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The birth of a new cropping system: towards sustainability in the sub-tropical lowland agriculture

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ABSTRACT

Developing cropping systems that meet multiple demands of high production, resource-use efficiency and low ecological footprint is a major global challenge. In Southern Brazilian lowlands, irrigated rice (*Oryza sativa* L.) in combination with fallow for beef production is the dominant cropping system. This system is key to Brazilian food security but faces problems of resource use efficiency, soil preservation and greenhouse gas emissions typically associated to rice irrigation. In this research, a multi-criteria analysis of the usual rice-fallow system, and a number of alternative production Schemes – i.e., the more recent rice-soybean (*Glycine max* (L.) Merr.) rotations and the newly developed systems based on large ridges, was made. The latter is based on the construction of large ridges (8 m width) on which rainfed maize (*Zea mays* L.) and soybean, conducted in no-tillage, are integrated with either beef-livestock production or cover crops in winter. This study was done in an experiment that lasted for nine years. The five cropping systems were managed as independent fields and a range of indicators related to crop management, productivity and sustainability was measured. The Rice-Fallow system required the lowest amount of energy, but it had the lowest energy use efficiency and highest carbon-based environmental footprints, when expressed as greenhouse gasses emitted per kg of food produced. The rice-soybean rotation system presented an improved performance for the carbon-based footprints in comparison to the rice-fallow system. Within rice-soybean rotation, using minimum-tillage instead conventional tillage increased the overall carbon balance and the carbon sequestered into the soil as organic matter. Most strikingly, the new ridge-based systems exhibited the most favourable values for many of the indicators. The more diverse rotation system, and particularly the extension of the growing season to winter, resulted in improvements in soil quality, biomass production and carbon sequestration into the soil. Water- and light- use efficiency were increased, whereas greenhouse gas emissions reduced. The ridge-based crop-livestock integration offered the best balance between food production and environmental preservation. This cropping system is potentially one of best alternatives to increase agricultural diversification and sustainability in the sub-tropical lowlands such as in southern Brazil. This shows that modifications of cropping systems can result in major simultaneous improvements in yield, resource-use efficiency and ecological sustainability.

1. Introduction

Current cropping systems are under an increased pressure of producing more food with less inputs and to combine this high efficiency with the smallest possible negative impact on the environment (Brentrup et al., 2004; Schipanski et al., 2014). Engineering systems that meet these multiple demands is complex, particularly for agriculture in sensitive environments, like the lowlands (Durno et al., 1992). The lowlands in sub-tropical South America comprise important agricultural production systems, a large repository of freshwater and wild life. In the south of Brazil the lowlands cover a total area of 6 million hectares. Next to the environmental services provided by the natural landscapes, food production, an important additional ecosystem service, is provided through agriculture. Approximately eighty percent of rice, the main food of the Brazilian population, is produced under surface irrigation in the temperate lowlands in the south of Brazil.

Irrigated rice has been the main crop in the lowlands of south Brazil for more than a century. Rice is cultivated in 1.2 million hectares yearly, but a large part of the anthropic lowlands commonly remains fallow, or are destined for extensive beef-cattle production. The most

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common soils in this environment, gleysols and planosols, are characterized by poor drainage and a high bulk density (Lima et al., 2009). These conditions make the fields well suited for irrigated rice production, but form serious restrictions for species which do not tolerate waterlogging. As a result, rice is the main crop, and usually even the sole crop, in the agricultural systems of the lowlands.

There is however no doubt that alternation of irrigated rice with other crops bears positive implications for sustainability of the lowland agro-ecosystems (Komatsuzaki and Ohta, 2007; Hokazono and Hayashi, 2015). Crop rotation helps reduce weed problems (Erasmo et al., 2004; Andres et al., 2012) and increases soil quality (Everaarts et al., 2015). In addition, emissions of methane and other greenhouse gasses, typical for irrigated rice, can be reduced with crop rotation in lowlands (Nishimura et al., 2011; Weller et al., 2016). Despite the advantages of more diversified cropping systems and the high demand for grains other than rice in local and international markets, the use of crop rotation is not widely practiced in the wetlands. Currently, less than one-third of irrigated rice in south Brazil is rotated with other grain crops, mostly with soybean (IBGE, 2015). Also winter cover crops, like black oat, forage radishes and vetches (*Avena strigosa*, *Raphanus* sp. and *Vicia* sp., respectively), species which provide relevant environmental services for agricultural systems in the uplands (Schipanski et al., 2014; Teixeira et al., 2016), hardly adapt to the typical soil conditions in lowlands and are therefore almost absent. Obviously, the only way to create conditions that would support more diversified systems is by removing the inherent restrictions of hydromorphic soils for growing other crops. One alternative in this sense is the establishment of large ridge based systems (Fig. 1), where the alternation of ridges and small channels create a drier environment, well suited for the production of crops that do not tolerate waterlogging, as well as the introduction of cover crops during winter time. Due to the large area under fallow in the south Brazilian lowlands, introduction of such novel systems does not necessarily compete for land with the current rice production systems.

Identification of the most adequate cropping system for the lowlands, which would simultaneously achieve economic, environmental and technical demands, is an intricate task. Some production oriented, short-term studies indicated technical advantages of crop rotation and integrated crop-livestock systems over mono-crop models (Balbinot Junior et al., 2009; Vernetti Junior et al., 2009; Ferreira et al., 2014). However, long-term studies, in which sustainability is assessed from an integrated perspective and addressing a wide range of criteria, are missing. Such studies are required to capture differences that only become apparent in the long run, and also would prevent that erratic short-time events, like a drought in a specific cropping season, would distort the analysis. Considering that lowlands are one of the most attractive new frontiers for rainfed crops in southern Brazil (Feix and Leusin, 2015) and elsewhere (Durno et al., 1992), a critical analysis of current and alternative cropping systems is an important step for identifying how to best equilibrate increased food production with environmental preservation.

In this research, we analysed three rice-based cropping systems and two novel ridge-based production models implemented in the Brazilian temperate lowlands. For the rice-based models, the systems were distributed in a coherent range of configurations: one simple model (rice-fallow) plus two more elaborated systems (rice-soybean in conventional and minimum till). In addition, the ridge-based models represent two feasible alternatives: both contained summer rainfed grain crops, with one model prioritizing winter cover crops and the second focusing on crop-livestock integration. During nine consecutive years, data were collected in these cropping systems, which were composed by farm-size plots located side-by-side within an experimental station. For each of the cropping systems, indicators reflecting a range of aspects related to field and crop management, productivity and sustainability were assessed and analysed.

2. Material and methods

2.1. Site description

This study was conducted in the Lowlands Experimental Station (LES), which belongs to Embrapa (Brazilian Agricultural Research Corporation), near Pelotas, in Rio Grande do Sul (RS state), southern Brazil (31.8134 S; 52.4736 W). The experiment started in May 2006, when five cropping systems were established in a uniform 33-ha area inside LES. This field had been maintained in fallow with spontaneous vegetation since 2000, and cultivated with irrigated rice in the 2004/05 and 2005/06 cropping seasons. The terrain is flat, at 13 m above sea level and the soil is classified as Solodic haplic eutrophic Planosol, belonging to the Pelotas mapping unit (Streck et al., 2008). A soil analysis just prior to the start of the experiment indicated an average soil bulk density of 1.49 kg dm^{-3} and a composition of 283 g dm^{-3} clay, 551 g dm^{-3} silt and 608 g dm^{-3} sand. The climate is humid temperate (Cfa, according to Köppen's classification (Alvares et al., 2013)), with an average temperature of 17.8 °C and yearly precipitation of 1367 mm.

