Journal of Cleaner Production 278 (2021) 123771

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Rice-pasture agroecosystem intensification affects energy use efficiency

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ARTICLE INFO

*Article history:*
Received 11 October 2019
Received in revised form
23 July 2020
Accepted 15 August 2020
Available online 29 August 2020

Handling editor: Prof. Jiri Jaromir Klemeš

*Keywords:*
Life cycle assessment
Crop rotation
Cover crops
Perennial pasture
Integrated agroecosystems

ABSTRACT

Sustainable rice production systems are key to food security. Diversified farming systems are essential for ecological intensification and environmental enhancement. Energy use efficiency is one of the main sustainability indicators in agroecosystems. Thus, an assessment of consumption and efficiency of energy in contrasting cropping systems can discriminate their management practices and components sustainability. The goal of this study was to evaluate the energy performance through energy return on investment (EROI) in four rice-based rotation systems that belong to a long-term experiment located in the Temperate Grassland Terrestrial Ecoregion, at the Atlantic side of South America. Rotations analyzed consisted in: a) continuous rice ($R_c$); b) rice-soybean ($R-S$); c) rice-pasture for 1.5 years ($R-P_S$); and, d) rice-pasture for 3.5 years ($R-P_L$). The EROI estimations considered all the inputs and outputs of energy from cradle to farm gate. The greatest EROI was observed in R–S (7.2 $MJ\ MJ^{-1}$) and the lowest energy consumption in $R-P_L$ (10,607 $MJ\ (ha\ yr)^{-1}$). The $R-P_L$'s EROI (6.7 $MJ\ MJ^{-1}$) was 6.5% and 8% higher than $R_c$ and $R-P_S$ EROI, respectively. Rotations without pastures produced 79% more energy compared with rotations including pastures. However, energy inputs of rice-pasture rotations were 40% lower than either $R-S$ or $R_c$. The EROI (without animal production) of $R-P_S$, R–S and $R_c$ was 25%, 28% and 43% lower than the EROI of $R-P_L$ (10 $MJ\ MJ^{-1}$), respectively. For the analyzed South American ecoregion, EROI assessments of four business as usual rice production systems allowed to discriminate and hierarchize their sustainability and diversity.

## 1. Introduction

Global population growth and its food demands (Godfray et al., 2010; Tilman et al., 2011) are pushing for a 90% increase in worldwide agricultural production by 2050 (FAO, 2009). This has challenged the agricultural sector to find sustainable technological options for expansion and intensification, amid a climate change scenario. Rice is a major crop worldwide, mostly cultivated in continuous cropping systems in Asia (Seck et al., 2012) but also in other more diverse systems in the world (Bryant et al., 2012; Martins et al., 2016), being strategic for global food security (Seck et al., 2012). Sustainable increase of rice production implies the redesign of agricultural systems to mitigate environmental impacts and increase efficiency and ecosystems services (FAO, 2009). Ecological intensification examples of rice production sharing or alternating the land use are the rice-fish co-culture systems developed at asian regions (Conway, 2012; Wan et al., 2019b), the rice-soybeans systems in Arkansas USA and Brazil (Bryant et al., 2012; Martins et al., 2016), and the rice-beef rotation systems

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https://doi.org/10.1016/j.jclepro.2020.123771
0959-6526/

developed in Temperate Grassland terrestrial ecoregion of South America)(Bao et al., 2018; Olson et al., 2001; Pittelkow et al., 2016). These production systems could be alternatives to develop and achieve ecological intensification of agroecosystems.

Intensification of any process requires an increase in energy demands (Maraseni et al., 2015). In the case of agricultural intensification, any increase of energy efficiency should increase global energy consumption; situation that is known as the Jevons paradox (Pellegrini and Fernández, 2018). In this sense, not always an intensification of agriculture production could be environmentally positive. Today in agriculture, energy consumption is higher than it was before the Green Revolution, due to irrigation, fertilizers, pesticides, fuels, machineries, etc. (Conforti and Giampietro, 1997; Woods et al., 2010). Energy consumption among some of Africa's agricultural systems is less than 1000 MJ (MJ) per hectare (ha) compared with values of 30,000 $MJ\ ha^{-1}$ observed in the United States (Pimentel, 2009).

It is well known that current intensification models have many negative externalities (Godfray et al., 2010; Tilman et al., 2011). In the future, not only will be necessary to meet food demands, but regulation ecosystem services such as soil erosion control, climate regulation, and pest regulation will also require consideration. The concept of ecological intensification has been promoted in order to redesign agroecosystems using landscape approaches and considering the natural functionalities of ecosystems (Tittonell, 2014). Thus, differentiating systems for environmental sustainability is a challenge when designing new agricultural systems.

Two main factors improve energy performance and agriculture yield: reducing energy inputs (EI) and/or increasing energy equivalent produced (EP), the latter being embodied in the harvested biomass (Swanton et al., 1996). Therefore, the goal is to improve the energy return on investment (EROI), or the ratio between EP and EI.

The EROI performance assessment has focused primarily on single crops (Franzluebbers and Francis, 1995; Pittelkow et al., 2016). Few studies have evaluated either the effects of management practices (i.e. crop rotations) (Rathke et al., 2007) or their energy performance (i.e. production systems, rotations) (Theisen et al., 2017). Crop rotations were designed to minimize risks, maintain soil fertility, and interrupt weeds, pests, and diseases cycles (Bird et al., 1990; Liebman and Janke, 1990). Furthermore, the inclusion of legumes could reduce nitrogen (N) requirements from commercial fertilizers (Heichel and Barnes, 1984).

There are many models of ecological intensification, using various technological options, such as border crops in urban agriculture or rice-fish coculture systems (Wan et al., 2018, 2019b); among their other effects, these system types are able to reduce pesticide and nitrogen fertilizer use. Diversified farming systems and some forms of conservation agriculture represent other models of ecological intensification (Tittonell, 2014).

Integrated crop-pasture rotation systems are rare globally, except in some regions of Argentina (Díaz-Zorita et al., 2002), southern Brazil Carvalho et al. (2018); de Moraes et al. (2014), and Uruguay (García-Préchac et al., 2004). Compared with continuous rice systems, rice-pasture rotation systems allow farmers to sustain high productivity, maintain soil quality, diversify incomes, and minimize the use of fertilizers and pesticides (Deambrosi, 2003; Pittelkow et al., 2016). For example, a rice crop grown after a perennial grass-legume mix pastures in Uruguay is fertilized with 60–80 kg N $ha^{-1}$, 40–50 kg $P_2O_5\ ha^{-1}$, and 30–40 kg $K_2O$; fungicides are generally used once in the crop cycle and insecticides are virtually disused. Symbiotic nitrogen fixation of pasture legumes minimizes synthetic nitrogen fertilizer use and has indirect impacts on energy consumption (Heichel and Barnes, 1984). However, global market demands are pushing to reduced pasture areas and increase other crops, such as soybeans, within rotation systems. Thus, following short-term economic profits, the Uruguayan rice system has developed different technological options to reduce the proportion of perennial pastures within rotations (Deambrosi, 2003; Pittelkow et al., 2016). However, it is unclear whether these intensification processes are sustainable.

