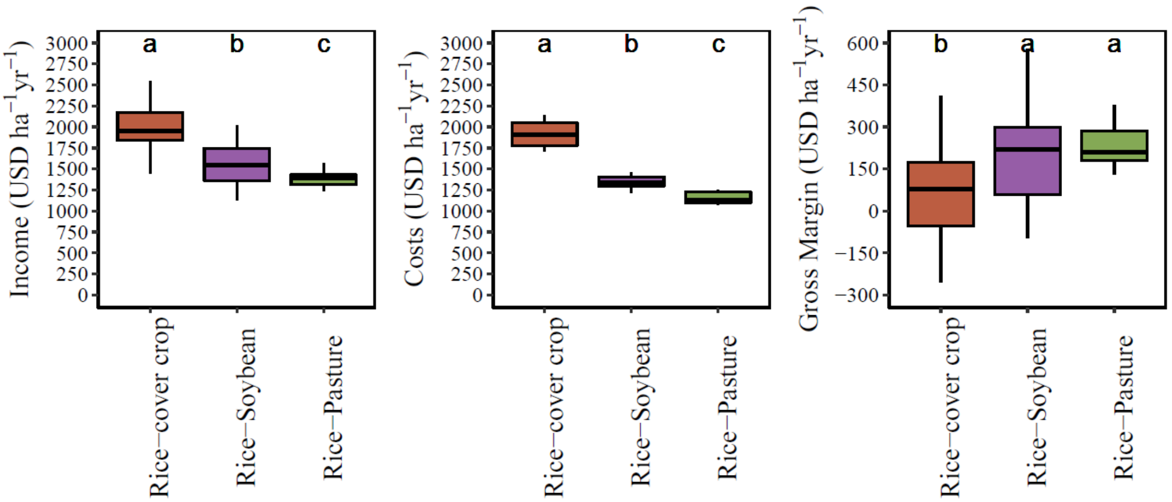

Figure 4. Boxplots for income, costs, and gross margin (USD ha^{-1} yr^{-1}GJ GJ^{-1}) in three rice-based systems. Different letters indicate differences between treatments ($p < .05$).

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 (Figure 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 (Figure 5 B).

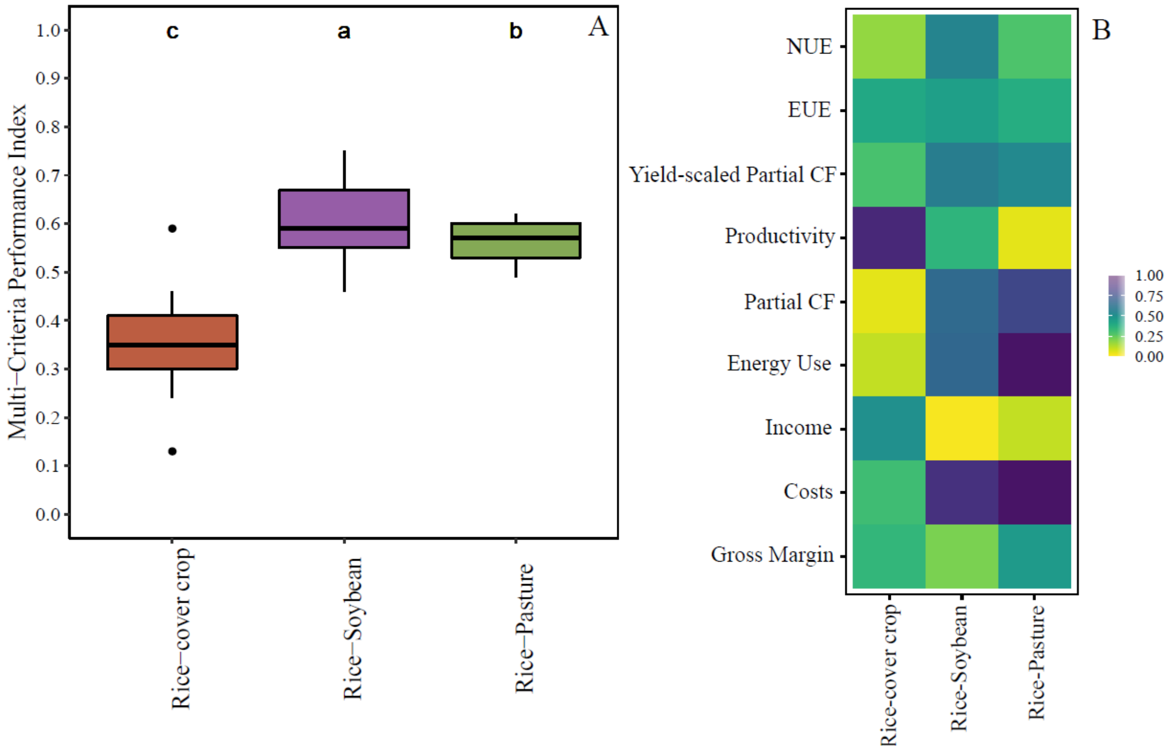

Figure 5. Boxplots for multi-criteria performance index (0-1) (A) and heatmap plot for normalized variables included in the multi-criteria performance index (0-1) (the closer to 1 the better) (B) in three rice-based systems. Different letters indicate differences between treatments ($p < .05$).

The sensitivity of the multi-criteria performance index was similar between rice-based rotations when one indicator at a time was excluded from calculations (Figure 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 crop had a similar positive slope but different intercepts (Figure 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 0.5-0.6), 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).

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

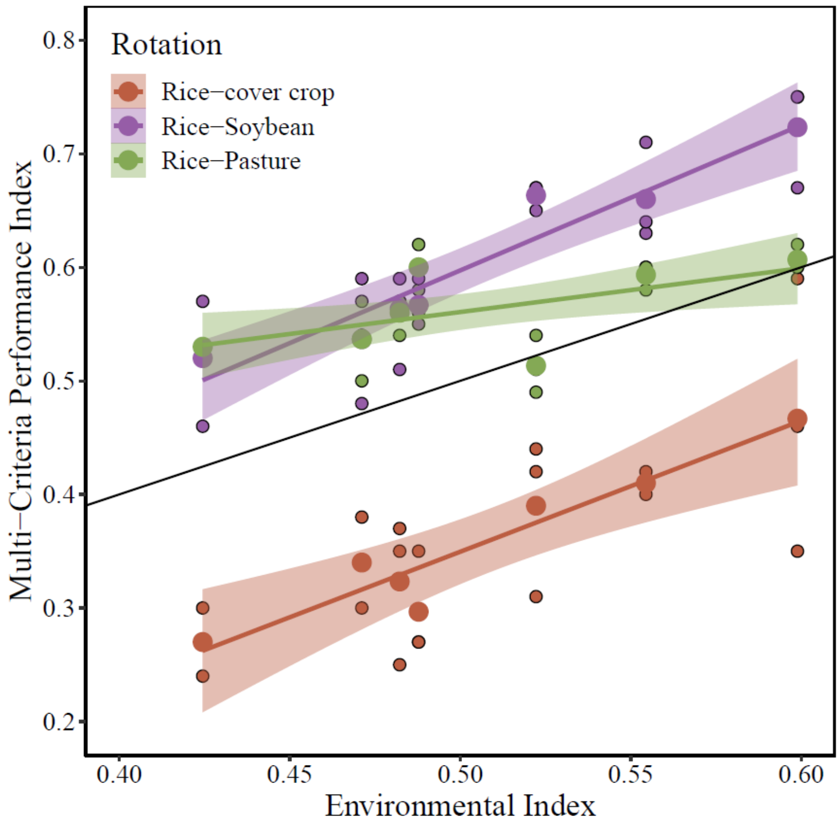

Figure 6. Stability of three rice-based systems as determined by the slope of FW regressions for multi-criteria performance index against environmental index. Black line illustrates the 1:1 line, big circles indicates the mean across the three observations and small circles represent individual observations.

DISCUSSION

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 because it not only had higher field GHG emissions but also embodied energy in inputs (Figure 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, Figure 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% (Figure 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 (Figure 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.

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 (Figure 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., 2021) 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.

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, 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.

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.

ACKNOWLEDGEMENTS

We thank the National Institute of Agricultural Research of Uruguay and the National Research and Innovation Agency (ANII-Uy, FSA_PP_2018_1_148336) for partly supporting this research. We are grateful for the invaluable help provided by Irma Furtado, Matias Oxley and Adan Rodriguez in the laboratory and field work. We thank the Department of Plant Sciences, UC Davis, and Fulbright Uruguay-ANII for supporting I.Macedo with graduate fellowships.

REFERENCES

Assefa, Y., Yadav, S., Mondal, M.K., Bhattacharya, J., Parvin, R., Sarker, S.R., Rahman, M., Sutradhar, A., Prasad, P.V.V., Bhandari, H., Shew, A.M., Jagadish, S.V.K., 2021. Crop diversification in rice-based systems in the polders of Bangladesh: Yield stability, profitability, and associated risk. Agric. Syst. 187. https://doi.org/10.1016/j.agsy.2020.102986

Basso, B., Jones, J.W., Antle, J., Martinez-Feria, R.A., Verma, B., 2021. Enabling circularity in grain production systems with novel technologies and policy. Agric. Syst. 193, 103244. https://doi.org/10.1016/j.agsy.2021.103244

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using {lme4}. J. Stat. Softw. 67, 1–48. https://doi.org/10.18637/jss.v067.i01

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future köppen-geiger climate classification maps at 1-km resolution. Sci. Data 5, 1–12. https://doi.org/10.1038/sdata.2018.214

Bell, L.W., Moore, A.D., Thomas, D.T., 2021. Diversified crop-livestock farms are risk-efficient in the face of price and production variability. Agric. Syst. 189, 103050. https://doi.org/10.1016/j.agsy.2021.103050

Brewer, K.M., Gaudin, A.C.M., 2020. Potential of crop-livestock integration to enhance carbon sequestration and agroecosystem functioning in semi-arid croplands. Soil Biol. Biochem. 149. https://doi.org/10.1016/j.soilbio.2020.107936

Carvalho, P.C. de F., Savian, J.V., Della Chiesa, T., De Souza Filho, W., Terra, J.A., Pinto, P., Posselt Martins, A., Villarino, S., Da Trindade, J.K., De Albuquerque Nunes, P.A., Piñeiro, G.,

2021. Land-use intensification trends in the Rio de la Plata Region of South America: toward specialization or recoupling crop and livestock production. Front. Agric. Sci. Eng. 8, 97. https://doi.org/10.15302/J-FASE-2020380

Chivenge, P., Angeles, O., Hadi, B., Acuin, C., Connor, M., Stuart, A., Puskur, R., Johnson-Beebout, S., 2020. Ecosystem services in paddy rice systems, in: The Role of Ecosystem Services in Sustainable Food Systems. Elsevier, pp. 181–201. https://doi.org/10.1016/B978-0-12-816436-5.00010-X

de Albuquerque Nunes, P.A., Laca, E.A., de Faccio Carvalho, P.C., Li, M., de Souza Filho, W., Robinson Kunrath, T., Posselt Martins, A., Gaudin, A., 2021. Livestock integration into soybean systems improves long-term system stability and profits without compromising crop yields. Sci. Rep. 11, 1–14. https://doi.org/10.1038/s41598-021-81270-z

Devkota, K.P., Pasuquin, E., Elmido-Mabilangan, A., Dikitanan, R., Singleton, G.R., Stuart, A.M., Vithoonjit, D., Vidiyangkura, L., Pustika, A.B., Afriani, R., Listyowati, C.L., Keerthisena, R.S.K., Kieu, N.T., Malabayabas, A.J., Hu, R., Pan, J., Beebout, S.E.J., 2019. Economic and environmental indicators of sustainable rice cultivation: A comparison across intensive irrigated rice cropping systems in six Asian countries. Ecol. Indic. 105, 199–214. https://doi.org/10.1016/j.ecolind.2019.05.029

DIEA, 2018. Anuario Estadístico Agropecuario 2018 [WWW Document]. Minist. Agric. Ganad. y Pesca, Editor. Hemisferio Sur. URL https://descargas.mgap.gub.uy/DIEA/Anuarios/Anuario2018/ Anuario_2018.pdf (accessed 10.10.19).

Emran, S.-A., Krupnik, T.J., Aravindakshan, S., Kumar, V., Pittelkow, C.M., 2021. Factors contributing to farm-level productivity and household income generation in coastal Bangladesh's rice-based farming systems. PLoS One 16, e0256694. https://doi.org/10.1371/journal.pone.0256694

Finlay, K.W., Wilkinson, G.N., 1963. The analysis of adaptation in a plant-breeding programme. Aust. J. Agric. Res. 14, 742–754.