The five production systems, for which a description is included below, varied in size between 3.1 and 11.0 ha. The size varied due the permanent structure (roads, channels, fences) in the experimental station. The names of cropping systems and the essential characteristics are, noting that systems d and e are novel:

a) Rice and fallow ("Rice-Fallow"): dry-seeded irrigated rice with

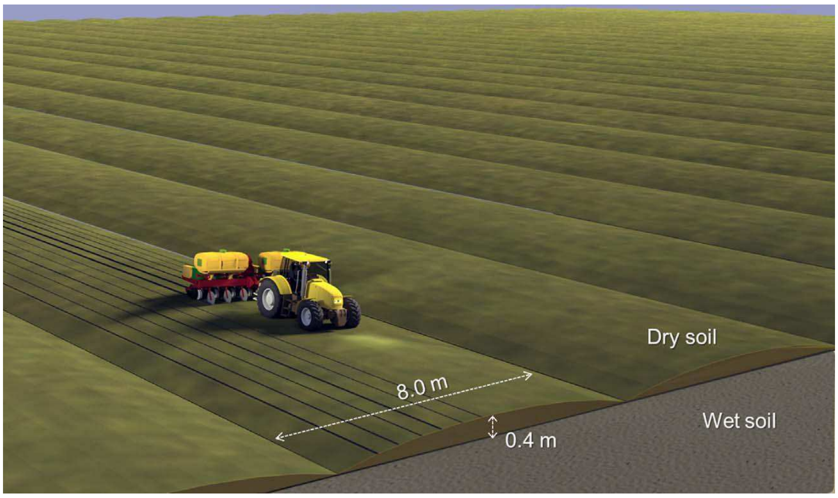

Fig. 1. Simplified drawing of a lowland field conducted with large ridges.

minimum-till soil management, cultivated for three consecutive cropping seasons, followed by a three-year interval without rice. During part of this fallow period, cattle for meat production occupied the fields (1.1 head ha^{-1}). This model of rice production, with small variations, is currently being used in the largest part of the lowlands in the RS state.

b) Rice and soybean, cultivated in conventional tillage ("Rice-Soybean CT"): dry-seeded irrigated rice cultivated for two consecutive cropping seasons, followed by two seasons of rainfed soybean. In the last cycle rice was repeated for three seasons. Main soil preparation using plough and harrow was performed in winter. In the next spring, just prior to seeding of the summer crop, one additional harrowing was conducted as seedbed preparation.

c) Rice and soybean, cultivated in minimum tillage ("Rice-Soybean MT"): The same as (b) but soil preparation was performed immediately after rice harvest; the soil was not prepared after harvesting soybean. Crops were seeded with a no-tillage seeder, after herbicidal control of spontaneous vegetation using glyphosate.

d) Rainfed crops integrated with beef-livestock, placed over large-based ridges ("Ridges and Cattle"): soybean and maize were cultivated sequentially (one crop per summer season) in no-tillage, on permanent large ridges (8.0 m wide and 0.4 m high in the center (Fig. 1)), constructed in mid-2006. In the winter seasons, the field was cultivated with pastures composed of Italian ryegrass (*Lolium multiflorum* Lam.) and black oats (*Avena strigosa* Schreb.). Beef cattle was placed on the pastures in winter, at a stocking rate adjusted to maintain a forage allowance of 12%; i.e. 12 kg of dry mass (DM) per 100 kg of cattle weight per day. Herbicidal control of the remaining vegetation was performed before seeding soybean and maize.

e) Rainfed crops integrated with cover crops, placed over large-based ridges ("Ridges and Cover crops"): the same as (d) except that during winter time the field was cultivated with cover crops (a mix of Italian ryegrass, black oats, hairy vetch (*Vicia sativa* L.) and radish (*Raphanus sativus* L.)), and, that in the last two cycles, beef cattle were placed at low density (forage allowance of 24%) on the cover crops.

All crops followed the regional standards for crop and pest management, using fertilizers, pesticides and critical levels of control according to the guidelines provided by Sosbai (2014) for rice, Reunião… (2013) for maize, and Embrapa (2012) for soybean.

2.2. Data acquisition

2.2.1. Soil quality and climatic data

The soil of the each plot was first analysed in May 2006, before the initiation of the treatments. Final soil analysis was done in August 2015, when twelve samples were collected in each cropping system. Climatic data were provided by a meteorological station located within the LES. For the timespan of the experiment, daily values of minimum and maximum temperature, precipitation and solar radiation were recorded.

2.2.2. Grains, plant biomass and beef-cattle production

Grain yield was assessed by collecting samples of crops (hand harvested) just before combine harvesting. Individual sample size varied between 6.0 m^2 (rice) to 20.4 m^2 (maize and soybean). The number of samples per crop in a season was on average 14, attaining to 40 samples in some years. The samples were threshed in an electrical threshing machine. Grain moisture was evaluated in an automatic analyser and the yield was standardized to 13% moisture for all crops.

The biomass of aerial parts of crops, cover crops, pastures and spontaneous vegetation was measured by collecting eight samples per system at the end of both winter and summer seasons, with an individual sample area of 2.25 m^2. Biomass was dried at 60 °C for 2 days before weighing. Root biomass was estimated as 20% of total dry mass (Poorter et al., 2012). Seed production from cover crops and spontaneous vegetation was assessed by collecting shattered seeds, using 15 units ha^{-1} of 12-cm diameter dishes, randomly distributed in each cropping system. The seeds were dried at 60 °C for 2 days before weighing.

Cattle production was evaluated by weighing each livestock unit on the days of entry and exit from the fields. The herd was composed of 1.5–2 year old steers and heifers of Charolaise breed. Production of cattle manure (dung + urine) was assumed as 6% of cattle live weight per day (Santos and Nogueira, 2012). Composition of nutrients in manure, as well as the nutrients exported by grains and cattle live weight, were calculated using standard values from the technical manual of soil fertility and fertilizers for southern Brazil (Comissão de Química e Fertilidade do Solo − RS/SC, 2004).

2.2.3. Data about field operations

All field procedures and machinery used were equivalent to that used in commercial farms. The data collected were: a) the time to achieve each field operation; b) the fuel consumption, measured by filling the fuel tanks before and after each operation and recording the difference in volume. For the aircraft operations (pesticide application once and nutrient application six times) fuel consumption was provided by the service supplier; c) the electricity consumption for pumping water to the rice fields, measured as the difference registered in the electric meter at the start and the end of the cropping season; d) the time the water pump was running; e) the weight of all equipment, with the weight of tires and tubes separately considered.

Description of the machinery, their weight, operational yield, average fuel consumption, embodied energy and total energy consumption is presented in Table A, in the Supplemental file. Embodied energy is the energy consumed to build the machinery. Embodied energy of machinery and the energetic depreciation in time was calculated using procedures described by Bowers (1992) and Pimentel (1992). Additionally, the amount and type of seeds, nutrients and pesticides used were registered for each cropping system.

To estimate the energy consumption related to labour, the recorded time of field operations was used as a basis. Additionally, 30 min extra for seeding and harvesting, and 15 min extra for soil operations, pesticide application, spreading nutrients and seeds, to account for loading and cleaning the machinery after use were added. Also, 25 min and 1 L of diesel were added to each field operation, to cover for the round trips between the LES machinery shelter (garage) and the farming systems (5.2 km). The time for managing the cattle and the time for monitoring and maintenance of channels and levees in rice fields were also recorded.

A pumping station located in a lake at approximately 1.5 km from the experimental area supplied water for irrigation of rice fields. A centrifugal horizontal pump (430 kg), running with a 100-CV three-phase electric motor (486 kg) was used for pumping.

The experimental farms were located at 16 km from the commercial point of acquisition of supplies and delivery of grains and cattle. To assess the transporting costs, the weight of main inputs (fertilizers, diesel fuel, seeds and pesticides) and outputs (grains and cattle) were considered in these calculations. Distance from the farms to the market point was multiplied by 2, to account for the return journeys. Data from a truck of 20 T load capacity yielding 2.75 km L^{-1} of diesel was used. The average time in transport of goods was 1.75 h for acquiring inputs and 2.0 h for delivering grains and cattle.

2.2.4. Energy content in inputs and outputs

The energy equivalent contained in inputs, grains, biomass and livestock are described in Table B, in the Supplemental file. Due to difficulties in finding reliable regional data about the energy content of inputs, we applied the following criteria for obtaining reasonable information: a) using data earlier described for similar cropping system evaluations; b) using data that included production, packaging and distribution costs; c) using the most recent data available in literature.