A long-term rice production system experiment (LTE-RC) was installed at the Uruguayan National Institute of Agriculture Research (INIA) to evaluate the environmental sustainability of different rotations. The hypothesis of this study was that the environmental sustainability performance of long-term rice rotation systems can be assessed using EROI, to rank ecological intensification pathways. The EROI of four rice-based cropping systems with different intensification levels was estimated for: rice in rotation with long-term pastures, with short-term pastures, with soybean crop, and continuous rice.

## 2. Materials and methods

In 2012, the LTE-RC was installed at the INIA Paso de la Laguna Experimental Station in Treinta y Tres, Uruguay (33°6′23″ S, 54°10′24″ W; located 22 m above sea level) (Fig. 1). Mean annual rainfall at the site is 1360 ± 315 mm; annual total potential evapotranspiration is 1138 ± 177 mm; mean monthly temperature is 22.3 ± 0.85°C and 11.5 ± 0.82°C during summer and winter, respectively. The dominant soil at the site is an Argialboll with a slope less than 0.5% (Durán et al., 2006).

### 2.1. Rice cropping systems

The LTE-RC evaluated six rice cropping system (i.e. rotation) intensities under no-till conditions. Cropping intensity treatments were differentiated based on the proportion and length of pastures vs. rice, and on crop phases in the rotation. For this study, four of the

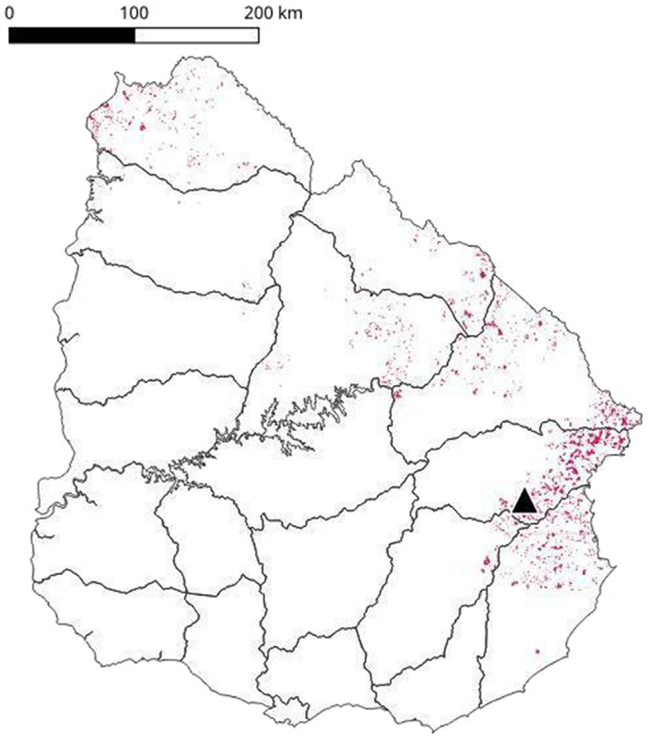


**Fig. 1.** Political map of Uruguay: rice cropping land use (solid pink polygons) and the LTE-RC location (black triangle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

six contrasting rotations were selected (Table 1).

Treatments were established in 20-m wide and 60-m long plots in a randomized complete block design with three replications; all rotation phases were present each year (Patterson, 1964). Crop and pasture management, including fertilization and pesticide application, followed INIA Rice Program recommendations. All crop and pasture operations (including seeding, fertilization, pesticide application, and harvesting) at each experimental unit were managed with machinery similar to that used by farmers. Routine crop management and performance data were recorded by INIA's Rice Program team. The crop rotations described above were evaluated in seasons 2015–2016 and 2016–2017. Rice was seeded in mid-October and soybean at the beginning of November. *Trifolium alexandrinum* and *Lolium multiflorum* (ryegrass) were seeded as cover crops immediately following rice and soybean harvests in April.

### 2.2. Rice cropping fertilization and pesticide use

Phosphorus (P) and potassium (K) fertilization in continuous rice ($R_C$) and rice-soybean (R–S) was equivalent to the previous crop extraction, while rice crops in rotation with pastures for 1.5 years ($R-P_S$) or 3.5 years ($R-P_L$) were fertilized according to sufficiency levels. Critical levels were 7 mg of P $kg^{-1}$ of soil (Hernández et al., 2013), and 78.2 mg of K $kg^{-1}$ of soil at pH 7 (Deambrosi et al., 2015). Cover crops *T. alexandrinum* and *L. multiflorum* were not fertilized. Fertilization with nitrogen in the Rc system was applied as needed to reach a yield of 10 $t\,ha^{-1}$. In other rotations, rice was fertilized with nitrogen based on critical soil nitrogen mineralization potential levels developed by Castillo et al. (2015). In all cases, nitrogen was split into two applications as urea: at tillering (dry application) and immediately before panicle initiation (flooded soil). Doses of N, $P_2O_5$, and $K_2O$ used for each rotation and crop are described in Table 2.

Fertilizer and pesticide management was based on INIA Rice Program recommendations, as shown in Table 3.

### 2.3. Irrigation

Irrigation was applied using a 150 HP diesel pump with a flow rate of 220 $L\,h^{-1}$ and diesel consumption of 14 $L\,h^{-1}$. Water consumption for rice cultivation was assumed in this experiment to be 10,000 $m^3\ ha^{-1}$ (Carracelas et al., 2019). Therefore, the estimated consumption of diesel oil by irrigation was 176.76 $L\,ha^{-1}$.