Franzluebbers, A.J., 2007. Integrated crop-livestock systems in the southeastern USA. Agron. J. 99, 361–372. https://doi.org/10.2134/agronj2006.0076

Franzluebbers, A.J., Sawchik, J., Taboada, M.A., 2014. Agronomic and environmental impacts of pasture-crop rotations in temperate North and South America. Agric. Ecosyst. Environ. 190, 18–26. https://doi.org/10.1016/j.agee.2013.09.017

Garrett, R.D., Niles, M.T., Gil, J.D.B., Gaudin, A., Chaplin-Kramer, R., Assmann, A., Assmann, T.S., Brewer, K., de Faccio Carvalho, P.C., Cortner, O., Dynes, R., Garbach, K., Kebreab, E., Mueller, N., Peterson, C., Reis, J.C., Snow, V., Valentim, J., 2017. Social and ecological analysis of commercial integrated crop livestock systems: Current knowledge and remaining uncertainty. Agric. Syst. 155, 136–146. https://doi.org/10.1016/j.agsy.2017.05.003

Harkness, C., Areal, F.J., Semenov, M.A., Senapati, N., Shield, I.F., Bishop, J., 2021. Stability of farm income : The role of agricultural diversity and agri-environment scheme payments. Agric. Syst. 187, 103009. https://doi.org/10.1016/j.agsy.2020.103009

Hassink, J., Whitmore, A.P., 1997. A Model of the Physical Protection of Organic Matter in Soils. Soil Sci. Soc. Am. J. 61, 131–139. https://doi.org/10.2136/sssaj1997.03615995006100010020x

Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous Inference in General Parametric Models. Biometrical J. 50, 346–363.

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, in: Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (Eds.), . IPCC, Switzerland.

Jaurena, M., Durante, M., Devincenzi, T., Savian, J. V., Bendersky, D., Moojen, F.G., Pereira, M., Soca, P., Quadros, F.L.F., Pizzio, R., Nabinger, C., Carvalho, P.C.F., Lattanzi, F.A., 2021. Native Grasslands at the Core: A New Paradigm of Intensification for the Campos of Southern South America to Increase Economic and Environmental Sustainability. Front. Sustain. Food Syst. 5. https://doi.org/10.3389/fsufs.2021.547834

Kumar, V., Jat, H.S., Sharma, P.C., Balwinder-Singh, Gathala, M.K., Malik, R.K., Kamboj, B.R., Yadav, A.K., Ladha, J.K., Raman, A., Sharma, D.K., McDonald, A., 2018. Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. Agric. Ecosyst. Environ. 252, 132–147. https://doi.org/10.1016/j.agee.2017.10.006

Li, M., Peterson, C.A., Tautges, N.E., Scow, K.M., Gaudin, A.C.M., 2019. Yields and resilience outcomes of organic, cover crop, and conventional practices in a Mediterranean climate. Sci. Rep. 9, 1–11. https://doi.org/10.1038/s41598-019-48747-4

Lin, B.B., 2011. Resilience in Agriculture through Crop Diversification : Adaptive Management for Environmental Change 61, 183–193. https://doi.org/10.1525/bio.2011.61.3.4

Linquist, B., Van Groenigen, K.J., Adviento-Borbe, M.A., Pittelkow, C., Van Kessel, C., 2012. An agronomic assessment of greenhouse gas emissions from major cereal crops. Glob. Chang. Biol. 18, 194–209. https://doi.org/10.1111/j.1365-2486.2011.02502.x

Macedo, I., Roel, A., Ayala, W., Pravia, M.V., Terra, J.A., Pittelkow, C.M., 2022. Irrigated rice rotations affect yield and soil organic carbon sequestration in temperate South America. Agron. J. 1–15. https://doi.org/10.1002/agj2.20964

Macedo, I., Terra, J.A., Siri-Prieto, G., Velazco, J.I., Carrasco-Letelier, L., 2021. Rice-pasture agroecosystem intensification affects energy use efficiency. J. Clean. Prod. 278, 123771. https://doi.org/10.1016/j.jclepro.2020.123771

Manning, P., Van Der Plas, F., Soliveres, S., Allan, E., Maestre, F.T., Mace, G., Whittingham, M.J., Fischer, M., 2018. Redefining ecosystem multifunctionality. Nat. Ecol. Evol. 2, 427–436. https://doi.org/10.1038/s41559-017-0461-7

McAuliffe, G.A., Takahashi, T., Lee, M.R.F., 2019. Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-019-01679-7

Mutyasira, V., Hoag, D., Pendell, D., Manning, D.T., Berhe, M., 2018. Assessing the relative sustainability of smallholder farming systems in Ethiopian highlands. Agric. Syst. 167, 83–91. https://doi.org/10.1016/j.agsy.2018.08.006

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, H., Giovannini, E., 2005. Handbook on Constructing Composite Indicators: Methodology and User Guide, Organisation for Economic Co-operation and Development: Paris, France. OECD, Paris, France. https://doi.org/10.1787/9789264043466-en

Patterson, H.D., 1964. Theory of Cyclic Rotation Experiments. J. R. Stat. Soc. Ser. B 26, 1–36. https://doi.org/10.1111/j.2517-6161.1964.tb00535.x

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57. https://doi.org/10.1038/nature17174

Peterson, C.A., Eviner, V.T., Gaudin, A.C.M., 2018. Ways forward for resilience research in agroecosystems. Agric. Syst. 162, 19–27. https://doi.org/10.1016/j.agsy.2018.01.011

Peyraud, J.L., Taboada, M., Delaby, L., 2014. Integrated crop and livestock systems in Western Europe and South America: A review. Eur. J. Agron. 57, 31–42. https://doi.org/10.1016/j.eja.2014.02.005

Pittelkow, C.M., Zorrilla, G., Terra, J., Riccetto, S., Macedo, I., Bonilla, C., Roel, A., 2016. Sustainability of rice intensification in Uruguay from 1993 to 2013. Glob. Food Sec. 9, 10–18. https://doi.org/10.1016/j.gfs.2016.05.003

Poffenbarger, H., Artz, G., Dahlke, G., Edwards, W., Hanna, M., Russell, J., Sellers, H., Liebman, M., 2017. An economic analysis of integrated crop-livestock systems in Iowa, U.S.A. Agric. Syst. 157, 51–69. https://doi.org/10.1016/j.agsy.2017.07.001

Prechsl, U.E., Wittwer, R., Heijden, M.G.A. Van Der, Lüscher, G., Jeanneret, P., Nemecek, T., 2017. Assessing the environmental impacts of cropping systems and cover crops : Life cycle assessment of FAST , a long-term arable farming fi eld experiment. Agric. Syst. 157, 39–50. https://doi.org/10.1016/j.agsy.2017.06.011

Quilty, J.R., Mckinley, J., Pede, V.O., Buresh, R.J., Correa, T.Q., Sandro, J.M., 2014. Field Crops Research Energy efficiency of rice production in farmers ’ fields and intensively cropped research fields in the Philippines. F. Crop. Res. 168, 8–18. https://doi.org/10.1016/j.fcr.2014.08.001

R Core Team, 2021. R: A Language and Environment for Statistical Computing.

Reig Martinez, E., Gomez Limon, J.A., Picazo Tadeo, A.J., 2011. Ranking farms with a composite indicator of sustainability. Agric. Econ. 42, 561–575. https://doi.org/10.1111/j.1574-0862.2011.00536.x

Riccetto, S., Davis, A.S., Guan, K., Pittelkow, C.M., 2020. Integrated assessment of crop production and resource use efficiency indicators for the U.S. Corn Belt. Glob. Food Sec. 24, 100339. https://doi.org/10.1016/j.gfs.2019.100339

Saito, K., Six, J., Komatsu, S., Snapp, S., Rosenstock, T., Arouna, A., Cole, S., Taulya, G., Vanlauwe, B., 2021. Agronomic gain: Definition, approach, and application. F. Crop. Res. 270, 108193. https://doi.org/10.1016/j.fcr.2021.108193

Sanford, G.R., Jackson, R.D., Booth, E.G., Hedtcke, J.L., Picasso, V., 2021. Perenniality and diversity drive output stability and resilience in a 26-year cropping systems experiment. F. Crop. Res. 263, 108071. https://doi.org/10.1016/j.fcr.2021.108071

Selene, L., Bergier, I., Ortega, E., Moraes, A., Bayma-silva, G., Ribeiro, M., 2015. Soil improvement and mitigation of greenhouse gas emissions for integrated crop – livestock systems : Case study assessment in the Pantanal savanna highland , Brazil. Agric. Syst. 137, 206–219. https://doi.org/10.1016/j.agsy.2014.11.004

Song, X.P., Hansen, M.C., Potapov, P., Adusei, B., Pickering, J., Adami, M., Lima, A., Zalles, V., Stehman, S. V., Di Bella, C.M., Conde, M.C., Copati, E.J., Fernandes, L.B., Hernandez-Serna, A., Jantz, S.M., Pickens, A.H., Turubanova, S., Tyukavina, A., 2021. Massive soybean expansion in South America since 2000 and implications for conservation. Nat. Sustain. 4, 784–792. https://doi.org/10.1038/s41893-021-00729-z

Stuart, A.M., Devkota, K.P., Sato, T., Pame, A.R.P., Balingbing, C., My Phung, N.T., Kieu, N.T., Hieu, P.T.M., Long, T.H., Beebout, S., Singleton, G.R., 2018. On-farm assessment of different rice crop management practices in the Mekong Delta, Vietnam, using sustainability performance indicators. F. Crop. Res. 229, 103–114. https://doi.org/10.1016/j.fcr.2018.10.001

Theisen, G., Silva, J.J.C., Silva, J.S., Andres, A., Anten, N.P.R., Bastiaans, L., 2017. The birth of a new cropping system: towards sustainability in the sub-tropical lowland agriculture. F. Crop. Res. 212, 82–94.

Thompson, L.R., Rowntree, J.E., 2020. INVITED REVIEW: Methane sources, quantification, and mitigation in grazing beef systems. Appl. Anim. Sci. 36, 556–573. https://doi.org/10.15232/aas.2019-01951

Tseng, M.C., Roel, Á., Macedo, I., Marella, M., Terra, J.A., Pittelkow, C.M., 2021a. Synergies and tradeoffs among yield, resource use efficiency, and environmental footprint indicators in rice systems. Curr. Res. Environ. Sustain. 3, 100070. https://doi.org/10.1016/j.crsust.2021.100070

Tseng, M.C., Roel, A., Macedo, I., Marella, M., Terra, J.A., Zorrilla, G., Pittelkow, C.M., 2021b. Field-level Factors for Closing Yield Gaps in High-Yielding Rice Systems of Uruguay. F. Crop. Res. 264. https://doi.org/10.1016/j.fcr.2021.108097

Vogel, E., Martinelli, G., Artuzo, F.D., 2021. Environmental and economic performance of paddy field-based crop-livestock systems in Southern Brazil. Agric. Syst. 190, 103109. https://doi.org/10.1016/j.agsy.2021.103109

White, M., Heros, E., Graterol, E., Chirinda, N., Pittelkow, C.M., 2020. Balancing Economic and Environmental Performance for Small-Scale Rice Farmers in Peru. Front. Sustain. Food Syst. 4, 1–14. https://doi.org/10.3389/fsufs.2020.564418

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wittwer, R.A., Bender, S.F., Hartman, K., Hydbom, S., Lima, R.A.A., Loaiza, V., Nemecek, T., Oehl, F., Olsson, P.A., Petchey, O., Prechsl, U.E., Schlaeppi, K., Scholten, T., Seitz, S., Six, J., Heijden, M.G.A. Van Der, 2021. Organic and conservation agriculture promote ecosystem multifunctionality. Sci. Adv. 7, 1–13. https://doi.org/10.1126/sciadv.abg6995

Zorrilla, G., 2015. Uruguayan rice: the secrets of a success story. Rice Today 14, 18–19.

SUPPLEMENTAL MAERIAL

Supplemental table S1. One replicate of the long-term experiment.

			Rotations							
			Rice-cover crop	**Rice-soybean**		**Rice-pasture**				
			Plots							
			1	2	3	4	5	6	7	8
Block	Calendar year	Year								
1	2012	0	Rice	Rice	Soybean	Rice	Rice	Pasture	Pasture	Pasture
1	2013	1	Rice	Soybean	Rice	Rice	Pasture	Pasture	Pasture	Rice
1	2014	2	Rice	Rice	Soybean	Pasture	Pasture	Pasture	Rice	Rice
1	2015	3	Rice	Soybean	Rice	Pasture	Pasture	Rice	Rice	Pasture
1	2016	4	Rice	Rice	Soybean	Pasture	Rice	Rice	Pasture	Pasture
1	2017	5	Rice	Soybean	Rice	Rice	Rice	Pasture	Pasture	Pasture
1	2018	6	Rice	Rice	Soybean	Rice	Pasture	Pasture	Pasture	Rice
1	2019	7	Rice	Soybean	Rice	Pasture	Pasture	Pasture	Rice	Rice

Table S2. Energy conversion factors per unit of input/output and estimated CO_2 equivalents (CO_2e) per unit of input used in the analysis. Adapted from Pittelkow et al. (2016)

Input/Output	Unit	Energy		CO2	
		MJ unit^{-1}	Ref	CO_2e unit^{-1}	Ref
Diesel	L	47.7	a	3.2	b
Electricity	kWh	9.4	b	0.6	b
Nitrogen	kg N	63.5	a	5	c
Phosphorus	kg P_2O_5	13.95	a	1.77	c
Potassium	kg k_2O	6.69	a	0.69	c
Herbicide	kg	303.8	a	20.96	d
Insecticide	kg	418.4	a	28.87	d
Fungicide	kg	115	a	7.935	d
Seeds				0.7	b
Seed forage grass	kg	36.1	f		
Seed forage legume	kg	17.2	g		
Soybean Grain	kg	23.5	e	Not applicable	-
Rice Grain	kg	17.6	e	Not applicable	-
Beef	kg	9.3	h	Not applicable	-

(a) Quilty, J.R., McKinley, J., Pede, V.O., Buresh, R.J., Correa, T.Q., Sandro, J.M., 2014. Energy efficiency of rice production in farmers' fields and intensively cropped research fields in the Philippines. Field Crops Res. 168, 8-18.