2.2.5. Carbon (C) in soil, greenhouse gas emissions (GHG) and CO_2-e balance (global warming potential)

The accumulation of C in the soil (0–20 cm) was calculated as the difference between the content of soil organic matter (SOM) at the start and the end of the experiment. The C in SOM was assumed as 58% and was adjusted to soil bulk density, as described in Rosa et al. (2011). The value for carbon in plant residues was estimated to be 45% of the dry mass, following data for similar crops from Aita and Giacomini (2003) and Niu et al. (2016). GHG emissions (CH_4 and N_2O) were estimated in CO_2-equivalent units (CO_2-e), using conversion indexes 25 and 298, for CH_4 and N_2O, respectively, as proposed by IPCC (2006). The CO_2-e balance (net Global Warming Potential) for each cropping system was assessed by calculating the difference between the C from emissions (converted from CO_2-e) and the C sequestered as organic matter in the soil.

GHG emission values adopted for inputs were 3.368 kg CO_2-e L^{-1} for diesel (2.966 kg CO_2-e from combustion (IPCC, 2006) + 0.320 kg CO_2-e from production (Carvalho, 2012) + 0.082 kg CO_2-e from transports (Eriksson and Ahlgren, 2013)); 5.15 kg CO_2-e kg^{-1} for urea, 2.03 kg CO_2-e kg^{-1} for di-ammonium-phosphate, 0.27 kg CO_2-e kg^{-1} for super triple phosphate, and 0.25 kg CO_2-e kg^{-1} for potassium chloride (Fertilizers Europe, 2014). For pesticides, an emission of 0.069 kg CO_2-e per MJ required to produce 1 kg a.i. was assumed (Audsley et al., 2009). The GHGs emitted for seeding material (seed production, processing, packaging and transport) were estimated as a function of seed energy content (adapted from Heichel, 1980).Values used were 3.02; 0.97; 0.98; 1.09; 1.17; 1.06 and 1.02 CO_2-e kg seed $^{-1}$ for maize, rice, soybean, ryegrass, black oats, vetches and radish seeds, respectively. Emission of CH_4 from enteric fermentation by cattle was calculated following *Tier 2* from IPCC for the RS State (45 kg CH_4/head yr^{-1}); N_2O released from manure excreted in pastures was assumed as 2% of the N content of manure (Lima et al., 2010). CH_4 emissions from irrigated rice followed the regional standards of 0.395 and 0.266 Mg CH_4/ha $season^{-1}$ for conventional and minimum-tillage, respectively (Bayer et al., 2013). Emissions from crop and cover crop residues followed the assumption that 1% of nitrogen in the residues are emitted as N_2O (IPCC, 2006). Content of N in biomass was 2.43% for the leguminous and 1.25% for the non-leguminous species (Aita and Giacomini, 2003; Assmann et al., 2015). GHG emissions associated with production and maintenance of machinery was assumed to be 5.38 kg CO_2-e kg^{-1} for small tractors (75 CV) and implements, 4.93 kg CO_2-e kg^{-1} for medium-size tractors (121 CV) and 4.94 kg CO_2-e kg^{-1} for harvesters (Mantoam et al., 2016).

2.2.6. Data adjustment in rice-fallow cropping system

The Rice-Fallow cropping system completed 1.5 full cycles in the timespan of this study. The missing part of the 2nd cycle corresponds to the period in which the system would be on rice production. For some indicators, this imbalance would result in biased, incorrect results. To correct for this, we included additional seasons for this cropping system through simulation. The new data, simulating three additional cropping seasons, were estimated using the Bayesian Monte Carlo's method, in WinBugs software (Lunn et al., 2000). To generate the new set of data, initial yield predictions for 2016, 2017 and 2018 based on a squared-regression of the yearly rice yields from the 12 municipalities near LES between 2000 to 2015, were combined with the grain yield obtained in the experimental Rice-Fallow system registered in 2010, 2011 and 2012. For input data, the amount of inputs used in the previous rice growing period (2010–2012) was increased with 2%, to follow the regional trend. Cattle and other biomass production used in the simulated period was the same as registered in 2010–2012 cropping seasons. All comparisons evolving from these adjusted data, or the indicators derived from it, were normalised on a yearly basis.

2.2.7. Data summary and indicators established

The first step of this analysis consisted of a check on the grain yields obtained in the experimental condition for rice, soybean and maize, as well as the respective regional averages (Table C, in the Supplemental file). In the second step, we summarized the fraction of time the field in each cropping system was left fallow or occupied by grain crops, cover crops, pastures or cattle. Subsequently, the partitioning of biomass produced by the cropping systems was analysed. Newly produced biomass was separated in grains from cash crops, any other plant biomass and gains in cattle live weight. Hereafter, the yield of grains and cattle weight gains destined for human consumption will simply be termed as "food". Biomass production was further distinguished according to the season it was produced in, either summer or winter. The balance of main nutrients (N, P_2O_5 and K_2O) was calculated based on the difference between the nutrients applied and the nutrients exported as food. Nutrient cycling within the cropping systems by means of cattle manure were also calculated. For this, we used the guidelines from Comissão de Química e Fertilidade do Solo – RS/SC (2004).

For each cropping system, the total energy consumed (TEC) was calculated. For the TEC, a distinction was made between direct and indirect energy sources. Direct energy sources include production-related energy expended on-farm: fuels, electricity, seeds and human labour; indirect energy sources is the production related off-farm energy use, including energy costs of producing fertilizers, pesticides and energy embodied in the machinery (Campos and Campos, 2004).

$$\mathrm{TEC}(\mathrm{M\,Jha^{-1}}) = \Sigma\ \mathrm{inputs}(\mathrm{direct\ energy} + \mathrm{indirect\ energy}) \tag{1}$$

The energy balance (EB) was calculated by subtracting the total energy consumed (TEC) from the energy contained in both grains and gains in cattle live weight (EnFood).

$$\mathrm{EB}(\mathrm{MJ\,ha^{-1}}) = \mathrm{EnFood} - \mathrm{TEC} \tag{2}$$

The net energy ratio (NER), also called Energy Return on Energy Investment, represents the energetic conversion of a production system. Net energy ratios for the cropping systems were calculated according to the formula below.

$$\mathrm{NER}(\mathrm{MJ\,ha^{-1}}) = \frac{\mathrm{EnFood}}{\mathrm{TEC}} \tag{3}$$

The capacity of cropping systems to convert natural resources, particularly water and solar radiation, in grains, was assessed by means of the productivity indicators Water Productivity (WP) (Kijne et al., 2003) and Solar Radiation Productivity (SRP). The resource availability of both indicators was calculated based on the daily weather records. WP and SRP were estimated at three integration levels: for individual crops; for all grain crops within a cropping system; and for the overall cropping system. The period considered for determining the available water for calculation of WP started five days before crop seeding and finished at the date of harvest. WP included rains and water used in rice irrigation. The SRP is a modified version of the Radiation Use Efficiency indicator (Campillo et al., 2012). In the SRP, rather than using the intercepted radiation, the incident photosynthetically active radiation (PAR) is considered. The start date for SRP was at crop emergence, and the final date was at crop maturity, which corresponded to one week after the R9 growth stage for rice, growth stage R8 for soybean and growth stage R6 for maize. PAR was estimated as 47% of the total solar incident radiation (Assis and Mendez, 1989). To calculate the SRP of the whole system, all biomass produced by a cropping system was considered, not just the grains. The following formulas were used:

$$\mathrm{WP}(\mathrm{kgm\,m^{-1}}) = \frac{\mathrm{grains}(\mathrm{kg\,ha^{-1}})}{\mathrm{rainwater{+}irrigation}(\mathrm{mm\,ha^{-1}})} \tag{4}$$

$$\mathrm{SRP}(\mathrm{kg\ GJ\ PAR^{-1}}) = \frac{\mathrm{grains}(\mathrm{or\ biomass})(\mathrm{kg\,ha^{-1}})}{\mathrm{PAR}(\mathrm{GJ\,ha^{-1}})} \tag{5}$$

The capability of cropping systems to deliver a social benefit (number of people fed per unit of area cultivated per year (PFY)) was estimated. To calculate PFY, the energy and the protein harvested as food were divided by the consumption of an average person. Average daily human consumption was set to 80 g d^{-1} and 8.7 MJ d^{-1} for protein and energy, respectively. The protein levels used to calculate PFY were 9% for maize, 7% for rice husked grains (65% milling yield), 36% for soybean and 64% for the cattle meat on dry mass basis. The energetic content of rice, maize, soybean and meat is listed in Table B, in the Supplemental file.