**Table 2**
Profile of nutrients used in each crop rotation system. Values are expressed as $kg\ (ha\ yr)^{-1}$.

| Treatment | Crop | N | $P_2O_5$ | $K_2O$ |
|---|---|---|---|---|
| $R_C$ | rice | 166 | 75 | 51 |
| $R-S$ | rice | 79 | 61 | 63 |
| | soybean | 5 | 91 | 45 |
| $R-P_S$ | rice | 99 | 15 | 72 |
| | pasture | 23 | 45 | 22 |
| $R-P_L$ | $1^{st}$ rice | 79 | 15 | 31 |
| | $2^{nd}$ rice | 83 | 15 | 44 |
| | pasture | 8 | 46 | 8 |

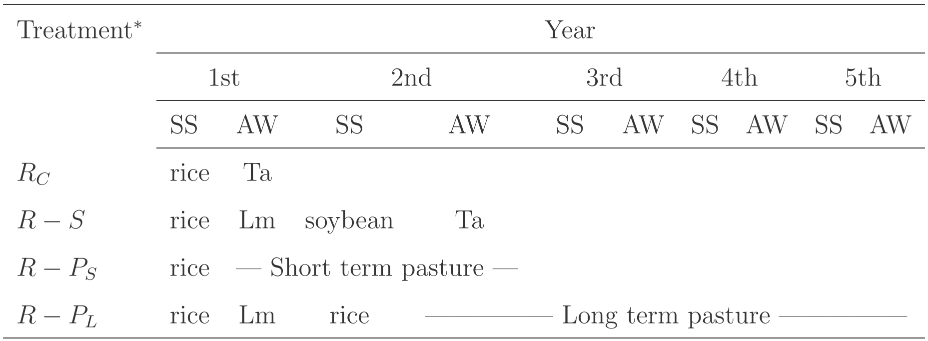
### 2.4. Estimate forage for grazing

Perennial $R-P_S$ and $R-P_L$ pastures were rotational grazed with sheep 7–8 times a year for each plot, although meat production was not quantified because the 7-10-day grazing periods were too short. Therefore, beef cattle production was estimated as a function of measured forage production, assuming variable use (40–70%) depending on age and growing season in $R-P_L$, and 60% utilization in $R-P_S$ (Rovira et al., 2009). In this study was assumed that in $R-P_S$, 14 kg dry weight (DW) pasture was needed to produce 1 kg of meat and that for $R-P_L$, 12–14 kg DW of grass was needed to produce 1 kg of meat (NRC, 2000). In addition, it was assumed a stocking rate of two calves per ha, with a live weight (LW) of 160 kg each, in $R-P_S$. After 1.5 years, these animals each weighed 290 kg LW. In $R-P_L$, each animal-starting at 160 kg LW-achieved 537 kg after 2.5 years, after which two more animals entered and after 1 year weighed 293 kg each.

### 2.5. Energy performance

The energy performance scope assessed herein followed a life cycle assessment approach: the life cycle inventory (LCI) included inputs and outputs from the cradle to the farm gate (Table 4). The energies involved in the transport of inputs, products, manual labor, solar radiation and the biological fixation of nitrogen were not considered. The functional unit of this study was the EP from the EI of each crop rotation by year and per ha. For this reason, each item listed by the LCI was converted into equivalent energy units expressed in MJ. As EI and EP were expressed in $MJ\ (ha\ yr)^{-1}$, the EROI - the ratio between EP and EI - was expressed in $MJ\ MJ^{-1}$ (Table 4). The LCI considered all inputs and outputs of sowing, postplanting (fertilization, application of pesticides), and harvest operations. Input data were from the following sources: INIA LTE-

**Table 1**
Crop rotation systems, annual and seasonal schedules (SS, spring-summer; AW, autumn-winter).



| Treatment* | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | | 2nd | | 3rd | | 4th | | 5th | |
| | SS | AW | SS | AW | SS | AW | SS | AW | SS | AW |
| $R_C$ | rice | Ta | | | | | | | | |
| $R-S$ | rice | Lm | soybean | Ta | | | | | | |
| $R-P_S$ | rice | — Short term pasture — | | | | | | | | |
| $R-P_L$ | rice | Lm | rice | ———— Long term pasture ———— | | | | | | |

*$R_c$, continuous rice; R–S, rice-soybean; $R-P_S$, rice-short-term pasture; $R-P_L$, rice-long-term pasture. Rice, *Oryza sativa* L. Soybean, *Glycine* max L. Lm, *Lolium multiflorum*. Ta, *Trifolium alejandrinum*. Short term pasture, mix of: *Trifolium pratense* and *Lolium multiflorum*. Long-term pasture, mix of: *Festuca arundinacea*, *Trifolium repens*, and *Lotus corniculatus*.

**Table 3**
Fertilizers and pesticide ($kg\ ha^{-1}$) use (and frequency) applied, based on crop and pasture cycle in each rotation system.

| | | Rc | R–S | | $R-P_S$ | | R–P | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | rice | rice | soybean | Rice | pasture | 1st rice | 2nd rice | pasture yr 1 | pasture yr 2 | pasture yr 3 |
| Fertilizers ($kg\ ha^{-1}$) N-($P_{sol}$ /$P_{total}$)-K | Triple super phosphate) (0–46/46-0) | | $100^{(1)}$ | $165^{(1)}$ | | | | | | | |
| | Diammonium phosphate (18–46/46-0) | $130^{(1)}$ | | | | | | | | | |
| | Potassium chloride (0-0/0-60) | $60^{(1)}$ | $80^{(1)}$ | $50^{(1)}$ | $95^{(1)}$ | | $27^{(1)}$ | $48^{(1)}$ | | | |
| | Chemical synthesized (9–25/25-25) | $60^{(1)}$ | $60^{(1)}$ | $60^{(1)}$ | $60^{(1)}$ | | $60^{(1)}$ | $60^{(1)}$ | | | |
| | Physical synthesized (15–30/30-15) | | | | | $150^{(1)}$ | | | $150^{(1)}$ | | |
| | Phosphate rock (0–12/23-0) | | | | | | | | | $200^{(1)}$ | $200^{(1)}$ |
| | Urea (46–0/0-0)* | $150^{(2)}$ | $130 + 30^{(1)}$ | | $86 + 117^{(1)}$ | | $90 + 70^{(1)}$ | $100 + 70^{(1)}$ | | | |
| Herbicides (kg of a.i.$ha^{-1}$) | Glyphosate | $1.68^{(2)}$ | $1.68^{(2)}$ | $1.68^{(3)}$ | $1.68^{(2)}$ | $1.92^{(1)}$ | $1.68^{(2)}$ | $1.68^{(2)}$ | $1.92^{(1)}$ | | |
| | 2,4-D | $0.72^{(1)}$ | $0.72^{(1)}$ | | $0.72^{(1)}$ | | $0.72^{(1)}$ | | | | |
| | Imazapyr + Imazapic | $0.098^{(2)}$ | | | | | | | | | |
| | Fluroxypyr | $0.1^{(1)}$ | $0.1^{(1)}$ | | $0.1^{(1)}$ | | $0.1^{(1)}$ | | | | |
| | Clomazone | | $0.4^{(1)}$ | | $0.4^{(1)}$ | | $0.4^{(1)}$ | $0.4^{(1)}$ | | | |
| | Quinclorac | | $0.38^{(1)}$ | | $0.38^{(1)}$ | | $0.38^{(1)}$ | $0.38^{(1)}$ | | | |
| | Pyrazosulfuron | | $0.04^{(1)}$ | | $0.04^{(1)}$ | | $0.04^{(1)}$ | $0.04^{(1)}$ | | | |
| | Penoxsulam | | $0.64^{(1)}$ | | $0.64^{(1)}$ | | $0.64^{(1)}$ | $0.64^{(1)}$ | | | |
| | Propaquizafop | | | $0.15^{(1)}$ | | | | | | | |
| | Metolachlor | | | $0.96^{(1)}$ | | | | | | | |
| | Flumetsulam | | | | | $0.06^{(1)}$ | | | $0.06^{(1)}$ | | |
| | Clethodim | | | | | | | $0.168^{(1)}$ | | | |
| Fungicides (kg of a.i. $ha^{-1}$) | Azoxystrobin + kresoxim-methyl + ciproconazole | $0.2^{(1)}$ | $0.2^{(1)}$ | $0.2^{(1)}$ | $0.2^{(1)}$ | | $0.2^{(1)}$ | $0.2^{(1)}$ | | | |
| | Azoxystrobin + ciproconazole | | | $0.175^{(1)}$ | | | | | | | |
| Insecticides (kg of a.i.$ha^{-1}$) | Trichlorfon | | | $0.8^{(1)}$ | | | | | | | |
| | Imidacloprid + beta-cyfluthrin | | | $0.115^{(1)}$ | | | | | | | |