(b) Grassini, P., Cassman, K.G., 2012. High-yield maize with large net energy yield and small global warming intensity. Proc. Natl. Acad. Sci U.S.A. 109, 1074–1079.

(c) Kool, A., Marinussen, M., Blonk, H., 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: GHG Emissions of N, P and K fertilizer production. Blonk Consultants, Gouda, the Netherlands.

(d) Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the Greenhouse Gas Emissions from Agricultural Pesticide Manufacture and Use. Cranfield University, 20pp

(e) Macedo I, Terra J A, Siri-Prieto G, Velazco J I, Carrasco-Letelier L. Rice-pasture agroecosystem intensification affects energy use efficiency. Journal of Cleaner Production, 2021, 278: 123771.

(f) Fuksa, P., Hakl, J., Brant, V., 2013. Energy balance of catch crops production. Zem-dirbyste-Agriculture 100 (4), 355e362.

(g) Muhammad, D., Misri, B., El-Nahrawy, M., Khan, S., Serkan, A., 2014. Egyptian Clover (Trifolium Alexandrinum); King of Forage Crops. Regional 0ffice for the Near East and North Africa. Food and Agriculture Organization of the United Nations, Cairo. URL. http://www.fao.org/3/a-i3500e.pdf.

(h) Restle, J., Cerd?otes, L., Vaz, F.N., Brondani, I.L., 2001. Carcass and meat characteristics of charolais and 3/4 charoles 1/4 nellore heifers, finished in feedlot (Caracter- ísticas de carcaça e da carne de novilhas Charol^es e 3/4 Charol^es 1/4 Nelore, terminadas em confinamento). Rev. Bras. Zootec. 30 (3), 1065e1075

Table S3. Fuel/energy consumption of the management practices activities.

Activity	Unit	Consumption*
Planting	L ha^{-1} of Diesel	8
Planting overcast	L ha^{-1} of Diesel	1
Spray (Pesticides)	L ha^{-1} of Diesel	1
Fertilization	L ha^{-1} of Diesel	1
Rice Harvest	L ha^{-1} of Diesel	50
Leveling (levis)	L ha^{-1} of Diesel	2
Soybean Harvest	L ha^{-1} of Diesel	15
Irrigation	kWh m^{-3}	0.0616

* Diesel consumption was obtained from the Camara Uruguaya de Servicios Agropecuarios.

http://www.cusa.org.uy/cusa/precios_servicios_agricolas

Supplemental Material S1. Equations from IPCC for Field Emissions used for partial carbon footprint.

Methane from rice

The following images are screenshots from IPCC guidelines, V4_05_Ch5_Cropland, V4_10_Ch10_Livestock and V4_11_Ch11_N2O&CO2.

EQUATION 5.2
ADJUSTED DAILY EMISSION FACTOR

$$EF_i = EF_c \bullet SF_w \bullet SF_p \bullet SF_o \bullet SF_{s,r}$$

Where:

EF_i = adjusted daily emission factor for a particular harvested area

EF_c = baseline emission factor for continuously flooded fields without organic amendments

SF_w = scaling factor to account for the differences in water regime during the cultivation period (from Table 5.12)

SF_p = scaling factor to account for the differences in water regime in the pre-season before the cultivation period (from Table 5.13)

SF_o = scaling factor should vary for both type and amount of organic amendment applied (from Equation 5.3 and Table 5.14)

$SF_{s,r}$ = scaling factor for soil type, rice cultivar, etc., if available

EQUATION 5.3
ADJUSTED CH_4 EMISSION SCALING FACTORS FOR ORGANIC AMENDMENTS

$$SF_o = \left(1 + \sum_i ROA_i \bullet CFOA_i\right)^{0.59}$$

Where:

SF_o = scaling factor for both type and amount of organic amendment applied

ROA_i = application rate of organic amendment i, in dry weight for straw and fresh weight for others, tonne ha^{-1}

$CFOA_i$ = conversion factor for organic amendment i (in terms of its relative effect with respect to straw applied shortly before cultivation) as shown in Table 5.14.

Methane from enteric fermentation

EQUATION 10.21
CH_4 EMISSION FACTORS FOR ENTERIC FERMENTATION FROM A LIVESTOCK CATEGORY

$$EF = \left[\frac{GE \bullet \left(\frac{Y_m}{100}\right) \bullet 365}{55.65}\right]$$

Where:

EF = emission factor, kg CH_4 $head^{-1}$ yr^{-1}

GE = gross energy intake, MJ $head^{-1}$ day^{-1}

Y_m = methane conversion factor, per cent of gross energy in feed converted to methane

The factor 55.65 (MJ/kg CH_4) is the energy content of methane

Direct N_2O emissions

EQUATION 11.1
DIRECT N_2O EMISSIONS FROM MANAGED SOILS (TIER 1)

$$N_2O_{Direct}\text{–}N = N_2O\text{–}N_{N\,inputs} + N_2O\text{–}N_{OS} + N_2O\text{–}N_{PRP}$$

Where:

$$N_2O\text{–}N_{N\,inputs} = \left[\begin{array}{l}\left[\left(F_{SN} + F_{ON} + F_{CR} + F_{SOM}\right) \bullet EF_1\right] + \\ \left[\left(F_{SN} + F_{ON} + F_{CR} + F_{SOM}\right)_{FR} \bullet EF_{1FR}\right]\end{array}\right]$$

$$N_2O\text{–}N_{OS} = \left[\begin{array}{l}\left(F_{OS,CG,Temp} \bullet EF_{2CG,Temp}\right) + \left(F_{OS,CG,Trop} \bullet EF_{2CG,Trop}\right) + \\ \left(F_{OS,F,Temp,NR} \bullet EF_{2F,Temp,NR}\right) + \left(F_{OS,F,Temp,NP} \bullet EF_{2F,Temp,NP}\right) + \\ \left(F_{OS,F,Trop} \bullet EF_{2F,Trop}\right)\end{array}\right]$$

$$N_2O\text{–}N_{PRP} = \left[\left(F_{PRP,CPP} \bullet EF_{3PRP,CPP}\right) + \left(F_{PRP,SO} \bullet EF_{3PRP,SO}\right)\right]$$

Where:

N_2O_{Direct}–N = annual direct N_2O–N emissions produced from managed soils, kg N_2O–N yr^{-1}

N_2O–$N_{N\,inputs}$ = annual direct N_2O–N emissions from N inputs to managed soils, kg N_2O–N yr^{-1}

N_2O–N_{OS} = annual direct N_2O–N emissions from managed organic soils, kg N_2O–N yr^{-1}

N_2O–N_{PRP} = annual direct N_2O–N emissions from urine and dung inputs to grazed soils, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr^{-1}

F_{ON} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (Note: If including sewage sludge, cross-check with Waste Sector to ensure there is no double counting of N_2O emissions from the N in sewage sludge), kg N yr^{-1}

F_{CR} = annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N yr^{-1}

F_{SOM} = annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N yr^{-1}

F_{OS} = annual area of managed/drained organic soils, ha (Note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient Rich, and Nutrient Poor, respectively)

F_{PRP}= annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr^{-1} (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)

EQUATION 11.5
N IN URINE AND DUNG DEPOSITED BY GRAZING ANIMALS ON PASTURE, RANGE AND PADDOCK
(TIER 1)

$$F_{PRP} = \sum_{T} \left[\left(N_{(T)} \bullet Nex_{(T)} \right) \bullet MS_{(T,PRP)} \right]$$

Where:

F_{PRP} = annual amount of urine and dung N deposited on pasture, range, paddock and by grazing animals, kg N yr^{-1}

$N_{(T)}$ = number of head of livestock species/category T in the country (see Chapter 10, Section 10.2)

$Nex_{(T)}$ = annual average N excretion per head of species/category T in the country, kg N $animal^{-1}$ yr^{-1} (see Chapter 10, Section 10.5)

$MS_{(T,PRP)}$ = fraction of total annual N excretion for each livestock species/category T that is deposited on pasture, range and paddock[12] (see Chapter 10, Section 10.5)

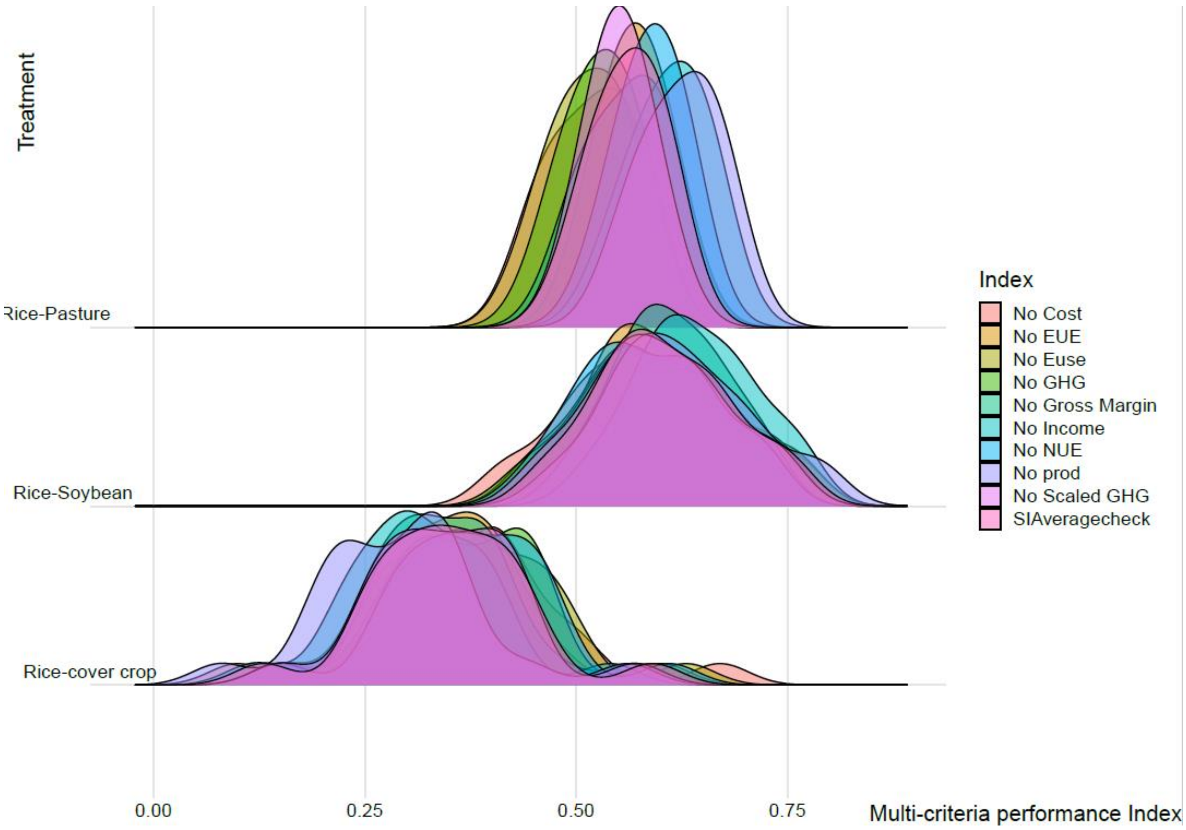

Figure S1. Density plots for multi-criteria performance index in three rice-based systems for 9 different indices leaving one indicator out at a time and the 1 with all the indicators in three rice-based systems.