Two sets of carbon-based footprints were calculated for each cropping system. The first set was based on the average annual amount of GHG emissions, whereas the second set was based on the soil-atmosphere CO_2-e balance. Both values were divided by the food produced in a system, resulting in the “GHG Intensity Footprint” and the “CO_2-e Footprint”. Alternatively, both values (GHG emissions and CO_2-e balance) were divided by the number of persons fed per year (PFY) on energy basis, resulting in the “Personal GHG Footprint” and the “Personal CO_2-e Footprint” indicators.

2.2.8. Statistical analysis

Each crop system was conducted in a unique large plot, and the analysis performed with data collected during nine cropping seasons. Data were tested for normality assumption by using the Shapiro-Wilk test, provided by the Proc Univariate in SAS software version 9.3 (SAS Institute, 2016). Descriptive statistics (means, medians, standard error of means (SEM) and standard deviation (SD)) were obtained in SAS, using the Proc Means procedure. Mixed models, with cropping systems as the fixed factor and cropping seasons as random factors, were applied to data using Proc Mixed in SAS. The cropping systems were compared by the differences of least squares means (LSMeans), using a critical level of $p = 0.05$. The carbon-based footprint indicators presented non-normal data distribution and were reported with medians and SD, instead of means and SEM. Extreme values in some cropping seasons skewed the means far from the realistic values, and this could easily result in an incorrect interpretation of results. Medians were more robust descriptors of data in this case. Indicators and variables are presented as annual means and their corresponding SEM, except if indicated otherwise.

3. Results

3.1. Grain yields

In the study period (2007–2015), the average grain yield of rice, soybean and maize for the 14 municipalities near the experimental area were 7.4 (rice), 2.2 (soybean) and 2.7 (maize) Mg ha^{-1} (IBGE, 2016). Under the experimental conditions, the average grain yield of rice and soybean obtained in the three rice-based cropping systems were similar to these regional averages. In contrast, in both ridge-based cropping systems, the average grain yields of soybean and maize were superior over the regional yields. For soybean, the average yield was about 15% higher. For maize a much more substantial difference was observed, as average grain yield in these new systems was around 140% higher than the regional average. It shows that particularly maize benefitted from the conditions provided by the ridge-based systems.

3.2. Distribution of activities over time

Cash crops (rice, soybean and maize) were only cultivated in summer. In the Rice-Fallow system, the land was used for grain production during 20% of the time, whereas in the remaining 60% land was kept fallow. Cattle was kept for about 20% of the time (Fig. 2). In the other cropping systems, the use of land for cash crops more or less doubled, to around 40% of the time. In the rice-soybean systems the land was on fallow for approximately 60% of time, period that corresponds to winter, when fields are unused.

Contrarily to the other production models, the ridge-based systems did not include a fallow. The dry soil provided by the ridges permitted the cultivation of pastures (in Ridges and Cattle) and cover crops (in Ridges and Cover crops) during winter. Cattle were kept in the field for a small portion of time in the ridge-based systems (22% of wintertime for Ridges and Cattle, and 8% of wintertime for Ridges and Cover crops).

3.3. Biomass production

Biomass production patterns differed between the cropping systems ($p < 0.05$). In the Rice-Fallow, grains (rice) corresponded to 44% of the total biomass produced by this cropping system. In both rice-soybean systems, the biomass from grains made up the larger part (53%) of the total biomass produced. But this fraction was only 33% for the ridge-based systems (Table 1). While the production of grains in the rice-soybean systems was 5.07 Mg per year, the crops cultivated in the ridge-based systems produced around 9% less. However, in the ridge-based systems the biomass remaining in the soil was two times larger than in the rice-soybean systems. In cropping systems producing cattle, the gains in livestock weight made up only a very small amount of the total biomass production. The total biomass produced in the ridge-based systems was on average 13.5 Mg ha yr^{-1}, which was significantly larger than the biomass produced by the Rice-Fallow system. The difference between these systems was approximately 5.2 Mg ha yr^{-1}.

No differences in residue biomass of the summer crops were observed between the five cropping systems. On average, an estimated 3.96 Mg ha^{-1} DM per year was produced in summer (Fig. 3). Clearly, the large differences in biomass production between cropping systems occurred in winter: that of the ridge-based systems being 12–33 times higher than in rice-soybean systems and 4.5–5.5 times higher than the Rice-Fallow system.

3.4. Carbon in soil, GHG emissions and carbon balance

In 2006, the amount of carbon in the soil (0–20 cm deep) was approximately 27 Mg ha^{-1}. At the end of experiment (2015), the content varied between 27 and 34 Mg ha^{-1} (Table 2). Except for the Rice-Fallow system, all cropping systems sequestered carbon into the soil, with values ranging from 0.13 to 0.77 Mg C ha^{-1} per year. The rice-soybean cropping systems accumulated less C (around 0.5 Mg ha yr^{-1} less, on average) than the ridge-based systems.

The emissions of GHG varied between 2.2 and 7.2 Mg ha yr^{-1} for the five cropping systems (Table 2). On average, the rice-soybean rotations emitted more GHG than the ridge-based systems. Rice-soybean conducted in conventional tillage emitted 30% more CO_2-e than in minimum tillage. This difference, however, was not statistically significant ($p = 0.53$). Cropping systems containing irrigated rice emitted, on average, 3.5 Mg ha yr^{-1} more than the systems without rice (ridge-based). The emission of methane from the flooded fields caused this difference. Methane represented approximately 70% of all GHG emissions in the three cropping systems containing irrigated rice (data not shown).

The Rice-Fallow system, even though it left the level of SOM unchanged, presented a negative CO_2-e balance and had a negative profile in terms of global warming potential. Negative CO_2-e balances also occurred in both rice-soybean cropping systems. The amount of biomass produced and sequestered into the soil was not sufficient to guarantee a net accumulation of C in these systems. On the other hand, the cropping systems conducted on ridges had a net accumulation of carbon into the soil, estimated to be equivalent to 0.16 Mg CO_2-e per ha per year, averaged over both systems (Table 3). The carbon from biomass effectively sequestered into the soil organic matter varied between cropping systems, being calculated as less than 1% for the Rice-Fallow system, 6% for Rice-Soybean CT, 12% for Rice-Soybean MT, and between 16 and 20% for the ridge-based systems.

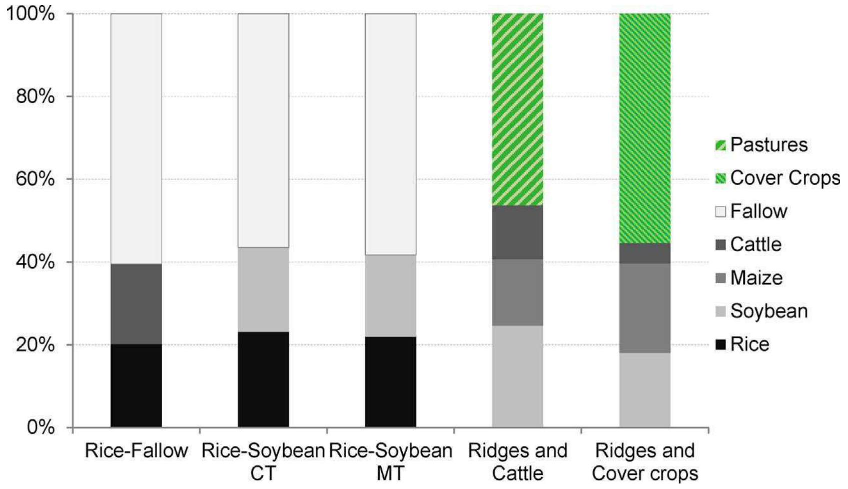

Fig. 2. Cumulative fraction of time fields were occupied with a main crop (rice, soybean or rice), cattle, pastures, cover crops, or were left fallow in five cropping systems.