* Urea split in all rice crops: at tillering and panicle initiation stage; *a.i.*: active ingredient. Rice and soybean seeds were treated with difenoconazole (0.00006 $kg\ kg^{-1}$ of seed) and thiamethoxam (0.00035 $kg\ kg^{-1}$ of seed).
** N–P–K expressed as percentage.

**Table 4**
Energy conversion factors used for different inputs used in the studied rice-cropping systems.

| LCI inputs | Energy conversion factor | References |
|---|---|---|
| | Seeds ($MJ\ kg^{-1}$) | |
| Rice | 17.6 | Determined by the study |
| Soybean | 23.50 | Determined by the study |
| Forage legume | 17.20 | Muhammad et al. (2014) |
| Forage gramineae | 36.10 | Fuksa et al. (2013) |
| | Fertilizer ($MJ\ kg^{-1}$) | |
| Nitrogen | 51.47 | Hill et al. (2006) |
| Phosphorus | 9.17 | Hill et al. (2006) |
| Potassium | 5.96 | Hill et al. (2006) |
| | Fuels ($MJ\ L^{-1}$) Fuels | |
| Diesel | 43.99 | Nagy (1999) |
| Aviation gasoline | 34.78 | Petroleum Products Division (2016) |
| | Pesticides ($MJ\ kg^{-1}$) | |
| Glyphosate | 454.00 | Audsley et al. (2014) |
| 2-4 D amine | 87.00 | Audsley et al. (2014) |
| Fluroxypyr-meptyl | 518 | Audsley et al. (2014) |
| Herbicides | 303.80 | Pimentel and Pimentel (2007) |
| Insecticides | 418.40 | Pimentel and Pimentel (2007) |
| Fungicides | 115.00 | Pishgar-Komleh et al. (2011) |

RC records; the Uruguayan Association of Agricultural Services (CUSA, 2017); and personal interviews with companies that conducted specific operations (e.g. aerial fertilizations). The LCI of rice-cropping systems was organized into seven categories: irrigation; fuel; machinery; phosphorus and potassium fertilization; nitrogen fertilization; pesticides (herbicides, insecticides, and fungicides); and others (seed, cattle). The energy produced, expressed in $MJ\ ha^{-1}$, considered both the grain yield of rice (paddy) and soybean crops and the potential meat production of pasture production in those rotations. For all products were estimated their energy equivalent using the corresponding calorific power: 19.6 $MJ\ kg^{-1}$ for forage (Portugal-Pereira et al., 2015) and 9.3 $MJ\ kg^{-1}$ for meat (Restle et al., 2001). The calorific power value of the paddy rice and the soybean grain was determined according to ASTM D 4442-07 standard, “Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials, Method A” (Table 4).

### 2.6. Statistical analysis

Productivity of each crop was compared, using single-sample t tests, to the official national mean annual yield record for: rice, 8390 $kg\ ha^{-1}$; soybean, 2400 $kg\ ha^{-1}$; pastures, 5500 $kg\ ha^{-1}$; and bovine cattle beef 148 $kg\ ha^{-1}$ (DIEA, 2018; Simeone et al., 2008). Mean EP and EROI comparisons between crop rotation, all phases (rice, soybean, and pasture/cattle), and rice-only crops in different rotations systems were made using Fisher’s ANOVA tests when parametric assumptions (normality and homoscedasticity) were satisfied, with Tukey’s honest significant difference tests for post hoc analyses. Otherwise, comparisons were made using post hoc Kruskal-Wallis and Dunn’s tests. All statistical tests were run with the statistical package R version 2.12.0 (R Development Core Team, 2018) for the platform i686-pc-Linux-gnu (64-bit) with R Commander 1.5–4 (Fox, 2011; R Core Team, 2013) on a GNU/Linux operating system.

## 3. Results

### 3.1. Biomass production

Rice experimental yield (10,147 $kg\ ha^{-1}$) was 21% higher than the commercial mean yield of the corresponding years. The lowest rice productivity was found in $R_C$ (9741 $kg\ ha^{-1}$) and the highest was the first rice in $R-P_L$ (11,043 $kg\ ha^{-1}$).

Mean soy yield at the site was 2868 $kg\ ha^{-1}$, which is 20% greater than the national average of 2400 $kg\ ha^{-1}$ reported by DIEA (2018). Annual pasture biomass production ranged between 4240 and 7337 $DM\ ha^{-1}$, with a mean value of 5897 $kg\ ha^{-1}$. Pasture productivity was higher in $R-P_L$ (p-value = 0.0099) compared with $R-P_S$, which is comparable with commercial farm values described by Simeone et al. (2008). Finally, annual estimated beef production was 257 $kg\ ha^{-1}$, which is higher (p-value<0.0001) than commercial productivity reported by Simeone et al. (2008) (Fig. 2).

### 3.2. Crop rotation energy efficiencies

The R–S rotation’s EROI was 11% higher than that of $R-P_L$, but no improvements were found in other rotations. However, when animal production was excluded, the EROI of $R-P_L$and $R-P_S$ was 74% and 36% greater, respectively (Table 5).