Treatment	Range	r	CV (%)	r	Temporal Variance	r	FW slope	r	Overall rank
	Productivity GJ ha-1 yr-1								
Rice-Pasture	19.19	1	8.15	1	532.67	1	0.45	1	1.0
Rice-Soybean	57.76	2	11.74	3	3002.21	2	1.20	2	2.3
Rice-cover crop	64.58	3	11.18	2	3920.60	3	1.35	3	2.8
	Partial CF (kg CO2eq ha-1 yr-1)								
Rice-Pasture	2695.60	2	37.15	3	10609649.00	2	0.64	2	2.3
Rice-Soybean	1996.06	1	15.58	1	5312665.00	1	0.48	1	1.0
Rice-cover crop	6084.44	3	23.02	2	68922252.00	3	1.88	3	2.8
	Energy Use (GJ ha-1yr-1)								
Rice-Pasture	1367.46	1	5.98	2	6153250.00	1	0.49	1	1.3
Rice-Soybean	1965.77	2	4.69	1	9981726.00	2	0.72	2	1.8
Rice-cover crop	5391.73	3	6.57	3	58116998.00	3	1.79	3	3.0
	Income (USD ha-1yr-1)								
Rice-Pasture	337.81	1	6.70	1	128467.00	1	0.44	1	1.0
Rice-Soybean	890.71	2	16.58	3	1149762.00	3	1.34	3	2.8
Rice-cover crop	1091.40	3	13.25	2	921695.00	2	1.22	2	2.3
	Costs (USD ha-1yr-1)								
Rice-Pasture	185.08	1	5.69	2	86473.00	1	0.71	2	1.5
Rice-Soybean	239.74	2	5.53	1	101341.00	2	0.70	1	1.5
Rice-cover crop	425.58	3	7.49	3	407108.00	3	1.60	3	3.0
	Gross Margin (USD ha-1yr-1)								
Rice-Pasture	246.75	1	30.54	1	56680.00	1	0.28	1	1.0
Rice-Soybean	677.12	3	96.27	2	619305.00	3	1.73	3	2.8

Rice-cover crop	665.83	2	216.62	3	198474.00	2	0.99	2	2.3
	Scaled-Partial CF (kg CO2eq GJ-1)								
Rice-Pasture	40.12	2	36.74	3	2222.70	2	1.09	2	2.3
Rice-Soybean	17.75	1	18.96	1	590.92	1	0.57	1	1.0
Rice-cover crop	51.53	3	23.41	2	2412.33	3	1.34	3	2.8
	EUE (GJ GJ-1)								
Rice-Pasture	1.89	1	7.41	1	5.01	1	0.74	1	1.0
Rice-Soybean	3.20	3	9.62	2	7.91	3	1.29	3	2.8
Rice-cover crop	2.66	2	10.97	3	5.27	2	0.97	2	2.3
	NUE (GJ kg N-1)								
Rice-Pasture	0.73	1	14.72	2	1.28	1	0.71	1	1.3
Rice-Soybean	1.26	2	11.42	1	1.76	3	1.07	2	2.0
Rice-cover crop	1.29	3	26.65	3	1.68	2	1.22	3	2.8

Table S4. Stability parameters for all indicators included in the multi-criteria performance index and overall rank for three rice-based rotation systems.

*r= rank of the parameters (range, CV, Temporal varienace and FW slope)

Chapter 3: Spatial Agronomy at Work: Geospatial Data Analysis in Uruguayan Farmers' Rice Fields.

Ignacio Macedo[a,b,*], Cameron M. Pittelkow[a] , José A. Terra[b], Jesús Castillo[b], Alvaro Roel[b]

[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

*Corresponding author at: Department of Plant Sciences, Univ. of California, Davis, CA, USA.

E-mail address: macedoyapor@gmail.com (I. Macedo).

ABSTRACT

While crop productivity is influenced by multiple factors, exploring the complex interactions in agricultural farmers' fields throughout different seasons could provide valuable insights. Unfortunately, this area remains largely unexplored, representing a significant missed opportunity. Despite growing investment in data analytics and technology, we are not aware of studies that have harnessed farmer records in a geospatial framework to identify yield-limiting factors across different regions in a country, while also testing for tradeoffs in environmental sustainability related to nitrogen (N) fertilizer use. Working in high-yielding rice systems of Uruguay, we conducted an exploratory geospatial data analysis using geographically weighted random forest models across 2042 fields representing 220,000 ha total (~55,000 ha yr^{-1}). Seeding date, variety, P rate, and K rate were the most important variables explaining variation in rice yield, with important differences between regions. Addressing these factors improved yield by 1.4-1.8 Mg ha^{-1} across regions. Equally important, addressing these factors did not increase the risk of environmental N losses or soil N mining, highlighting the potential for sustainable intensification by improving N use efficiency through spatial agronomy. This research presents a successful example of data sharing among industry and researchers to guide agronomy decisions that sustain or increase yield while minimizing negative environmental externalities with potential future implications on extension and regional research programs as well as a guide to orient investments in agricultural research. It also strengthens the call for bold new methods and partnerships to leverage the power of on-farm data which could have significant impacts on food security and environmental sustainability.

INTRODUCTION

Sustainable intensification calls for increasing yield on the current agricultural land base without negative impacts on soil and water resources and non-agricultural land ecosystems (Cassman & Grassini, 2020). Rice is one of the main crops globally, and the staple food for around approximately 50% of the global population and uses 21-25% of the nitrogen (N) fertilizer in the world (Chauhan et al., 2017), thus making it an important crop to investigate ways to increase productivity without negative environmental externalities. To increase crop productivity, it is critical to identify management practices explaining yield differences among the top and the average performer fields or farmers. For example, a study in soybean in the US showed differences of 1.5 Mg ha^{-1} (4 vs. 2.5 Mg ha^{-1} between top and average farmers) or more than 2 Mg ha^{-1} in irrigated rice in Uruguay (10 vs 8 Mg ha^{-1}) (Grassini et al., 2014; Tseng et al., 2021). In addition, N could be lost to the environment contributing to global warming or water pollution, which is why achieving proper nitrogen use efficiency in agricultural systems is essential (EU Nitrogen Expert Panel, 2015). Most research efforts have been conducted to identify generalized influential factors affecting yield (Silva et al., 2017b; Tseng et al., 2021). However, these factors could vary from farmer to farmer or place to place, making it essential to explore this variation.

Investments in agricultural technology has increased 80% annually since 2012 ($0.5 billion in 2012) (Sparapani, 2017). On the other hand, public funding for agricultural research and development has fallen in the last 20 years in the U.S (Service, 2022). Clearly, we cannot just do what we have historically done through field trials. We must be more strategic. Basic principles of agronomy are site specific, but current practices do not always reflect that - either doing research on station or on farm where possible to collaborate - not necessarily representative of region. Also does not reflect complexity of many decisions and nonlinear interactions. The reality is that farmers run ‘experiments’ generating data from season to season from different sources such as sensors, yield monitors, or field records. These data, combined with the advancements in data processing and relatively new computational capacities, have the potential to allow for greater exploration of data-driven agricultural decision-making (Kharel et al., 2020; Sinha & Dhanalakshmi, 2022). In other words, the information is there, and we can learn from it. The big question for global agriculture is the power of data analytics and what type of partnerships it takes for it to work in terms of data collection, analysis, and information sharing/recommendations. We are not aware of a case study illustrating its importance and different features that will make it successful.

Here, we present a successful example of data sharing among industry and researchers that could be replicated in other regions and crops to pursue sustainable intensification goals. We performed an exploratory geospatial data analysis using 2042 field observations, covering 55,000 ha annually from rice farmers in Uruguay across four seasons (from 2017 to 2020). We used machine learning and geospatial machine learning algorithms to explore the relative contribution and spatial variation of explanatory variables. The objective was to quantify the relative importance of soil and crop management features as well as the spatial variation of the feature importance on rice yield and ways to improve nitrogen use efficiency. In addition, we assessed yield gaps by comparing groups of the most important features with the top 20% yielding fields. We discussed and provided a tangible example of a farmers' data assessment with a geospatial framework in the field of agronomy. Our analysis allowed us to identify regions where some features were more important than others, which could help increase yield and reduce environmental impact with potential future implications on extension and regional research programs as well as a guide to orient investments in agriculture research.

RESULTS AND DISCUSSION

The main characteristic of rice production by region are presented in Table 1. The highest average rice yield across the 4 cropping seasons was obtained in the North region (9110 kg ha^{-1}), which was 6 and 1.5 % higher than the Central and East regions, respectively. The average field size was 36 and 22 ha smaller in the Central and North region, respectively compared to fields in the East (116 ha). The East, Central, and North regions account for 68, 12, and 20 % of the total annual rice area (54,048 ha). The most planted variety in the East region was Inia Merin, accounting for one-third of the fields, while in the Central and North regions was Inia Olimar, accounting for approximately half of the fields in both regions. Regarding fertilization management, the Central region applied 22 fewer N units than the North and East (93 kg ha^{-1}). Phosphorus fertilization was similar between regions (~43 kg ha^{-1}). The East region applied the highest rate (41 kg ha^{-1}) of K, 24 and 64 % higher than the Central and North regions, respectively. In addition, there were 9, 24, and 46% of the fields for the East, Central, and North regions, respectively that did not apply K fertilizers. The dominant time of the year for tillage was summer, fall-winter, and spring while the most common field history was sown pasture, rice, and rice for the East, Central, and North regions, respectively. The main soils were Argialbolls (silt loam), Natracuolls (loam), and Hapludert (clayey) for the East, Central, and North regions, respectively with average soil organic carbon contents of 2, 1.8 and 3.6%.

Even though a previous study reported a small yield gap (~20%) for Uruguay rice systems, farmers increased rice yield compared to the previous period (2012-2017) (Tseng et al., 2021). Yield increases averaged 500, 300, and 700 kg ha^{-1}, for the East, Central, and North region, respectively. These yield increases could be explained partially by the use of new cultivars such as INIA Merin, which have been reported to have greater yield potential than other varieties previously used in Uruguay (Perez de Vida et al., 2016). Another explanation could be related to fertilization management. First, the higher use of N in the East and North region but Central could be highlighting the higher increase in yield in these two regions (Tseng et al., 2021). Second, when comparing the K fertilization of the prior study (Tseng et al., 2021) and ours the East region increased K fertilization from 26 kg ha^{-1} to 41 kg ha^{-1} of K_2O and reduce the number of fields that did not apply K from 27 to 9%. The Central region did not increase K fertilization while the North did (from 18 to 25 kg ha^{-1} of K_2O). However, these two regions still have a high frequency of fields that did not apply K fertilizers which could be limiting rice yield. Finally, tillage timing may also explain some of the yield improvements. Tseng et al. (2021) reported that half of the fields were prepared during the same spring that rice was planted (East and Central regions), thus potentially delaying the planting date which is an important variable explaining yields (Roel et al., 2007; Tseng et al., 2021). A shift in our study was that most of the tillage operations were made either the previous summer or fall/winter which could allow for time optimization for other activities, such as planting.

Table 1. Descriptive summary of yield, management, and soil characteristics of three rice production regions in Uruguay.

Region	Yield	Field Size	Total Annual Area	Main Varieties	N	P_2O_5	K_2O*	Tillage Timing	Field History	Soil Type	SOC	Texture (Clay, Silt, and Sand)
	(kg ha^{-1})	(ha)	(ha)	-	(kg ha-^{1})	(kg ha^{-1})	(kg ha^{-1})	-	-	-	(%)	(%)
East	8975 ± 1316	116 ± 94	36691	Inia Merin (28%), Inia Tacuari (22%)	90 ± 21	42 ± 11	41 ± 23	Summer (51%), Spring (45%)	Sown Pasture (40%), Raw Pasture (28%)	Argialbol (65%), Endoacuol (18%)	2 ± 0.6	23, 56, 21
Central	8589 ± 1176	80 ± 57	6598	Inia Olimar (48%), Inia Merin (27%)	71 ± 15	41 ± 12	33 ± 25	Fall-winter (80%), Summer (13%)	Rice (34%), Raw Pasture (23%)	Natracuol (33%), Argiudol (27%)	1.8 ± 1.18	26, 48, 26
North	9110 ± 1291	94 ± 91	10759	Inia Olimar (55%), Inia Merin (17%)	96 ± 21	45 ± 12	25 ± 29	Spring (60%), Fall-winter (11%)	Rice (32%), + 1 yr Rice (23%)	Hapludert (45%), Argiudol (40%)	3.6 ± 1.02	47, 38, 15

*9, 24, and 46% of fields did not apply K fertilizer in the East, Central, and North region, respectively.

We often focus on soils, which is important for soil conservation and crops yields, for example, trying to link crops yield and soil organic carbon (Oldfield et al., 2019) but our results suggests that fine-tuning crop management opportunities are huge with relatively low importance of soil features. The crop management variables were more important than soil features in the three rice regions (Figure 1). The top 3 management variables are double to almost triple in importance relative to the soil variables. For example, seeding date importance in the East region showed a 30% increase in MSE, and the highest importance for soil features was found in the sand content with less than a 10% increase in MSE. For the East region, seeding date, variety, and tillage timing were the most important features; while K rate, N rate, and the start of irrigation were for the Central region and N rate, seeding date, and tillage method for the North region. Variance explained by the model was 47, 40, and 39% for the East, Central and North region, respectively.