Table 1
Average annual production of biomass and the partition of this biomass over grains, cattle and other biomasses in five cropping systems.

Product	Cropping system				
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops
	kg ha yr^{-1}				
Grains	3652 (265)	5196 (992)	4943 (871)	4896 (990)	4159 (630)
Cattle	50 (14)	–	–	152 (23)	42 (5)
Other biomasses	4617 (537)	4492 (719)	4523 (615)	8713 (927)	9093 (994)
Total	8319 (1595)b	9688 (1711)ab	9466 (1483)ab	13761 (1764)a	13294 (1477)a

The mass of grains is adjusted to 13% of moisture, the mass of cattle as gains in live weight and the other biomasses as dry mass. Means followed by the same letter are not significantly different at $p < 0.05$. Values between parentheses are the SEM.

3.5. Soil characteristics and nutrient balance

The level of soil organic matter was around 1.6% in 2006, but varied between 1.7% and 2.3% in 2015 (Fig. 4). The changes in SOM were small in the systems containing rice, but increased 46% in the cropping systems conducted on ridges.

Between 2006 and 2015, soil K and P levels declined in the Rice-Fallow, while P increased in all other systems. In the ridge-based cropping systems, the levels of P increased between 10 (Ridges and Cover crops) and 36 (Ridges and Cattle) times. In the cropping systems with crop rotation and minimum- or no-tillage Rice-Soybean MT, Ridges and Cattle, and Ridges and Cover crops, the level of K was increased (Fig. 4).

The amount of N, P_2O_5 and K_2O applied as fertilizer in the cropping systems followed the official recommendations for soil nutrition in south Brazil for medium to high grain yields of the respective crops (Comissão de Química e Fertilidade do Solo – RS/SC, 2004), and thus received distinct average annual amounts of nutrients. The ridge-based systems received more nutrients through fertilizers than the other cropping systems (Table 3). Use of fertilizers during winter was the main reason for this difference. Around 25% of fertilizers in the ridge-based systems were applied during winter, on pastures or cover crops. In most cropping systems, K_2O was the nutrient applied in the highest quantity. However, for the Rice-Fallow system, which did not have leguminous crops included, N was the nutrient applied in the highest quantity.

On average, the yearly exports of food from the cropping systems contained 95 kg N ha^{-1}, 39 kg P_2O_5 ha^{-1} and 38 kg K_2O ha^{-1} (Table 3). For all systems, the simplified balance between applied and exported nutrients was positive: more nutrients were applied than removed from the fields. The ridge-based systems accumulated around 150 kg/ha yr^{-1} of nutrients (N + P_2O_5 + K_2O), rice-soybean systems accumulated 97 kg/ha yr^{-1} and the Rice-Fallow system around 39 kg/ha yr^{-1}.

3.6. Manure production and nutrient cycling within the cropping systems

The integration of irrigated rice with beef-cattle is used in large parts of the lowlands in the RS state. The nutrients contained in manure, cycled from cattle into the soil, corresponded to 52%, 44% and

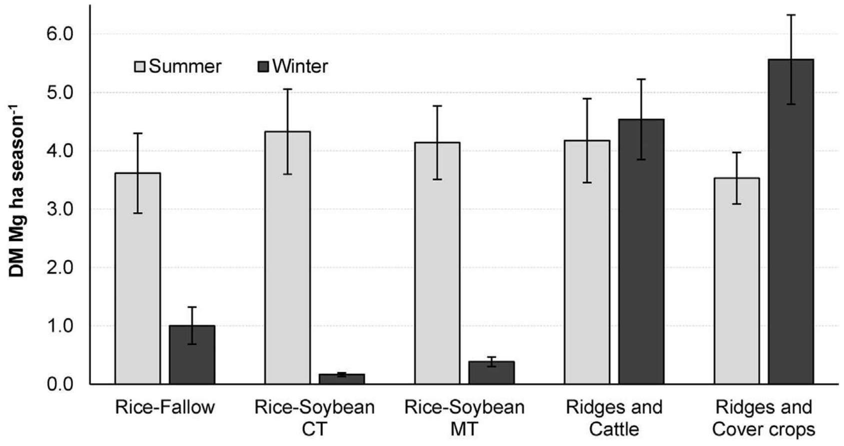

Fig. 3. Biomass production (Mg DM ha^{-1} per season) in summer and winter in five cropping systems. Includes aerial biomass, roots and seeds. Grains from cash crops and gains in cattle live weight are not included. Error bars are the SEM.

Table 2
Organic carbon in soil (0–20 cm), carbon sequestered in organic matter, CO_2-e emitted and balance of CO_2-e between 2006 and 2015 in five cropping systems.

	Cropping system				
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops
Carbon in soil	Mg C ha^{-1} in soil				
C content (2006)	27.77	26.43	26.43	27.36	27.36
C content (2015)	27.92	27.59	28.61	34.33	33.16
C sequest. (yr^{-1})	0.016	0.129	0.243	0.774	0.645
Emissions and balance[a]	Mg CO_2-e ha yr^{-1}				
CO_2-e emitted	5.03 (1.32)ab	7.23 (2.02)a	5.56 (1.46)a	2.64 (0.30)bc	2.23 (0.19)c
CO_2-e balance	-4.97 (1.32)b	-6.75 (2.02)b	-4.67 (1.46)b	0.19 (0.30)a	0.13(0.19)a

[a] CO_2-e calculated from fuels, machinery, electricity for irrigation, seeds, fertilizers, pesticides, methane from enteric fermentation in cattle and from rice fields, N_2O from cattle manure on pastures and from biomass decomposition. Negative values in the balance indicate net emissions into the atmosphere. Means in a row followed by the same letter are not significantly different at $p < 0.05$. Values between parentheses are the SEM.

Table 3
Nutrients applied, exported through grains and cattle and nutrient balance in five cropping systems.

Nutrient	Cropping systems				
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops
	Nutrients applied (kg ha yr^{-1})				
N	48.6	67.2	67.2	86.2	87.0
P_2O_5	38.3	77.0	77.0	77.7	86.8
K_2O	37.4	83.7	83.7	105.9	97.8
Total	124.3	227.9	227.9	269.8	271.5
	Nutrients exported through grains and cattle (kg ha yr^{-1})				
N	41.2	94.4	94.8	135.0	109.5
P_2O_5	25.9	39.2	37.6	50.0	41.9
K_2O	18.4	40.0	39.9	49.8	40.6
Total	85.5	173.6	172.3	234.9	192.0
	Nutrient balance (kg ha yr^{-1})				
N	7.4	13.1[a]	16.2[a]	53.0[a]	60.2[a]
P_2O_5	12.4	37.8	39.3	27.7	44.9
K_2O	19.0	43.7	43.8	56.0	59.3
	38.8	94.7	99.4	136.7	162.3

[a] The balance was adjusted assuming that N for soybean was supplied by symbiosis with *Bradyrhizobium*, at efficiency rates of 85% in rice-soybean systems and 95% in ridge-based systems.

9% of all external nutrients applied into the Rice-Fallow, Ridges and Cattle and Ridges and Cover crops systems, respectively (Table 4). For the Rice-Fallow, the manure probably was the most important source of nutrients available to plants in winter, besides some residual nutrients from the previous rice cultivation. Manure is a known source of nutrients, supports soil microbial live and can affect the nutrient balance in the soil, but a detailed evaluation of how manure decomposition affected soil fertility was not an objective of the present study.

3.7. *Energy consumption, balance and conversion*

Of all systems evaluated, the Rice-Fallow consumed the smallest amount of energy (Fig. 5). This is not surprising, since rice cultivation, the most energy-demanding activity, was present in the field for a relatively short period of time. Fallow and cattle production demand a low amount of energy compared to rice production. The rice-soybean cropping systems required, on average, 45% more energy than the Rice-Fallow system. The ridge-based systems, in turn, required on average 30% more energy than the Rice-Fallow but 11% less energy than the rice-soybean systems.