Rice rotations with perennial pastures ($R-P_L$ and $R-P_S$) had 44% lower EP compared with continuous cropping systems (R–S and $R_C$). The $R_C$ EP was 231% higher than that of $R-P_L$. However, when animal production was excluded, the EP of these systems matched those of the R–S rotation. Conversely, $R_C$ had a 246% higher EI than $R-P_L$ (Table 5).

Three components explained approximately 60% of the EI in all systems: irrigation, fuel use and nitrogen fertilization (Fig. 3). In the R–S system, the EI in pesticides (17%) and phosphate and potassium fertilization (7%) had higher relative weights compared with other systems in which these components were 6–10% (pesticides) and about 4% (P and K fertilization). Nitrogen fertilization explained 33% of the EI in $R_C$, while in other systems its relative weight was 14–22% of EI.

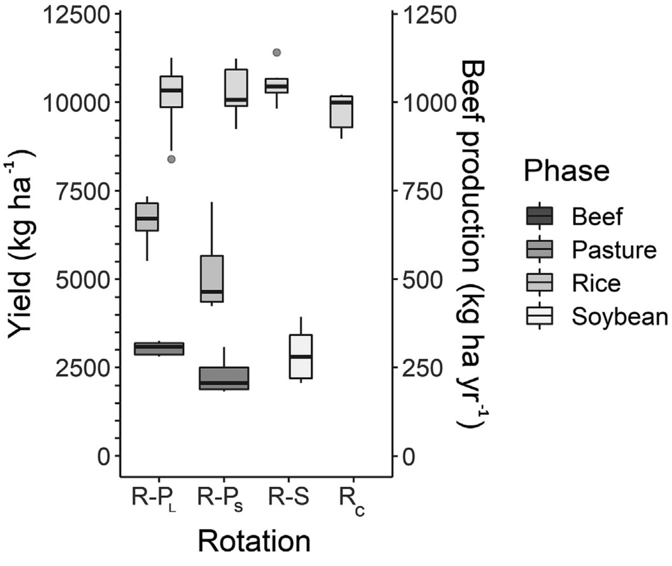


**Fig. 2.** Box plot of rice and soybean grain yields and forage production of pasture crops, and potential beef production in 2015–2017 in different rotation systems. Yields considered a dry weight with 13% humidity. Grain yield and forage are scaled to the left axis, and beef production is scaled to the right axis. Grain yield is expressed as kg ha-1 and forage and meat as $kg\ (ha\ yr)^{-1}$.

### 3.3. Energy balance in the rotation phases

Examining the rotation phases, soybean and rice crops recorded similar EROI values (˜7 $MJ\ MJ^{-1}$), except in $R_C$which had 5.7 $MJ\ MJ^{-1}$ and differed only from the first rice in $R-P_L$. The EROI values of pasture phases when animal production was included were the lowest among all phases. However, when animal production was excluded, and only forage production was accounted for, the values obtained by pastures were the highest, particularly in $R-P_L$ (Table 6).

The EP for soybean crops was 6% lower than the average for all rice phases (155,374 $MJ\ (ha\ yr)^{-1}$). When animal production was excluded from the pasture phases, EP increased 15 and 17 times for $R-P_S$ and $R-P_L$, respectively, with a similar EP for soybeans. Soybean and pasture phases had 64% and 77% lower EI, respectively, than corresponding rice phases (Table 6).

Irrigation, fuel, and nitrogen fertilization accounted for approximately 70% of rice phase EI (Fig. 4). Both pastures and soybean phases had low EI demands, related to nitrogen fertilization. However, the EI for phosphorus and potassium fertilization was 8–14%, which is significantly higher than the EI in rice phases, at 2–4%. Pesticides represented 38% of the EI in the soybean phase in R–S, while it varied for other phases from 7% to 14%. In the pasture phases, other components (e.g. animals, seeds) became more relevant and represented 63% and 55% in $R-P_L$ and $R-P_S$, respectively.

EI related to the depreciation of machinery was irrelevant and did not exceed 1% in any of the phases evaluated.

### 3.4. Rice crop energy balance in different rotation systems

The highest EROI was found in the first rice following long-term pastures ($R-P_L$) and in rice in rotation with soybeans (R–S). Rice in rotation with short-term pastures did not differ compared with rice rotated with soybean or with the second rice in $R-P_L$. Finally, EROI

**Table 5**
Energy information expressed in $MJ\ (ha\ yr)^{-1}$ for mean value and standard deviation of invested energy; produced energy, with (+A) and without (-A) beef production of: continuous rice with pasture during the winter ($R_C$) (n = 6); rice-soybean ($R-S$, 2 years) (n = 6); rice, followed by short pastures ($R-P_S$, 2 years) (n = 6) and $1^{st} rice - 2^{nd} rice$followed by a three and a half year pasture ($R-P_L$, 5 years) (n = 6). The EROI is expressed in $MJ\ MJ^{-1}$.

| Crop rotation | EP | | EI | EROI | |
|---|---|---|---|---|---|
| | + A | -A | | + A | -A |
| $R-P_L$ | 64,540 ± 2309 $^D$ | 106,361 ± 2901 $^b$ | 10,607 | 6.1 $^B$ | 10.0 $^a$ |
| $R-P_S$ | 80,697 ± 6117 $^C$ | 109,010 ± 10,135 $^b$ | 14,500 | 5.6 $^C$ | 7.5 $^b$ |
| R–S | 109,803 ± 11,279 $^B$ | 109,803 ± 11,279 $^b$ | 15,153 | 7.2$^A$ | 7.2 $^b$ |
| $R_C$ | 149,158 ± 8765 $^A$ | 149,158 ± 8765 $^a$ | 26,117 | 5.7 $^{BC}$ | 5.7 $^c$ |

Values followed by the different letter are significant different for a $P < 0.05$.