The greater importance of crop management over soil features could be explained for a few reasons. First, since rice in Uruguay is grown in flooded soils, it is expected that soil features are not as crucial as in rainfed cropping systems where available soil water is critical in defining yield (Usowicz & Lipiec, 2017). For example, a modeling study of irrigated rice in the Philippines that compared models with and without soil properties found that all soil variables tested were not significant when included in the model (Silva et al., 2017a). Second, the variation in farmers' crop management dataset is greater than in the soil data, which may also explain the higher importance of crop management over soil features. In addition, the soil data used in our study was generated in the '60-'70s, thus underestimating the effect of some soil variables that could have changed more with time. Crop management practices during the past 40-50 years may have contributed to sustaining certain soil properties, such as SOC. Firstly, the adoption of high-yielding and locally developed varieties may have increased the amount of residues returned to the soil. Secondly, reduced tillage practices could have minimized SOC losses through mineralization. Lastly, the increased adoption of N and P fertilizers (from 15% and 10% in the early 1970s to 100% and 97%, respectively, in 2010) and top-dress N fertilizer (from 26 to 45 kg ha-1 in the same period) may have also contributed to increased yields, residues returned to the soil, and sustained nutrient budgets (Blanco et al., 2010). We acknowledge these two points as limitations and future research that incorporate current soil conditions in the field, as well as detailed soil maps (under development in Uruguay), are needed to better understand the relative contributions of soil and management to rice yield.

Similar results were found by Tseng et al., 2021 where seeding date and N rate were among the most important features. One thing we did differently was that we discriminated the analysis by region and included soil features. This allowed us to identify that the seeding date was not as important in the Central as in the East and North region, highlighting the importance of regional assessments.

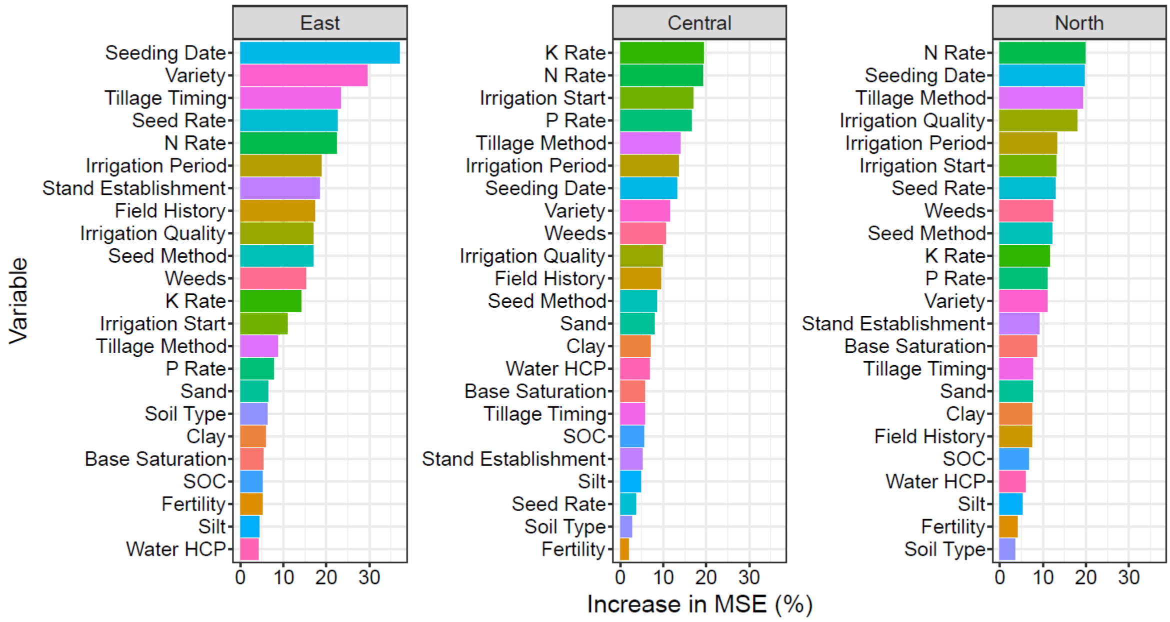

Figure 1. Soils and management feature importance (% increase in Mean Squared Error) for the three rice production regions in Uruguay.

The map in Figure 2 shows the most important feature for rice yield by location for the three main rice regions in Uruguay obtained from the local models (geographically weighted random forest). The East region (n = 1260, fields) had seeding date as the most frequent feature (40% of observations). In the Central region (n = 328, fields), the most frequent features were the P rate followed by the K rate accounting for ~30 and ~20% of the fields, respectively. In the North of Uruguay (n = 454, fields), seeding date was the most frequent feature, accounting for ~30 % of the observations (Figure 3). Variety, seed rate, tillage method, and nitrogen rate were also identified as some of the most important features across all regions (Figure 2, 3).

Previous research using farmers' data in Uruguay used global models (Tseng et al., 2021) (they used the whole data for fitting one model) while our study used local models (using the whole data but fitting one model per location/field utilizing a certain number of nearby observations). This allows for highlighting areas of interest that would have not been possible using global models. For example, in our study, we identified fields where seeding date was the most important feature and other fields that did not (Figure 2). These results could be useful to advise farmers through extension programs or guide research priorities to better understand processes affecting rice yield. This approach has been previously used in population dynamics (Georganos et al., 2021) and land use change studies (Santos et al., 2019) but to our knowledge has not been used in agronomy, thus making it an exciting tool to complement other geospatial approaches that are more focused on the analysis of yield gaps (Bonilla-Cedrez et al., 2021; Rattalino Edreira et al., 2018). In addition, our study strengthens the call for new agronomic research methods that complement traditional experiments (Cassman & Grassini, 2020) and the importance of farmers' data, since in the former, we can only evaluate 2-3 variables while farmers have to deal with many more factors.

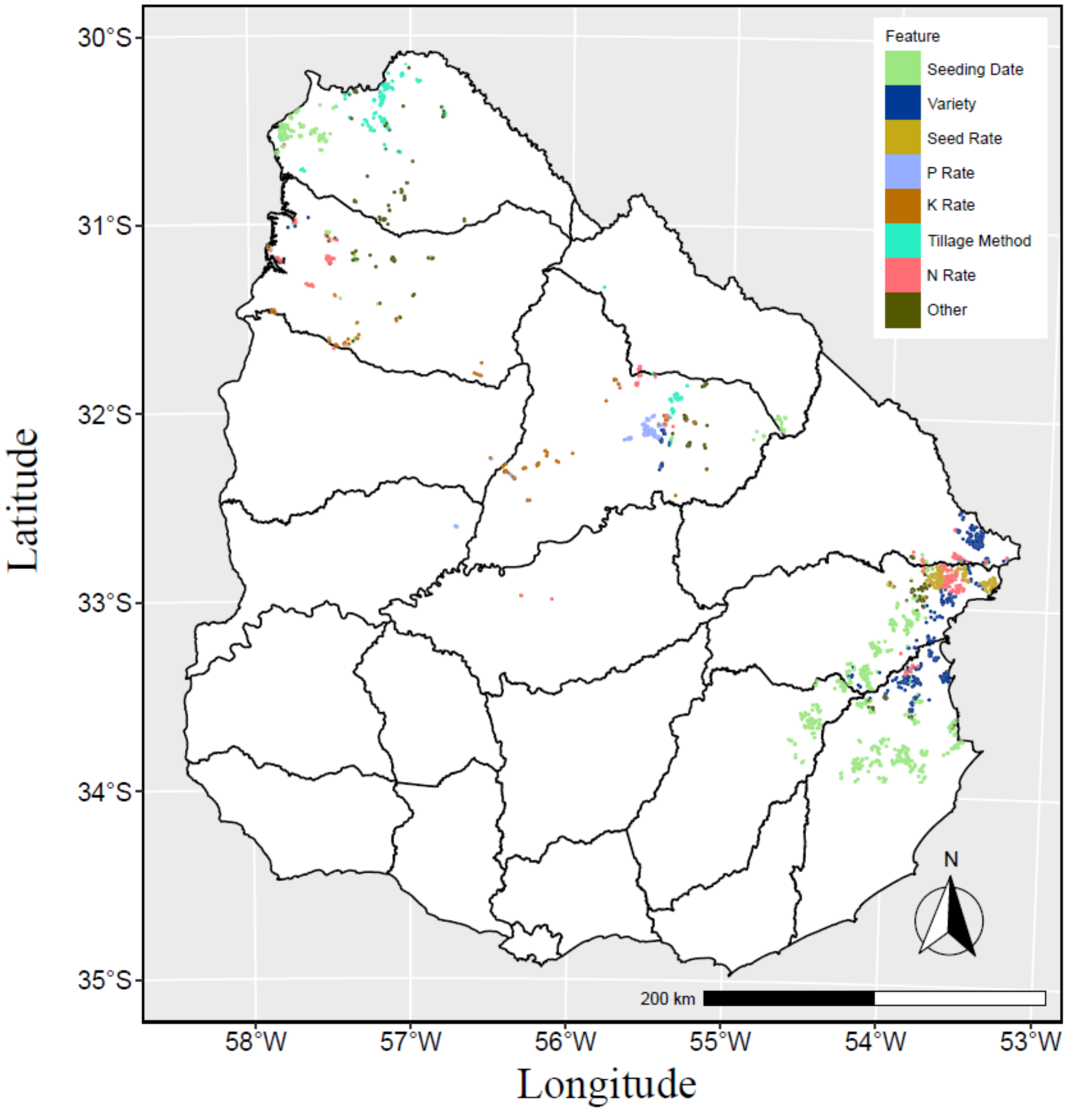

Figure 2. Map of Uruguay with its departments (equivalent to states) and the most important feature of each rice field based on geographically weighted random forest models.

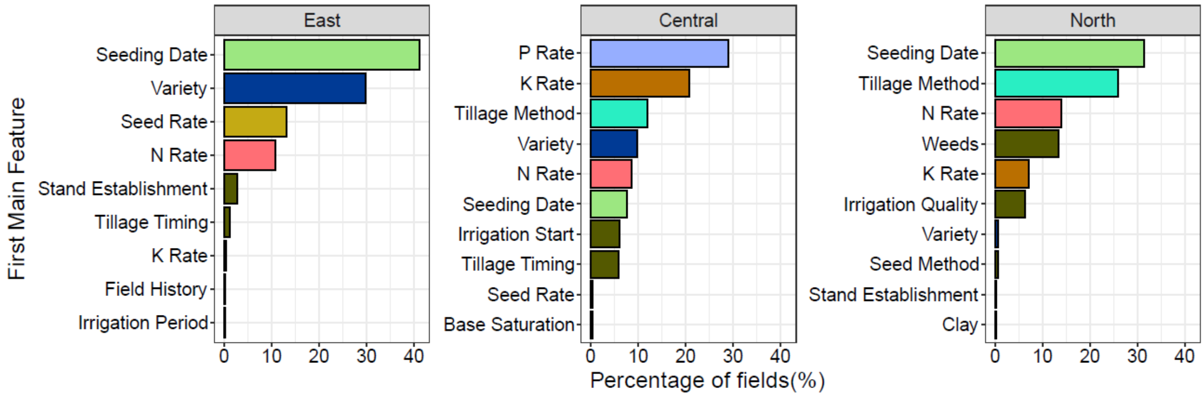

Figure 3. Percentage of fields for the most important feature for each rice region in Uruguay.

It is important to clarify, that if one variable does not show up as the most important, it does not mean that is not important, maybe it is a crop management variable that farmers handle very well, or there is not much variation for that variable in certain locations. To have a better idea of the importance of each variable across locations, we can explore quantitatively the local feature importance of independent variables as the spatial variation of the % increase in MSE in maps. This is shown in figure 4 and allows us to see the importance of a variable across all locations in a smoother manner and not just see the most important feature as we saw in figure 2. For example, if we focus on the fields further north of the East region, variety was the most important feature for these fields, we can also see that the seeding date is also important (Figure 4, East, seeding date) since the % increase in MSE for those fields still high (darker colors). In addition, from the model predictive capacity point of view (not in our goals) this could help to identify specific variables (to be included or not) for specific regions to increase the predictive capacity of the models. For example, the seed rate in the central-southern part of the East region does not seem to have strong importance (most of the locations have yellow colors). Or the opposite could be observed in the southern side of the East region with the seeding date that showed high values of % increase in the MSE.