In the systems containing irrigated rice, the proportion of direct energy was apparently higher than in the other systems. Energy for irrigation makes the difference in this case (data not shown). For the ridge-based cropping systems, direct and indirect energy were roughly consumed in similar amounts. The overall values of energy consumed in the cropping systems [15–22 GJ ha yr^{-1}] are within the range previously reported for studies on energy use in diversified cropping systems (Alipour et al., 2012; Fuksa et al., 2013; Sá et al., 2013).

All cropping systems had a positive energy balance: the energy produced as food was higher than the energy supplied to produce it. The net energy balance varied between 44 and 63 GJ ha year^{-1} and did not differ significantly between cropping systems ($p = 0.72$). The net energy ratio (NER) however did differ between cropping systems, being, on average, 56% and 9% higher in the ridge-based systems than in the rice-fallow and rice-soybean systems, respectively (Table 5).

3.8. *Water productivity*

Water Productivity from individual crops varied between 4.4 and 18.0 kg mm^{-1} (Table 6). Maize was the most efficient crop: it produced almost three times more grain weight per unit of water than soybean or rice. On average, the crops in the ridge-based systems were 2.3 times more efficient in using water than in the other cropping systems. When analysing water productivity at the cropping systems level, which included the rains occurred during winter and summer, a significant difference ($p < 0.05$) was found between the rice-fallow system and the novel ridge-based systems. On average, production of grains per unit of water in the ridge-based systems was around 3.7 times more efficient than in rice-fallow. These differences are partly inherent to the distinct crops used in these systems, but also due to the large time rice-fallow remains not cultivated. Obviously, water from rains during the fallow period is mostly ‘wasted’ and hardly used for grain production.

3.9. *Solar radiation productivity*

Values estimated for SRP of individual crops varied from 0.17 to 0.81 kg GJ PAR^{-1} (Table 7). Maize and rice were approximately 3.5 times more efficient than soybean. For maize, this result probably arises from a combination of the C4 photosynthetic pathway and the short growing cycle. For irrigated rice, the result occurred from a combination of a short growing cycle (110 days from emergence to maturation, on average) with the high grain yield produced under irrigation. Irrigation, in this case, seems to be the key factor to compensate the less efficient C3 photosynthetic pathway.

When all biomass produced over the entire year was considered, the systems conducted on ridges had higher SRP values than the rice-and-fallow system ($p < 0.05$). Such difference can be attributed from the higher biomass produced during winter (Fig. 3), as SRP’s of grain crops (produced during summer) did not differ significantly between systems. The SRP in summer was similar between the cropping systems (average of 0.69 kg GJ PAR^{-1}). For the winter, cropping systems running on ridges presented SRP of 0.46 kg GJ PAR^{-1}, but only 0.06 kg GJ PAR^{-1} was calculated for the systems running in flat soil (data not shown).

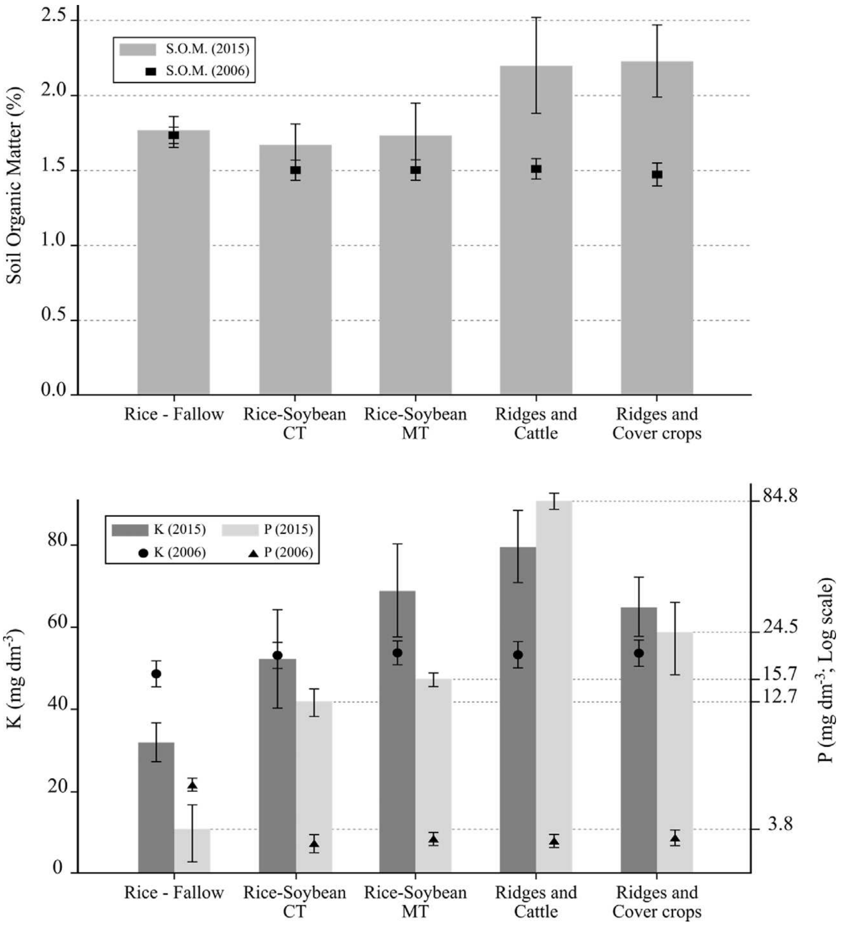

Fig. 4. Level of Soil Organic Matter (S.O.M.), P and K in 0–10 cm soil profile in five cropping systems in 2006 and after nine years of rotation. Error bars are the SEM.

Table 4
Manure produced and respective amount of nutrients cycled into the five cropping systems.

Component	Cropping Systems				
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops
	kg ha yr^{-1}				
Dung + urine	1478	0	0	2729	525
N	22.2	0	0	40.9	7.9
P_2O_5	20.7	0	0	38.2	7.5
K_2O	22.2	0	0	40.9	7.9
Total nutrients	65.1	0	0	120.0	23.3

3.10. *Theoretical number of persons fed per unit of land cultivated*

Taking account of the daily requirement of energy for an average person, the theoretical number of persons fed in one year by the food produced on one hectare varied from 12 to 26 (Fig. 6). For the protein requirement, the values varied from six persons, in Rice-Fallow system, to 30 persons, in the Ridges and Cattle system. This result stems from the fact that the Rice-Fallow produced predominantly rice, which has low protein content. Despite the relatively high content of protein in the meat, the contribution of cattle to the overall protein production in the cropping systems was low. Cattle represented only 2.0% of food produced in the Rice-Fallow system and 3.2% and 1% for Ridges and Cattle, and Ridges and Cover crops, respectively.

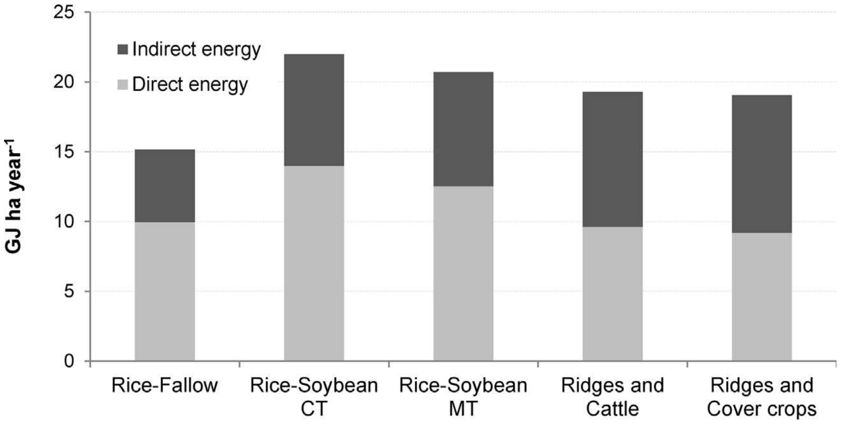

Fig. 5. Average annual energy consumption (TEC), distinguished according to source type (direct or indirect), by five cropping systems.