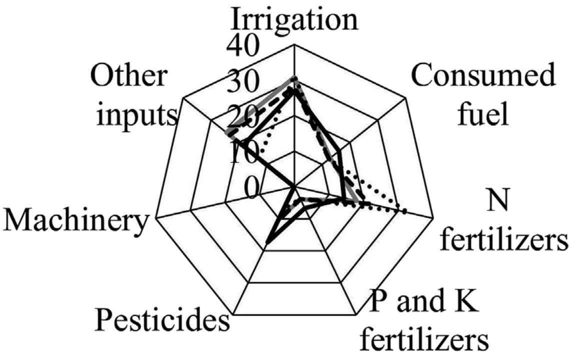


**Fig. 3.** Distribution of energy invested in four rice production systems, expressed in percentage units. Continuous rice ($R_C$, black dots); rice-soybean (R–S, black solid line); rice with short-term pastures ($R-P_S$, black dashed line), and first to second rice followed by long-term pasture ($R-P_L$, grey solid line).

estimated in rice monoculture was 21% lower than the average of the rice crops in rotation and showed a pattern similar to the second rice in $R-P_L$ (Fig. 5). There were no large variations in rice EP between rotations. On average, EP was 155,374 $MJ\ ha^{-1}$; the maximum value was found for the first rice in $R-P_L$, which was 9.6% higher than the second rice in the same rotation (Fig. 5). The two rice crops seeded on rice residues (second rice in $R-P_L$ and $R_C$) had the lowest EP, different from the bedside rice in $R-P_L$ and the rice in R–S (Fig. 5). The first rice in $R-P_L$ had the lowest EI. The second rice in $R-P_L$, the rice in rotation with short-term pastures, and with soybeans had EI values increased by 1%, 6%, and 3%, respectively, compared with the first rice in $R-P_L$. The rice in $R_C$ had a 23% higher EI than the first rice in $R-P_L$. Energy consumption by irrigation, fuel, and nitrogen fertilization accounted for approximately 70% of the EI in rice cropping in all rotations. The EI in nitrogen fertilization was higher in rice monoculture compared with other rice crops in rotation, representing 33% of the EI. Meanwhile, phosphorus and potassium fertilization EI in rice in R–S and $R_C$ was 4%, while in rice in rotation with pastures ($R-P_L$ and $R-P_S$) was 2% (Fig. 6).

## 4. Discussion

Conservation management practices including diversified farming systems are critical to reach an ecological intensification of food production in agroecosystems (Cassman, 1999). However, intensification pathways do not always fit with ecological intensification principles (Zhao et al., 2009), especially when the agroecosystem has a high dependence of inputs such as fertilizers, pesticides, and fossil energy (Godfray et al., 2010; Pimentel, 2009; Tilman et al., 2011). The challenge of intensified agriculture imply an efficient, smart and strategic use of inputs (e.g. pesticides, fertilizers, etc.), minimizing emissions (e.g. green-house gases, water pollution, etc.) increasing natural capital (e.g. soil organic carbon, soil structure), diversifying production and promoting environmental services that strengthening resilience as purpose by Conway (2012); FAO (2009); Soemarwoto and Conway (1992). This goal to request go beyond the Green Revolution principles, because in addition to increase productivity, in a lower yield gap situation, needs a holistic and broad assesment. Then, it is necessary to select specific management practices that may allow our agroecosystems to be adjusted, in the best possible way, with their intrinsic characteristics (for example, incidence of weeds, pests and diseases, soil fertility and climate change). Examples of this are the Javanese Home Garden, in several tropic regions for rice production (Soemarwoto and Conway, 1992); the rice-fish co-culture systems (Wan et al., 2018, 2019b; a, 2020) and the integrated rice-beef systems observed at Temperate Grassland terrestrial ecoregion (South America) (Denardin et al., 2019; Olson et al., 2001). However, in the rice-livestock systems, there are some questions still remaining in the designing and fine tuning of the prevalent rotations and their sustainability. Rice rotation systems analyzed in this paper, with different proportion and length of pastures and other

**Table 6**
Energy information expressed in $MJ\ (ha\ yr)^{-1}$ for mean value ± standard deviation (number of replicates) of invested energy and produced energy, with (+A) and without (-A) beef production of crops used in crop rotations: continuous rice with pasture during the winter ($R_C$); rice-soybean (R–S, 2 years); rice, followed by short pastures ($R-P_S$, 2 years) and $1^{st} rice - 2^{nd} rice$ followed by a three and a half year pasture ($R-P_L$, 5 years). The EROI is expresed in $MJ\ MJ^{-1}$.

| Crop rotation | Crop | EP | | EI | EROI | |
|---|---|---|---|---|---|---|
| | | +A | -A | | +A | -A |
| $R-P_L$ | $1^{st}$Rice | 161,809 ± 6986 (6) $^A$ | 161,809 ± 6986 (6) $^a$ | 21,183 | 7.6 $^A$ | 7.6 $^b$ |
| | $2^{nd}$rice | 147,583 ± 16,981 (6) $^{AB}$ | 147,583 ± 16,981 (6) $^a$ | 21,134 | 7.0 $^{AB}$ | 7.0 $^{bc}$ |
| | Pasture | 4435 ± 279 (18) $^{CD}$ | 74,137 ± 7577 (18) $^b$ | 3573 | 1.2 $^{CD}$ | 20.7 $^a$ |
| $R-P_S$ | Rice | 157,353 ± 12,120 (6) $^{BC}$ | 157,353 ± 12,120 (6) $^a$ | 22,23 | 7.1 $^{AB}$ | 7.1 $^{bc}$ |
| | Pasture | 4040 ± 466 (6) $^D$ | 60,666 ± 13,752 (6) $^b$ | 6771 | 0.6 $^D$ | 9.0 $^b$ |
| R–S | Rice | 160,967 ± 8179 (6) $^A$ | 160,967 ± 8179 (6) $^a$ | 22,276 | 7.2 $^{AB}$ | 7.2 $^{bc}$ |
| | Soybean | 58,640 ± 16,295 (6) $^{BC}$ | 58,640 ± 16,295 (6) $^b$ | 8031 | 7.3 $^{AB}$ | 7.3 $^{bc}$ |
| $R_C$ | Rice | 149,158 ± 8765 (6) $^{AB}$ | 149,158 ± 8765 (6) $^a$ | 26,117 | 5.7 $^{BC}$ | 5.7 $^c$ |

Values followed by the different letter are significant different for a $P<0.05$.