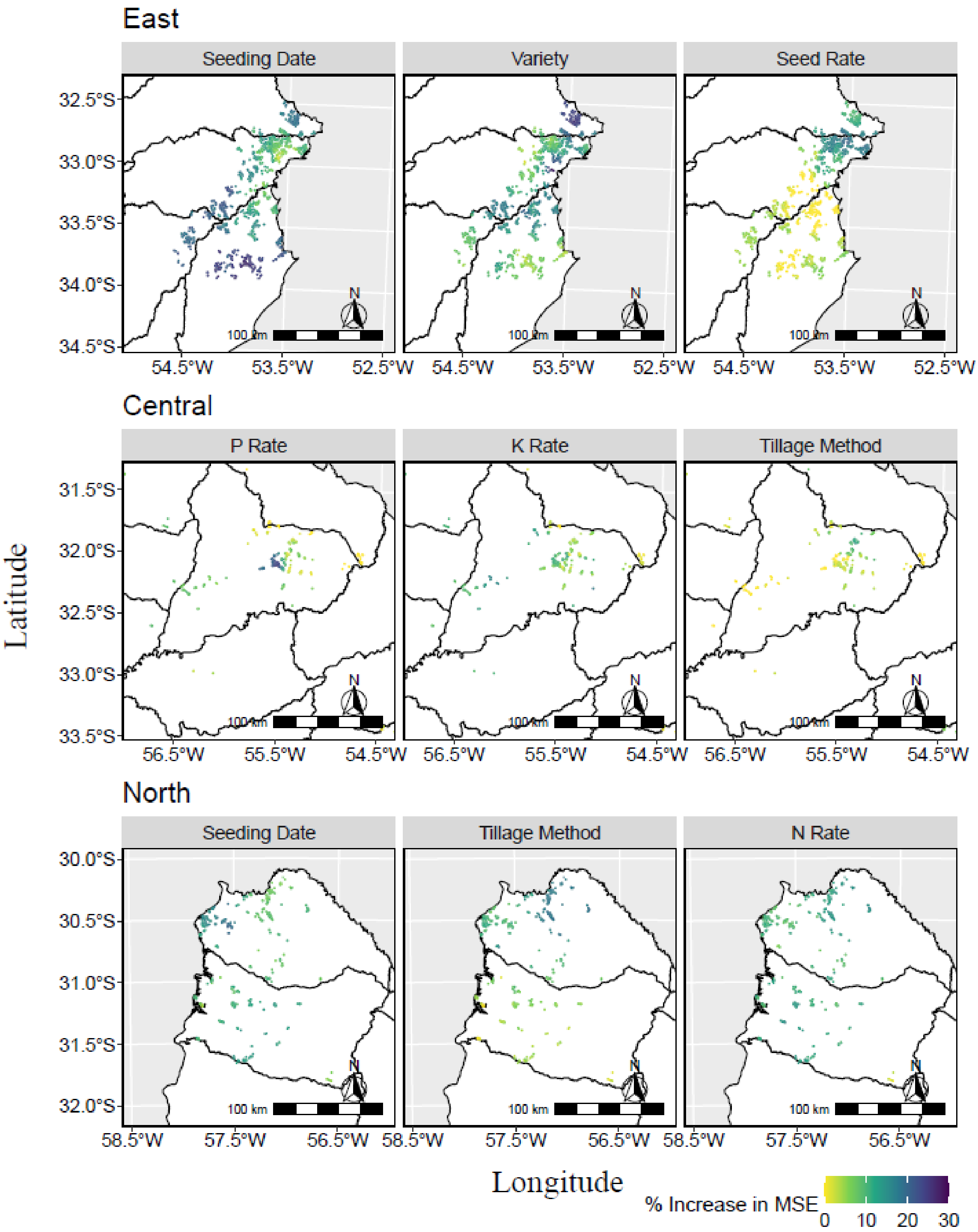

Figure 4. Map of the spatial variation of the importance (% increase in Mean Squared Error (MSE)) on yield for the three most frequent variables for each rice region in Uruguay.

To assess the potential room for improving rice yield we compared the three most frequent features with the top 20% (yielding) fields in each region. The average top 20% yield was 10775, 10227, and 10880 kg ha^{-1} for the East, Central, and North regions, respectively (Table 2). In the East region, the fields where the seeding date was the most important feature the yield was 9047 kg ha^{-1}, 16% lower than the top 20% yielding fields. These fields showed a seeding date 5 days later than the top 20%, which could be partially explaining the yield differences. Factors affecting seeding date could be operating either at field scale or at a larger spatial scale. For example, weather conditions, such as spring rainfall could be limiting seeding date in some regions while not in others. Factors that operate at the field level, such as tillage timing and field history, could also influence the seeding date. For instance, farmers can optimize time for seeding during the spring by anticipating soil preparation through summer tillage (the summer before the rice season) or when soybean is included in the rotation (soybeans release the field earlier than rice as a previous crop). Furthermore, the relationship between the landowner (mostly cattle production), and the rice farmer, who rents the land, could also be a factor in determining when the landowner permits the rice farmer to initiate operations. Another interesting comparison is the differences in yield and most used cultivars between the top 20% yielding fields and those that showed variety as the most important feature. The former group had a 20% higher yield than the latter and utilized more modern cultivars such as Inia Merin (40 vs. 28%) which has a greater yield potential and disease resistance than older cultivars (Perez de Vida et al., 2016). There were no differences in the seed rate among the groups.

In the Central region, the fields with P rate as the most important feature used a similar amount of P fertilizer as the top 20% yielding group (only 7 kg ha^{-1} P_2O_5 less in the top 20% yielding group). Interestingly, the group of fields where K rate was the most important feature used 30 kg ha-1 less than the top 20% yielding fields (~50 kg ha^{-1} K_2O). These differences in K fertilization rate could be partly explaining the yield differences (~1850 kg) since there is a younger history (no legacy effect) of K fertilization compared to P fertilizers in Uruguay's rice sector (Molina et al., 2019); and still 20% of the fields do not apply K to their fields (table 1). These results highlight the importance of monitoring soil nutrients and soil nutrient management programs that are currently being developed and increasing adoption in Uruguayan rice systems (Castillo et al., 2015; Castillo, Jesús et al., 2015; Deambrosi et al., 2015; Hernández et al., 2013).

In the North region for the top 20% yielding fields, the seeding date was approximately 4 days earlier than the fields where the seeding date was the most important feature. No differences in the type of tillage among groups were found. The top 20% yielding fields used 16% more N than the group of fields where the N rate showed up as the most important feature (~90 kg ha^{-1}). As we mentioned previously, seeding date and N rate have been previously reported as management variables affecting rice yield in Uruguay (Tseng et al., 2021), implying the need to still work on the constraints for achieving an optimum seeding date and N management.

Table 2. Descriptive summary for the three most frequent feature groups and the top yielding (20%) fields for each rice region in Uruguay.

Region	Feature*	Group									
		Important					Top 20% Yield				
		n	Mean	Range	Most frequent category	Rice Yield	n	Mean	Range	Most frequent category	Rice Yield
East	Seeding date	520	23	-12:57	-	9047±1331	252	17.8	-12:55	-	10775±580
	Variety	375	-	-	Inia Merin 28%, Inia Tacuari 22%, El Paso 144 11%	8968±1252	252	-	-	Inia Merin 40%, Inov 17%, XP 113 14%	10775±581
	Seed Rate	167	109	45:162	-	8960±1299	252	113	45:188	-	10775±582
Central	P Rate	95	47	20:73	-	8920±1078	66	40.4	18:60	-	10227±549
	K Rate	68	21.5	0:72	-	8378±1217	66	50	0:104	-	10227±549
	Tillage Method	39	-	-	Light disk harrow tillage + Landplane 51%, Landplane 36%	8366±888	66	-	-	Light disk harrow tillage + Landplane 49%, Landplane 29%	10227±549
North	Seeding date	143	21.4	-13:57	-	9434±1127	91	17.8	-10:57	-	10880±668
	Tillage Method	118	-	-	Deep disk harrow tillage + fine finish + Landplane 39%	8942±1227	91	-	-	Deep disk harrow tillage + fine finish + Landplane 65%	10880±668
	N Rate	63	91.4	41:179	-	9082±1284	91	105	51:181	-	10880±668

* Seeding date (deviation from Oct 1st); Seed Rate, P Rate, K Rate, and N Rate (kg ha^{-1}).

Increasing yield is also important for reducing environmental impacts, if inputs do not increase at higher rates and decrease efficiencies. To include a resource use efficiency metric, we evaluated the NUE of farmers' fields and account for fields within the safe zone, with potential soil N mining, and potential N losses to the environment. Interestingly, most of the fields within the desired level of NUE (0.5-0.9) with 88, 82, and 86% of the observations within this range for the East, Central, and North regions, respectively, thus highlighting low risk of potential soil N mining or potential N losses. There were 44, 38, and 43% of the fields within the safe zone for the East, Central, and North region, respectively (Figure 5). There were 44, 44, and 43% fields for the East, Central, and North regions, respectively that did not reach the safe zone because they were below the desired N output threshold (defined by the mean yield); not because they were at risk of soil N mining or potential N losses zones. There were no (Central region) or a few observations (5 and 6% for East and North, respectively) with a potential risk of N losses (NUE < 0.5) while also the low frequency of fields with risk of soil N mining (NUE > 0.9), with 7, 18, and 8% of the fields for the East, Central and North region, respectively.

To assess potential ways to achieve the desired range of NUE in these fields we plotted some of the most important features previously discussed filling with a color scale for each observation in the dispersion plot (Figure 5). For example, the East and North region observations were color-filled with the seeding date variable. We can intuitively see that the frequency of fields in the safe zone with earlier seeding dates (brighter colors) is higher than with later seeding dates. If the seeding date variable would be classified as early (before Oct 20th), intermediate (between Oct 21 and Nov 10th), and late (after Nov 10th), the frequency of fields within the safe zone was ~60, ~40, and ~24 % (data not shown) for early, intermediate, and late seeding date, respectively. For the Central region, we plotted the P rate and the K rate as dot size and color scale, respectively. There is no clear relationship with the P rate increasing the number of fields within the safe zone. However, higher K rates (darker dots) increase the frequency of fields within the safe zone compared to lower rates.

These results highlight ways toward the improvement of NUE in farmers' rice fields. For example, there is room for improved N output (rice yield) and increase frequency of fields to the safe zone at no economic or environmental cost (with non-input-related management variables) just improving the seeding date. This is something that farmers know, so urge the necessity to understand the manageable constraints limiting this management variable. For example, around 70% of rice farmers rent land and sometimes they do not access land on time for optimum operations. Better agreements among the rice farmers and the landowners are needed to improve the yield and NUE of rice fields. Conversely, the Central region provides hints that yield and NUE could be limited by input-related management variables. As we described, this region applied less N than the other two regions (Table 1), K rate and P rate showed up as the most important feature for most of the fields (Figure 3). A guided and objective nutrient management plan with tools already available (Castillo et al., 2015) could lead to an increase in yield and NUE in this region with the agronomists' advice.

Here we evaluated the NUE at the crop level, further research that incorporates the analysis at the crop-rotation system level is needed since a crop can achieve a high NUE during the crop phase but if rotate with perennial pastures that fixates N from biological N fixation not necessarily mean risk of soil N mining. This is particularly interesting in the Uruguayan context since rice - perennial pastures is a common rotation system (Castillo et al., 2021).

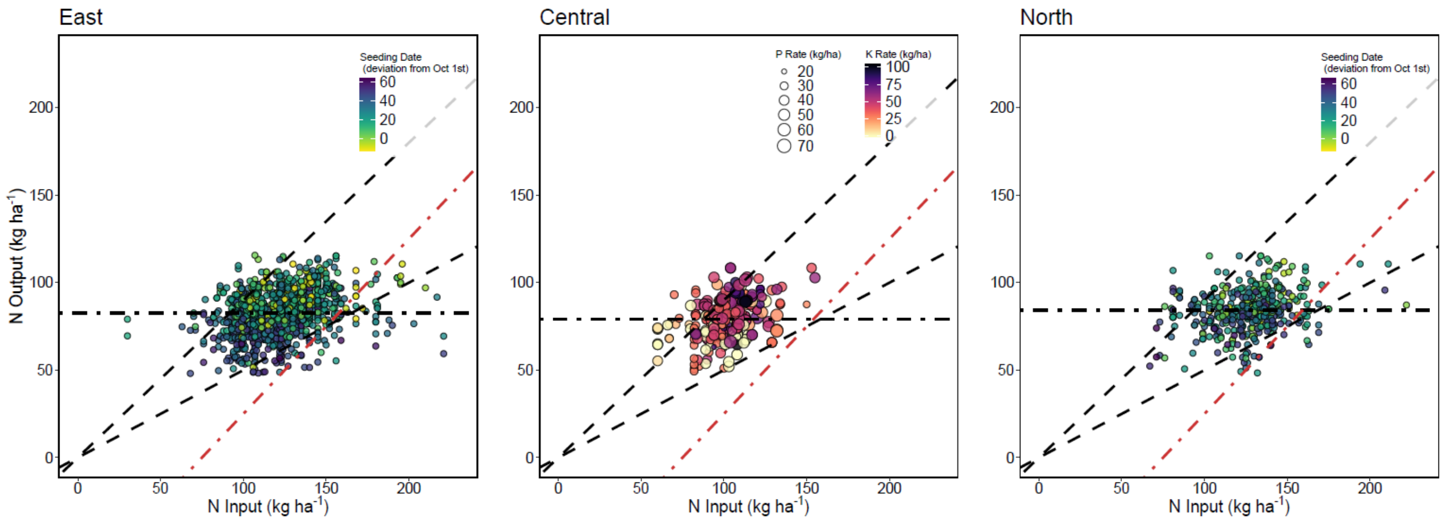

Figure 5. Dispersion plot of N input (N form fertilizer + 30 kg of biological fixation) and N output in harvested rice for three rice regions in Uruguay. The upper and lower black dashed lines indicate 0.9 and 0.5 nitrogen use efficiency, respectively. The horizontal dot-dashed lines indicated the desired level of N output (83, 79, and 84 kg ha^{-1} of N output for the East, Central, and North, respectively). The red dot-dashed line indicates a maximum value of 75 kg ha^{-1} of N balance. The colors of the dots indicate the seeding date (deviation from October 1st) for the East and North region. For the Central region, the size of the dots indicates the P fertilization rate while the color of the dots indicates the K fertilization rate. A field is considered in the safe zone if 1) has an NUE between 0.9 and 0.5, 2) has an N balance lower than 75 kg ha^{-1}, and 3) it achieves the minimum N output threshold.