Table 5
Energy balance (energy out – energy in, GJ ha $year^{-1}$) and net energy ratio (energy out:energy in) of the five cropping systems.

Indicator	Cropping systems				
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops
Energy Balance (GJ ha $year^{-1}$)*	43.75 (13.7)	61.79 (13.2)	59.07 (11.4)	62.86 (15.6)	49.89 (9.7)
Net Energy Ratio (MJ_{out} MJ_{in}^{-1})**	2.53 (0.54) b	3.56 (0.36) ab	3.68 (0.31) ab	4.18 (0.74) a	3.72 (0.56) ab

Values between parentheses are the SEM.
* The means did not differ between the cropping systems ($p = 0.72$).
** Means followed by the same letter are not significantly different at $p < 0.05$.

Table 6
Water Productivity of grain production (kg mm^{-1}) in five cropping systems.

Crop	Cropping systems					
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops	Average
	kg mm^{-1}					
Rice	5.07 (0.35)	5.67 (0.30)	5.26 (0.35)	–	–	5.32 (0.19)
Maize	–	–	–	18.04 (1.19)	12.58 (2.49)	15.49 (1.63)
Soybean	–	4.44 (0.24)	5.28 (0.85)	4.72 (0.62)	4.63 (0.20)	4.77 (0.27)
Crops average*	5.07 (0.35) b	5.44 (0.26)b	5.26 (0.32)b	14.17 (2.23)a	10.46 (1.96)a	–
System average**	1.30 (0.45) b	2.55 (0.63)ab	2.57 (0.65)ab	5.33 (1.70)a	4.29(1.34) a	–

Values between parentheses are the SEM.
* Means weighted averaged by the amount of grains produced by each crop in the respective cropping system; means followed by the same letter are not significantly different at $p < 0.05$.
** Yearly average estimated from the grains produced and the water from rains and irrigation, during the full time span of the experiment; means followed by the same letter are not significantly different at $p < 0.05$.

3.11. Carbon-based footprints

The carbon-footprint is a single, quantitative, but very robust indicator which integrates inputs and outputs to estimate the impact of the agricultural process in terms of the global warming perspective. The GHG Intensity Footprint represents the greenhouse gasses emitted per kg of food produced. The highest value for this indicator occurred in the Rice-Fallow system, with 3.3 kg CO_2-e kg^{-1} food (Table 8). When rice was rotated with soybean, GHG intensity was reduced with around 62%. For the rice-soybean rotation the use of minimum tillage, instead of conventional tillage, represented a mitigation of 0.32 kg CO_2-e in emissions for each kg of food produced. The lowest values for this indicator occurred with the ridge-based systems, with around 0.62 kg kg^{-1}. The GHG emissions per kg of food produced in the ridge-based systems represented a fraction of just 19% in comparison with the Rice-Fallow system, and of 50% compared to the rice-soybean systems.

The Personal GHG Footprint represents the ratio between the quantities of GHG emitted for each person a cropping system is able to feed, in a year. Rice-Fallow presented a Personal GHG Footprint 3.3 times higher than that calculated for the rice-soybean systems. For each person the rice-soybean rotations are able to feed in a year, 330 kg CO_2-e is emitted to the atmosphere. Also from this perspective, the ridge-based systems are more efficient as the emissions were reduced to around 120 kg CO_2-e per person. This value corresponds to a fraction of 11% of that of the Rice-Fallow system, and of 36% compared to the rice-soybean systems.

The footprints based on the carbon balance (indicators 3 and 4 in Table 8), included not just GHG emissions, but also the carbon effectively sequestered into the soil through organic matter. All cropping systems with irrigated rice were carbon-emitters and presented negative profiles related to the global warming potential. For each kg of food produced the rice-based systems effectively emitted between 1.0 and 3.1 kg CO_2-e to the atmosphere. When minimum tillage substituted conventional tillage in the rice-soybean rotation, 0.38 kg CO_2-e per kg of food produced was kept in the soil, instead of being emitted to the atmosphere. Again, the cropping systems conducted on ridges were more environmentally benign from this point of view. For each kg of food produced, the ridge-based systems sequestered an equivalent of 0.13 kg CO_2-e, on average (Table 8).

The Personal CO_2-e Footprint followed the same trend. The systems on ridges performed best. For each person the ridge-based systems were theoretically able to feed in one year, a net 24.6 kg of CO_2-e was sequestered into the soil. The other cropping systems were carbon emitters. For each person Rice-Fallow was able to feed, 1005 kg CO_2-e was displaced to the atmosphere, and on average 309 kg was emitted by the rice-soybean rotations. If reduced tillage instead of conventional tillage was used in rice-soybean system, the emission into the atmosphere was reduced with around 100 kg CO_2-e for each person the system was able to feed.

4. Discussion

4.1. General aspects

The adoption of a novel cropping system by farmers requires a solid basis of convincing information (Rogers, 2010). For this reason, and to enable us to create a balanced picture of each cropping system

Table 7
Solar Radiation Productivity for grain and biomass production (kg GJ PAR^{-1}) in five cropping systems.

Crop	Cropping systems					
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops	Average
	kg GJ PAR^{-1}					
Rice	0.717 (0.03)	0.778 (0.05)	0.717 (0.04)	–	–	0.737 (0.02)
Maize	–	–	–	0.810 (0.08)	0.594 (0.05)	0.709 (0.06)
Soybean	–	0.168 (0.01)	0.187 (0.02)	0.233 (0.01)	0.221 (0.01)	0.206 (0.01)
Crops average*	0.706 (0.02)	0.669 (0.06)	0.609 (0.06)	0.623 (0.07)	0.490 (0.05)	–
System average**	0.408(0.08)b	0.471(0.09)ab	0.456(0.08)ab	0.648(0.09)a	0.638(0.08)a	–

Values between parentheses are the SEM.
* Means weighted averaged by the amount of grains produced by each crop in the respective cropping system; the means are not significantly different ($p = 0.25$).
** Yearly average; all food and biomass was included and considers the full time span of the experiment; means followed by the same letter are not significantly different at $p < 0.05$.

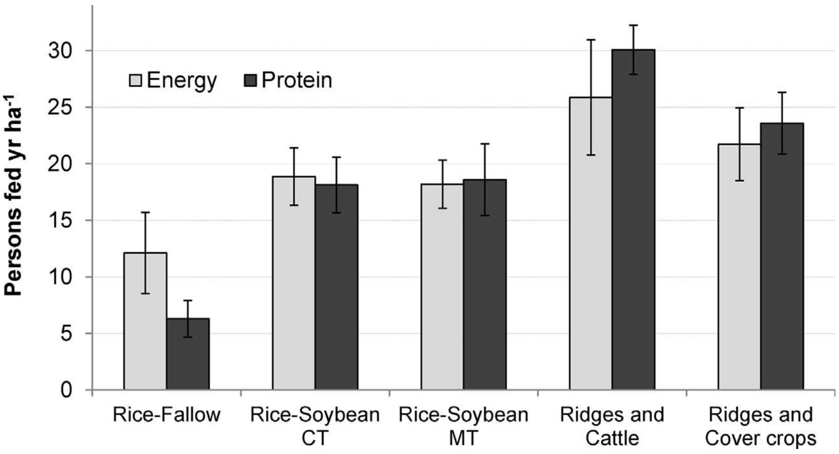

Fig. 6. Number of persons fed in one year (PFY) by the food produced in a cropping system, based on daily requirements of energy and protein. Results are presented for five cropping systems in the lowlands of South Brazil. Average human daily consumption rates are set to 8.7 MJ for energy and 80 g for protein. Error bars indicate the SEM.

Table 8
Carbon-based footprint indicators in five cropping systems.