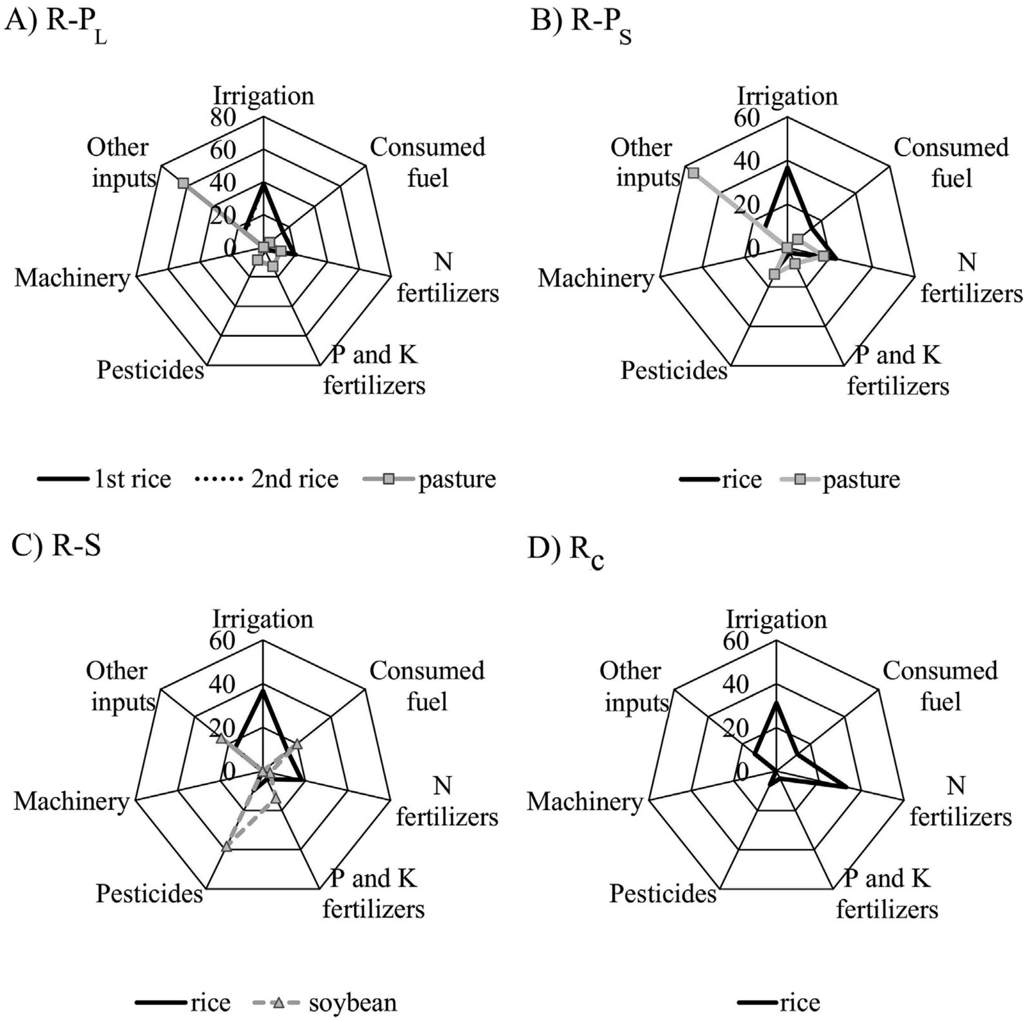


**Fig. 4.** Percentage distribution of the invested energy according to crop rotation phase: two rice crops followed by long-term pasture (A), rice with short-term pasture (B), rice-soybean (C), and continuous rice (D).

crops, are representative of the diversity and natural conditions of ecosystems from Temperate Grassland terrestrial ecoregion (Olson et al., 2001).

In the current study, intensification of a rice-pasture system, including a shorter-term pasture or replacing it with other crops, decreased the system's energy efficiency if animal production was not considered. These results are consistent with studies showing that less intense systems are more energy-efficient (Hülsbergen et al., 2001; Rathke et al., 2007). Similar to reports by Borin et al. (1997) and Kuesters and Lammel (1999), the results showed that increase in EI increased EP. However, this was nonlinear: energy efficiency was reduced by intensifying the rotation. Although the $R_C$ rotation had the highest EP, its efficiency was lower than other rice systems in rotation with pastures or soybeans. Similar results were found by Franzluebbers and Francis (1995) with sorghum and corn and by Rathke et al. (2007) with soybeans and corn in monoculture or in rotation. Pimentel (2019) found that nitrogen fertilization represented 16–35% of the total EI in corn production. The nitrogen fertilization was one of the most important components explaining EI in this study, ranging from 14% to 33% in R–S and $R_C$, respectively. In the most intensive systems, the increase in EI associated with nitrogen fertilizer was higher than the increase in EP. Franzluebbers and Francis (1995) also observed a reduction in energy efficiency with the addition of nitrogen. Conversely, Theisen et al. (2017) reported improvements in energy efficiency by intensifying a rotation of three years of rice and three fallow years (with grazing), with the inclusion of soybeans or pastures. The results of this work showed similar results when animal production was considered; in that case, only R–S system improved energy efficiency. The EI reported by Theisen et al. (2017) was higher than shown in the rotation systems evaluated in this study, which is likely due to differences in nitrogen fertilization (71 vs. 53 kg $(ha\ yr)^{-1}$). However, the EP reported by Theisen et al. (2017) was 27% lower than the EP observed herein; this is likely explained by their 26% lower rice productivity compared with the current study (10,147 $kg\ ha^{-1}$). Another important component explaining EI is the energy used to pump water for rice flooding. Rotation phases with rice had 264% more EI than rotation phases with pastures or soybean, which were not irrigated.Franzluebbers and Francis (1995), reported that irrigated maize and sorghum systems have energy costs that are 200–300% higher than the same systems under rain-fed conditions and, thus, lower energy efficiency. Although the current study compared different crops/phases, rice crops had similar energy efficiency to dry land soybean cropping (7.3 $MJ\ MJ^{-1}$). The EI in pesticides in the soybean phase was 38%. Ranges of 17–20% and 7–31% have been cited for pesticide EI in crops by Swanton et al. (1996) and Rathke et al. (2007), respectively. For the present study, the EI values for meat production during the pasture phases

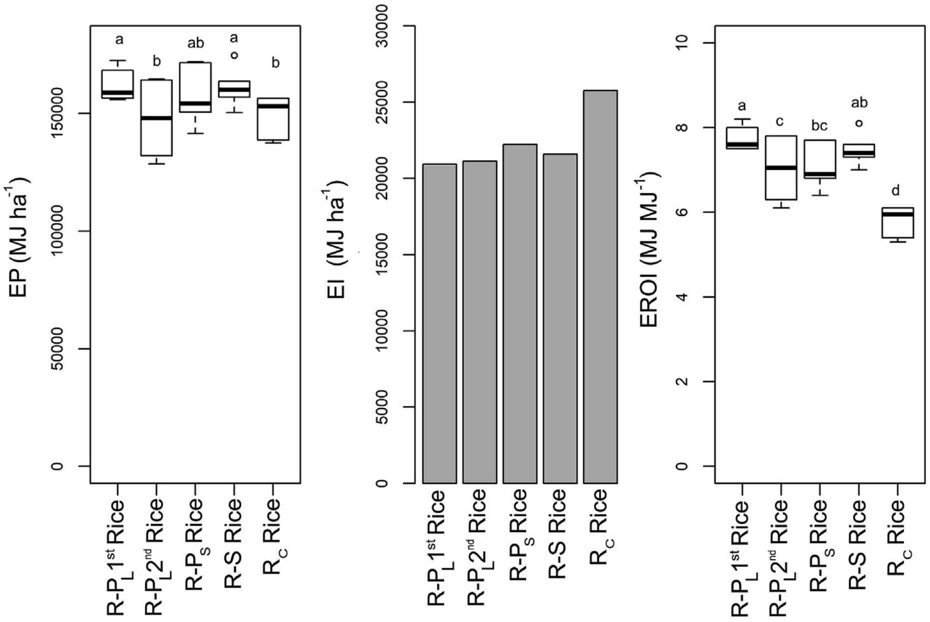


**Fig. 5.** Energy information for rice cultivation in different rice cropping systems: continuous rice ($R_C$); rice-soybean (R–S); rice and short-term pastures ($R-\ P_S$), and first rice crop followed by second rice crop and long-term pasture ($R-\ P_L$). EI: energy input; EP: produced energy; EROI: energy return on investment.