In summary, we conducted an exploratory geospatial data analysis using farmers' data from Uruguay accounting for approximately 220,000 ha total (~55,000 ha yr^{-1}) from 2042 field observations. We compared the relative importance of soils and management features on rice yield with the latter showing higher importance. Geographically weighted random forest models were fitted to explore the spatial variation of the most important features across regions. We not only identified the important variables but also determined their location within the territory. Seeding date, variety, P rate, K rate, N rate, and tillage method were among the most frequent important features highlighting areas of interest for extension and future research projects. This is a region with high rice yields and relatively low yield gap, meaning that in regions with more yield variations and sub-optimal management, larger opportunities with impactful results would be expected.

Our study also emphasizes the success of a partnership between the private and public sectors, where farmers willingly shared their data with researchers, resulting in meaningful insights and valuable findings. Farmer generate valuable data but one of the challenges is what to do with it? Or how can we turn that data into actionable information? This workflow where field agronomist from industry collect data, then share it with researchers and researcher share results or make recommendations back with them is promising compared for example with on-farm research that is valuable but requires more investments (Cui et al., 2018). We did a geospatial exploratory analysis, but this approach could also integrate remote sensing data, other types of modeling, and the production of prescription maps where the private sector can take action and make use of it to identify needs and step in with investment and technologies.

In addition, we evaluated the nitrogen use efficiency of rice fields finding a high proportion of the fields within the safe zone, with a low frequency of fields in the soil N mining or potential N losses zones. We showed potential ways to increase the frequency of fields within the safe zone which in two of the three regions evaluated could be done with non-input-related management practices. We recommend the use of this type of tool in other crops or regions to make use of the data obtained by farmers to better understand the factors that affect crop yields in real conditions. Our research strengthens the call for the importance of farmers' data and complements other geospatial approaches to guide agronomy decisions that sustain or increase yield while minimizing negative environmental externalities.

METHODS

Data description and acquisition

Data across 4 cropping seasons (2018-2021 harvest years) containing crop management records, rice yields, and georeferenced locations were collected from farmers' rice fields by the agronomists of SAMAN (Sociedad Anónima Molinos Arroceros Nacionales), the largest rice mill in Uruguay. A total of 2042 field observations were collected from three main production regions (East, Central, and North) with different climate conditions and yield potential, covering approximately 55,000 ha per year (40% of total rice area) (Figure 6). More details about these regions and yield potential can be found in (Carracelas et al., 2023). Soil types and soil properties of A horizon were obtained from the Uruguayan soil map at scale 1:1,000,000 from (http://sig.inia.org.uy) and linked to each field through their georeferenced location (Altamirano et al., 1976).

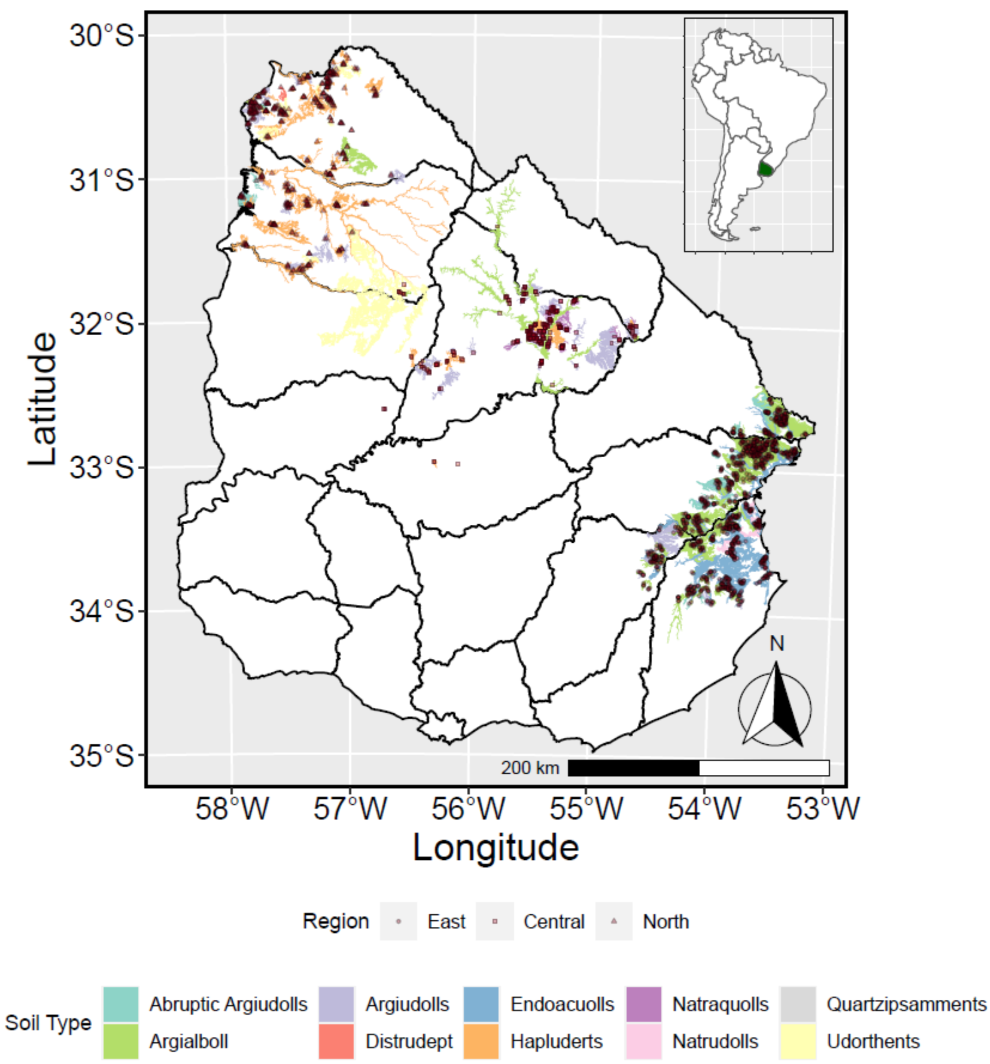

Figure 6. Map of South America with Uruguay highlighted in green (top-right) and map of Uruguay with the soil types by soil taxonomy classification and the 2042 georeferenced farmers' rice fields from Sociedad Anonima Molinos Arroceros Nacionales (SAMAN) in the East (circles), Central (squares) and North (triangles) rice regions.

The variables and its description included in the assessment are presented in table 3. These variables covered key management features and soil characteristics, some of which have been previously reported as important factors explaining yield variations such as seeding date, N rate, and Variety (Tseng et al., 2021). Others are important because of system characteristics. For example, field history was included in the analysis because rice in

Uruguay rotates with pastures and in recent years soybean has been included as another crop (Macedo et al., 2022). Another characteristic of Uruguay's rice systems is that rice farmers rent the land to grow rice, which is why tillage timing is an important feature considering this operation could conditionate the other ones such as seeding date. In addition, soil type and soil properties were included since are important features explaining yield in some crops (Usowicz & Lipiec, 2017).

Table 3. List of features included in this study.

Variable	Type	Unit	Description
Soil Type	Categorical	-	Type of soil based on Soil Taxonomy
Soil Organic Carbon	Numeric	%	The percentage of soil organic carbon in the soil
Fertility	Categorical		Classification of soil natural fertility
Clay	Numeric	%	The percentage of clay in the soil
Silt	Numeric	%	The percentage of silt in the soil
Sand	Numeric	%	The percentage of sand in the soil
Base Saturation	Numeric	%	Sum of Calcium, Magnesium, Potassium, and Sodium on a percentage basis
Water HC	Numeric	Mm	mm of soil water holding capacity
Field History	Categorical	-	The crop planted before the rice
Variety	Categorical	-	The name of the rice cultivar planted in the field
Tillage Method	Categorical	-	The method used for land preparation
Tillage Timing	Categorical	-	Time of the year in which tillage is performed

Seeding Date	Numeric	Days	The number of days between the seeding date and October 1 st
Seed Method	Categorical	-	The method used for seed implementation
Seed Rate	Numeric	kg ha^{-1}	kg of seed used per hectare
Stand Establishment	Categorical	-	The uniformity of stand establishment, determined by the agronomists
K Rate	Numeric	kg ha^{-1}	The amount of K_2O applied per hectare
N Rate	Numeric	kg ha^{-1}	The amount of N applied per hectare
P Rate	Numeric	kg ha^{-1}	The amount of P_2O_5 applied on per hectare basis
Irrigation Start	Numeric	Days	Number of days between planting and irrigation
Irrigation Period	Numeric	Days	Number of days of irrigation
Irrigation Quality	Categorical	-	The uniformity of irrigation, determined by the agronomists
Weeds	Categorical	-	The severity of weed infestation, determined by the agronomists
Yield	Numeric	kg ha^{-1}	The amount of cleaned rice harvested per hectare expressed with 13% of moisture content

Data analysis and modeling

Random forest (RF) regression models were used in each region to explore the relative importance of soil and management features on rice yield. These models were performed using the package 'ranger' (Wright & Ziegler, 2017) in R with a mtry (random number of variables selected to build each tree) = 5, and ntree (number of trees) = 500. Details about how RF works can be found in (Breiman, 2001). Management and soil variables' importance was evaluated with permutation, the higher the value in the % increase in mean squared error (MSE) the more important the variable.

To explore the spatial variation of soil and management features we used geographically weighted random forest regressions within each region with the R package 'SpatialML' (Kalogirou & Georganos, 2022). This approach allows the model to vary spatially (local models) and fit one model in each location using a certain number of nearest neighbors (explained later). In other words, GWRF is a decomposition of RF in the form of several local sub-models into geographical space (Georganos et al., 2021). The way it works is similar to geographically weighted regressions (Brunsdon et al., 1998) but GWRF has some advantages such as handling missing observations, multicollinearity, and non-linear relationships, which is important when working with farmers' field data (Georganos et al., 2021; Santos et al., 2019). One of the advantages of these local sub-models over global (aspatial) models is that allows for spatial differentiated model outputs assessments such as root mean squared error (RMSE), importance feature, and R^2. In addition, since these models are fitted locally, their outputs can be presented as maps and emphasize areas of interest that cannot be visualized through global models (Georganos et al., 2021; Santos et al., 2019).

Geographically weighted random forest models were fitted to each location using the appropriate bandwidth (the one that minimizes the RMSE). For that, we used the 'grf.bw' function from the 'SpatialML' package which allows us to explore a range of different bandwidths and the output is the optimum bandwidth to be used in the GWRF. Since our "sampling" density was different across the space we used an adaptive kernel or neighborhood (that means the same number of neighbors and an adaptive distance to fit each model at each location) (Brunsdon et al., 1998). After getting the optimum bandwidth for each rice region we fitted the GWRF using the '*grf*' function. This function is the local version of a RF model and uses the same syntax as the function '*ranger*' from the R package 'ranger' (Kalogirou & Georganos, 2022; Wright & Ziegler, 2017).

After fitting the models, variable importance was explored for each location. The most important feature (the one with the highest % increase in MSE) for each location was extracted and mapped. Then we calculated the percentage of fields for the most important feature for each region and we mapped the spatial variation of the % increase in MSE for the three most frequent variables/features in each region. Finally, we compared the three most frequent feature groups for each region with the top yielding (20%) fields. For numerical variables, we calculated the mean and range while for categorical we evaluated the most frequent categories. In addition, we reported the number of observations for each group and the rice yield.

Maps and plots were done using packages 'sf', 'terra', and 'ggplot2'(Hijmans, 2022; Pebesma, 2018; Wickham, 2016). All analyses were performed under R version 4.2.1(R Core Team, 2022).