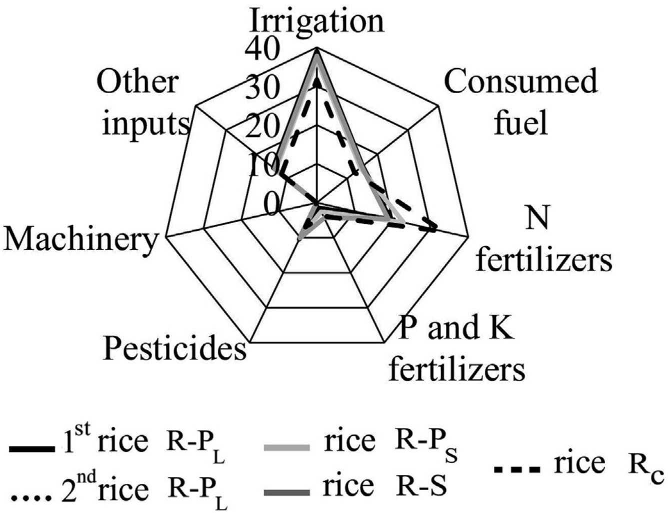


**Fig. 6.** Percentage of invested energy in each rice crop in different crop rotation systems.

were 7.5 and 12.5 $MJ\ kg\ LW^{-1}$ in $R-\ P_L$and $R-\ P_S$, respectively. Similar results have been reported by Modernel et al. (2013) in sown pastures.

Pasture longevity in $R-P_L$, allowed for some components of the EI seeding costs (fuel, fertilization, and pesticides) to be diluted by greater time compared with the pasture of $R-P_S$. The mean energy efficiency in the rice cropping observed in this work was approximately 7 $MJ\ MJ^{-1}$. Another rice study using 20 years of data from Uruguayan farmers showed similar results (6.88 $MJ\ MJ^{-1}$, EI of 17,000 $MJ\ ha^{-1}$, and net energy of 100,000 $MJ\ ha^{-1}$) for the end of the same period (2009–2013) (Pittelkow et al., 2016). Another study in Vietnam obtained similar efficiencies but calculated EP as the energy contained in both the stubble and grain (Truong et al., 2017). Truong et al. (2017) reported rice grain EP of 74,526–82,964 $MJ\ ha^{-1}$, values that are lower than the mean EP of 155,368 $MJ\ ha^{-1}$ observed herein. However, rice productivity in Truong et al. (2017) was 5–5.6 $Mg\ ha^{-1}$ compared with 10 $Mg\ ha^{-1}$ obtained in the current experiment.

The EI values for rice in rotation with pastures or soybean (R–S, $R-P_S$, and $R-P_L$) were lower than rice in monoculture and similar to the values of 17,000–20,000 $MJ\ ha^{-1}$ reported by (Pittelkow et al., 2016). In contrast, EI of 25,000–34,000 $MJ\ ha^{-1}$ was reported in high intensity rice systems of Central China (Yuan and Peng, 2017) and Vietnam (Truong et al., 2017), which are similar to those obtained in the Rc system (25,700 $MJ\ ha^{-1}$). This indicates a greater input dependence in high-intensity systems, which is mainly explained by the higher nitrogen fertilization of 1900–5900 $MJ\ ha^{-1}$ Yuan and Peng (2017) and 1900–8700 $MJ\ ha^{-1}$ (Truong et al., 2017), consistent with the values reported in this work. In the present study, the nitrogen fertilization EI in monoculture rice (8600 $MJ\ ha^{-1}$) was 95% higher than the EI in rice rotating with pastures or soybeans. Similarly, irrigation represented a higher proportion (40%) of the total EI in rice cropping compared with 15–20% of the total EI reported by Pittelkow et al. (2016). These differences can be explained by their predominant use of electric rather than diesel pumping.

## 5. Conclusions

This study showed that the highest energy production occurs in more intense rice systems, which use inputs that required higher energy levels. This must be balanced in the long term, when nonrenewable energy resources are finite. This study showed that, without considering animal production, the systems with the highest energy efficiency was rice in rotation with long-term perennial pastures.

Intensification alternatives exist for rice cropping systems, which improve energy efficiency compared with the rice-long-term pasture rotations. The rotation of rice with soybeans improved the energy return on investment compared with rotation of rice with long-term pastures, when animal production was accounted for. In any case, rice-pasture rotation consumed less energy, which makes it more sustainable. In addition, rice crops that rotated with either soybeans or pasture required less energy investment and achieved better energy use efficiency than rice monoculture.

From this perspective, the results of this study elucidate that increasing pasture participation in cropping systems play a significant role in achieving sustainable cropping rotation systems. For the Temperate Grassland Terrestrial Ecoregion of South America, EROI assessments of four business as usual rice production systems allowed to discriminate and hierarchize their sustainability and diversity.

Future studies should include other indicators to evaluate ecological intensification. They should also identify potential trade-offs between sustainability dimensions. This work focused on one aspect of environmental sustainability but did not assess other sustainability dimensions. Further works should use a holistic, integrated approach and potentially include carbon, water, and nutrients footprints.

## CRediT authorship contribution statement

**Ignacio Macedo:** Conceptualization, Methodology, Validation, Formal analysis, Investigation. **José A. Terra:** Conceptualization, Methodology, Writing - review & editing, Project administration, Supervision. **Guillermo Siri-Prieto:** Conceptualization, Writing - review & editing, Supervision. **José Ignacio Velazco:** Methodology, Resources. **Leonidas Carrasco-Letelier:** Conceptualization, Methodology, Writing - review & editing, Visualization.

## Declaration of competing interest

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

## Acknowledgments

We thank the National Institute of Agricultural Research (INIA) and the National Research and Innovation Agency (ANII) for funding this work through a national postgraduate scholarship (POS NAC 2015 1 109776).

## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2020.123771.

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