Quantification of N safe zones

To explore the nitrogen use efficiency (NUE) of the rice fields we follow the conceptual framework proposed by the EU nitrogen expert panel that has been previously used for the evaluation of agricultural systems (de Klein et al., 2017; EU Nitrogen Expert Panel, 2015; Zhang et al., 2019). This framework defines 4 different boundaries to be within a safe zone based on N inputs and N outputs. To be in the safe zone NUE (N output/ N input) must be higher than 0.5 and lower than 0.9. This is because a lower value of 0.5 of NUE could indicate potential N losses to the environment (low N removal by the crop and high N fertilization can result in excess N in the soil-plant environment, which may be prone to potential losses through leaching or volatilization), and a value higher than 0.9 could indicate soil mining (high N removal and low N fertilization can lead to soil N depletion) (EU Nitrogen Expert Panel, 2015). The third boundary is defined by the N balance or N surplus that is N inputs – N outputs, and the fourth boundary is defined by a desired level of N output.

Briefly, in our study N input was defined by N fertilizer plus 30 kg of N that was assumed from biological N fixation in rice-irrigated lowland systems (Herridge et al., 2008). Nitrogen output was calculated based on dry yield multiplied by rice grain N concentration (1.06%) (Dobermann & Fairhurst, 2000). The threshold defined for the maximum N balance was 75 kg ha^{-1} since N losses could increase substantially when exceeding this value (Yuan et al., 2021). The desired N output in this study was defined by the mean yield for each region; 8975, 8589, and 9110 kg ha^{-1} (13% grain moisture) which meant 83, 79, and 84 kg ha^{-1} of N output for the East, Central and North region, respectively.

The frequency of fields within the safe zone was quantified for each region. That was those fields that meet the following conditions: an NUE between 0.5 and 0.9, an N balance lower than 75 kg ha^{-1}, and an N output higher than the desired value previously defined. In addition, we quantified the frequency of fields with a potential risk of soil mining (NUE higher than 0.9) and the frequency of fields with a potential risk of N losses (NUE lower than 0.5). Based on the results obtained in GWRF models, we explored how some of the variables that showed up as important could improve the NUE.

ACKNOWLEDGMENTS

The authors acknowledge for the assistance of the following SAMAN agronomists for reporting field-level records and sharing the data: Raul Uraga, Muzio Marella, Eduardo Stinger, Santiago Fariña, Juan Carlos Ferres, Santiago Platero, Luis Amendola, Fernando Sanz, and Gaston Canosa. We thank the Department of Plant Sciences, UC Davis, and Fulbright Uruguay-ANII for supporting I. Macedo with graduate fellowships.

REFERENCES

Achim Dobermann, Thomas Fairhurst. (2000). *Rice: Nutrient disorders & nutrient management*. Int. Rice Res. Inst.

Altamirano, A., da Silva, H., Duran, A., Echevarría, A., Panario, D., Puentes, R. (1976). *Carta de Reconocimiento de Suelos del Uruguay. Tomo I. Clasificación de Suelos.* (Dirección de Suelos y Fertilizantes, Ministerio de Agricultura y Pesca).

Blanco, P., Roel, A., Deambrosi, E., Bonilla, C., Cantou, G., & Molina, F. (2010). Closing the yield gap in rice production in Uruguay: Impact of technological changes. *Proc. Intl. Rice Congr., Hanoi, Vietnam*. http://www.ainfo.inia.uy/digital/bitstream/item/3516/1/Congreso-Blanco-2010-1.pdf

Bonilla-Cedrez, C., Chamberlin, J., & Hijmans, R. J. (2021). Fertilizer and grain prices constrain food production in sub-Saharan Africa. *Nature Food*, *2*(10), 766–772. https://doi.org/10.1038/s43016-021-00370-1

Breiman, L. (2001). Random forests. *Machine Learning*, *45*(1), 5–32.

Brunsdon, C., Fotheringham, S., & Charlton, M. (1998). *Geographically weighted regression-modelling spatial non-stationarity*. 431–443.

Carracelas, G., Guilpart, N., Cassman, K. G., & Grassini, P. (2023). Distinguishing between yield plateaus and yield ceilings: A case study of rice in Uruguay. *Field Crops Research*, *292*, 108808. https://doi.org/10.1016/j.fcr.2023.108808

Cassman, K. G., & Grassini, P. (2020). A global perspective on sustainable intensification research. *Nature Sustainability*, *3*(4), 262–268. https://doi.org/10.1038/s41893-020-0507-8

Castillo, J., Kirk, Guy. J. D., Rivero, M. J., Dobermann, A., & Haefele, S. M. (2021). The nitrogen economy of rice-livestock systems in Uruguay. *Global Food Security*, *30*, 100566. https://doi.org/10.1016/j.gfs.2021.100566

Castillo, J., Terra, J. A., & Méndez, R. (2015). Indicadores objetivos para la recomendación de fertilización N en arroz. *XII Conferência Internacional de Arroz Para América Latina e Caribe*, 1.

Castillo, Jesús, Vaz, Pablo, & Terra, José. (2015). FERTILIZ-ARR: hacia una herramienta para la fertilización del cultivo de arroz. *Revista INIA*, 1–3.

Chauhan, B. S., Jabran, K., & Mahajan, G. (2017). Rice Production Worldwide. In B. S. Chauhan, K. Jabran, & G. Mahajan (Eds.), *Rice Production Worldwide*. Springer International Publishing. https://doi.org/10.1007/978-3-319-47516-5

Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., Zhang, W., Mi, G., Miao, Y., Li, X., Gao, Q., Yang, J., Wang, Z., Ye, Y., Guo, S., Lu, J., Huang, J., Lv, S., Sun, Y., … Dou, Z. (2018). Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, *555*(7696), 363–366. https://doi.org/10.1038/nature25785

de Klein, C. A. M., Monaghan, R. M., Alfaro, M., Gourley, C. J. P., Oenema, O., & Powell, J. M. (2017). Nitrogen performance indicators for dairy production systems. *Soil Research*, *55*(6), 479. https://doi.org/10.1071/SR16349

Deambrosi, E., Méndez, R., & Castillo, J. (2015). Elementos a considerar en la inclusión de potasio en la fertilización del arroz. *Inia*, 1–10.

EU Nitrogen Expert Panel. (2015). Nitrogen Use Efficiency (NUE) an indicator for the utilization of nitrogen in food systems. *Wageningen University, Alterra, Wageningen, Netherlands*.

Georganos, S., Grippa, T., Niang Gadiaga, A., Linard, C., Lennert, M., Vanhuysse, S., Mboga, N., Wolff, E., & Kalogirou, S. (2021). Geographical random forests: A spatial extension of the random forest algorithm to address spatial heterogeneity in remote sensing and population modelling. *Geocarto International*, *36*(2), 121–136. https://doi.org/10.1080/10106049.2019.1595177

Grassini, P., Torrion, J. A., Cassman, K. G., Yang, H. S., & Specht, J. E. (2014). Drivers of spatial and temporal variation in soybean yield and irrigation requirements in the western US Corn Belt. *Field Crops Research*, *163*, 32–46. https://doi.org/10.1016/j.fcr.2014.04.005

Hernández, J., Berger, A., Deambrosi, E., & Lavecchia, A. (2013). Soil Phosphorus Tests for Flooded Rice Grown in Contrasting Soils and Cropping History. *Communications in Soil Science and Plant Analysis*, *44*(7), 1193–1210. https://doi.org/10.1080/00103624.2012.756000

Herridge, D. F., Peoples, M. B., & Boddey, R. M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil*, *311*(1–2), 1–18. https://doi.org/10.1007/s11104-008-9668-3

Hijmans, R. J. (2022). *terra: Spatial Data Analysis*. https://CRAN.R-project.org/package=terra

Kalogirou, S., & Georganos, S. (2022). *SpatialML: Spatial Machine Learning*. https://CRAN.R-project.org/package=SpatialML

Kharel, T. P., Ashworth, A. J., Owens, P. R., & Buser, M. (2020). Spatially and temporally disparate data in systems agriculture: Issues and prospective solutions. *Agronomy Journal*, *112*(5), 4498–4510. https://doi.org/10.1002/agj2.20285

Macedo, I., Roel, A., Ayala, W., Pravia, M. V., Terra, J. A., & Pittelkow, C. M. (2022). Irrigated rice rotations affect yield and soil organic carbon sequestration in temperate South America. *Agronomy Journal*, *114*(2), 961–975. https://doi.org/10.1002/agj2.20964

Molina, F., Terra, J., & Roel, A. (2019). *1. EVOLUCIÓN DE ALGUNAS VARIABLES TECNOLÓGICAS EN EL CULTIVO DE ARROZ EN URUGUAY*. 3.

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *SOIL*, *5*(1), 15–32. https://doi.org/10.5194/soil-5-15-2019

Pebesma, E. (2018). Simple Features for R: Standardized Support for Spatial Vector Data. *The R Journal*, *10*(1), 439–446. https://doi.org/10.32614/RJ-2018-009

Perez de Vida, F., Blanco, P., & Molina, F. (2016). INIA Merín, nuevo cultivar de arroz: Alta productividad y resistencia a Pyricularia. *Revista INIA Uruguay*, *44*, 15–19.

R Core Team. (2022). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rattalino Edreira, J. I., Cassman, K. G., Hochman, Z., van Ittersum, M. K., van Bussel, L., Claessens, L., & Grassini, P. (2018). Beyond the plot: Technology extrapolation domains for scaling out agronomic science. *Environmental Research Letters*, *13*(5), 054027. https://doi.org/10.1088/1748-9326/aac092

Roel, A., Firpo, H., & Plant, R. E. (2007). Why do some farmers get higher yields? Multivariate analysis of a group of Uruguayan rice farmers. *Computers and Electronics in Agriculture*, *58*(1), 78–92. https://doi.org/10.1016/j.compag.2006.10.001

Santos, F., Graw, V., & Bonilla, S. (2019). A geographically weighted random forest approach for evaluate forest change drivers in the Northern Ecuadorian Amazon. *PLOS ONE*, *14*(12), e0226224. https://doi.org/10.1371/journal.pone.0226224

Service, U. E. R. (2022). Investment in U.S. Public Agricultural Research and Development Has Fallen by a Third Over Past Two Decades, Lags Major Trade Competitors. *Amber Waves*. https://www.ers.usda.gov/amber-waves/2022/june/investment-in-u-s-public-agricultural-research-and-development-has-fallen-by-a-third-over-past-two-decades-lags-major-trade-competitors/

Silva, J. V., Reidsma, P., Laborte, A. G., & van Ittersum, M. K. (2017a). Explaining rice yields and yield gaps in Central Luzon, Philippines: An application of stochastic frontier analysis and crop modelling. *European Journal of Agronomy*, *82*, 223–241. https://doi.org/10.1016/j.eja.2016.06.017

Silva, J. V., Reidsma, P., Laborte, A. G., & van Ittersum, M. K. (2017b). Explaining rice yields and yield gaps in Central Luzon, Philippines: An application of stochastic frontier analysis and crop modelling. *European Journal of Agronomy*, *82*, 223–241. https://doi.org/10.1016/j.eja.2016.06.017

Sinha, B. B., & Dhanalakshmi, R. (2022). Recent advancements and challenges of Internet of Things in smart agriculture: A survey. *Future Generation Computer Systems*, *126*, 169–184. https://doi.org/10.1016/j.future.2021.08.006

Sparapani, T. (2017). How Big Data and Tech Will Improve Agriculture From Farm to Table. *Forbes*. https://www.forbes.com/sites/timsparapani/2017/03/23/how-big-data-and-tech-will-improve-agriculture-from-farm-to-table/?sh=b0b76a959891

Tseng, M. C., Roel, A., Macedo, I., Marella, M., Terra, J. A., Zorrilla, G., & Pittelkow, C. M. (2021). Field-level Factors for Closing Yield Gaps in High-Yielding Rice Systems of Uruguay. *Field Crops Research*, *264*. https://doi.org/10.1016/j.fcr.2021.108097

Usowicz, B., & Lipiec, J. (2017). Spatial variability of soil properties and cereal yield in a cultivated field on sandy soil. *Soil and Tillage Research*, *174*(July), 241–250. https://doi.org/10.1016/j.still.2017.07.015

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

Wright, M. N., & Ziegler, A. (2017). ranger: A Fast Implementation of Random Forests for High Dimensional Data in C++ and R. *Journal of Statistical Software*, *77*(1), 1–17. https://doi.org/10.18637/jss.v077.i01

Yuan, S., Linquist, B. A., Wilson, L. T., Cassman, K. G., Stuart, A. M., Pede, V., Miro, B., Saito, K., Agustiani, N., Aristya, V. E., Krisnadi, L. Y., Zanon, A. J., Heinemann, A. B., Carracelas, G., Subash, N., Brahmanand, P. S., Li, T., Peng, S., & Grassini, P. (2021). Sustainable intensification for a larger global rice bowl. *Nature Communications*, *12*(1), 7163. https://doi.org/10.1038/s41467-021-27424-z

Zhang, C., Ju, X., Powlson, D., Oenema, O., & Smith, P. (2019). Nitrogen Surplus Benchmarks for Controlling N Pollution in the Main Cropping Systems of China. *Environmental Science & Technology*, *53*(12), 6678–6687. https://doi.org/10.1021/acs.est.8b06383