Footprint based on:	Cropping Systems				
	Rice-Fallow	Rice-Soybean CT	Rice-Soybean MT	Ridges and Cattle	Ridges and Cover crops
	GHG emitted/				
1) Food[a,c]	3.30 (14.4)	1.40 (0.66)	1.08 (0.49)	0.62 (0.18)	0.63 (0.15)
2) PFY (energy)[b,d]	1078 (5472)	374 (188)	287 (145)	118 (35)	121 (27)
	CO_2-e balance/				
3) Food[a,c]	−3.08 (13.25)	−1.36 (0.74)	−0.98 (0.62)	0.10 (0.29)	0.15 (0.17)
4) PFY (energy)[b,d]	−1005 (5058)	−359 (201)	−259 (166)	20 (56)	29 (32)

Name of indicators: 1) GHG Intensity Footprint; 2) Personal GHG Footprint; 3) CO_2-e Footprint; 4) Personal CO_2-e Footprint. All values presented are the medians followed by the respective SD. For footprints 3 and 4, negative values indicate net emissions to the atmosphere.

[a] Grains + gains in cattle live weight, in kg ha^{-1}.

[b] PFY = Persons fed per year, based on consumption of energy.

[c] Units: kg CO_2-e/kg food.

[d] Units: kg CO_2-e/PFY.

evaluated, we conducted a detailed analysis of five systems using a wide variety of performance indicators, which included food production, land use, soil quality, resources use-efficiency and carbon balance. The values of these indicators differed considerably between the systems. Particularly, the two novel systems based on ridges exhibited yields, buildup of soil organic matter and resource-use efficiencies that exceeded that of the rice-based systems, whereas they also presented lower GHG emissions and GHG footprints. This shows how innovative changes in cropping systems can meet multiple demands on production, resource use and ecological sustainability.

Farmers in south-Brazilian lowlands have encountered difficulties with the irrigated rice production system, like for instance yield limitations and high costs associated to poor soil fertility (Bueno and Lemos, 2006; Carmona et al., 2016) and herbicide resistant weeds (Goulart et al., 2014), which are spread out in many fields. Crop diversification is one of the keys to overcome such technical difficulties. Despite the positive characteristics of the rice-soybean rotation, further improvements that move beyond the mere transformation of a monoculture system into a simple crop rotation system are needed. Apart from technical motivations, the inclusion of multiple crops is also important to stimulate the development of industries at regional level, which constitutes a powerful driver for economic wealth, growth and job creation (Coronel et al., 2007). This wish-list was, in fact, at the basis of developing the two innovative ridge-based systems.

4.2. Land use and food production

Contrarily to the rice-based systems conducted in flat soils, the fields in the ridge-based systems are not water-saturated and are maintained free from flooding. This permits that no-tillage can be used for soil management, that a high amount of biomass can be produced during winter and that crop rotation is facilitated. Consequently, in this new system the three pillars of conservation agriculture (no-till, crop rotation and soil protection) are fulfilled (Palm et al., 2014). Flood avoidance is the primary reason why the ridge-based systems are beneficial for upland crops in lowlands. In the long run, however, also other soil-related aspects became apparent, of which the increase in soil organic matter is probably one of the most important points. Since the ridges keep the soil dry, the oxygen levels in the root zone can be more appropriate for plants than in the flat soils. Consequently, root growth (Guo et al., 2015), nutrient absorption (Elzenga and van Veen, 2010) and the incorporation of atmospheric N_2 by leguminous crops (Roberts et al., 2010) can be more efficient in the ridge-based systems than in the easily waterlogged, flat-soil systems.

We found that soil fertility in the ridge-based systems increased between 2006 and 2015, especially for OM and P levels. Evidence points out that the large amount of residual biomass and the presence of cattle in the field were probably responsible for this improvement (Faccio Carvalho et al., 2010; Fageria, 2012). The benefits of an improved soil fertility were likely reinforced through the bacterial biomass from the decomposing residues (Paul, 2014) and the manure (Braos, 2013), since both act as source of labile nutrients. In contrast to the improvements verified in ridge-based systems, P- and K-levels in the Rice-Fallow system reduced. In this system, the amount of crop residues and organic matter in the soil were probably insufficient to prevent the nutrients from leaching or to be transformed into a not promptly available form, as previously reported by Ferreira et al. (2011).

In the current study, the combination of extended use of land and the positive effects on soil fertility clearly benefited the productivity of crops, pastures and cover crops cultivated in the ridge-based systems. Besides the high grain yields obtained with the cash crops, the adequate level of soil humidity promoted by the ridges supported winter cultivation at a point that total annual biomass production was up to 33 times greater on the ridges than on flat areas. The differences between the cropping systems also spread into aspects like the quality of the food produced. In the ridge-based systems the produced food contained a higher protein-energy ratio (1.12:1) compared to the food in the rice-based systems (0.76:1). It is well established that the substitution of animal protein by plant protein in the human diet can reduce the negative environmental footprint caused by meat production and consumption (Gephart et al., 2016). However, while the change in consumption habits is a personal decision from the consumer (Raphaely and Marinova, 2014), the adequate provision of plant proteins depends on versatile farming systems.

Next to biomass production and food quality, the fraction of time fields were occupied with crops revealed a substantial difference between the cropping systems. In the systems with irrigated rice, fallow was maintained throughout the winter, with limited biomass production from spontaneous vegetation. This condition is similar to what happens in many commercial farms in lowlands, where soil restrictions associated to waterlogging restrict the development of species not adapted to such condition. Keeping a field fallow after a season of irrigated rice is not a choice, but a common situation forced by the frequent waterlogging. This limitation is an important reason why most of the winter cover crops traditionally used in the uplands in south Brazil are almost not cultivated in the lowlands. During summer, on the other hand, the length of time the fields were used was roughly similar between the cropping systems, except for Rice-Fallow. In this simple cropping system, the three-year interval between the seasons of rice cultivation diminishes the effective land use. In contrast, in the ridge-based systems all available time was used for agricultural production, be it with cash crops, pastures or cover crops. Compared to the rice-based models, the novel ridge-based systems effectively intensify the land use in wetlands.

4.3. Resources use-efficiency

Although the system based on rice and fallow used the lowest amount of energy, its net energy ratio, which indicates how efficiently the energy was used, was the lowest between the cropping systems evaluated. This simple farming system required fifty-six percent more energy to produce one unit of food than the ridge-based cropping systems, on average. The efficiency of the Rice-Fallow would benefit from the introduction of some feasible, low-energy demanding practices. For example, the construction of channels in the field during fallow, to avoid waterlogging, is likely to increase the biomass production of native pastures or cover crops. Subsequent actions would be a seeding of improved pastures and the provision of an adequate level of nutrients, which could enhance soil protection, simultaneously to improving gains in cattle weight. Since the crop-livestock integration is the larger production system in the lowlands of southern Brazil, and perhaps of all temperate South America (Cid et al., 2011), these relatively simple adjustments would result in considerable gains at both farm and regional levels. The systems based in the ridges already incorporated most of these practices, and turned out to be the most efficient cropping system in terms of energy use.

Water productivity from the ridge-based systems was almost twice that of the other production systems. This result largely stems from the high water-use efficiency of maize and from the presence of pastures and cover crops during wintertime. The ridge-based systems also presented higher efficiency on capturing the photosynthetically active radiation to produce biomass. The cultivation of maize, the better conditions for soybean growth, and the extended time the land was effectively cultivated, without wasting photosynthetically active radiation on fallow, positively affected the SRP index of these systems. For example, soybean produced on ridges used the PAR almost thirty percent more efficiently than the soybean produced on flat fields within the rice-soybean rotations. The innovative cropping system supplied more favourable conditions for the crop to use the available light and to express its yield potential.

4.4. Environmental issues and footprints

The soil is an essential component related to carbon emission and carbon sequestration by agricultural systems. Collected data show that the systems based on irrigated rice were net carbon emitters, while the systems based on the ridges sequestered carbon. The high C accumulation in the ridge-based systems are in agreement with earlier reported results for no-tillage fields (Costa et al., 2008). The model of production adopted in the ridges adequately join minimum soil disturbance with high organic matter input, which are the two fundamental keys supporting carbon sequestration into the soil (Ghimire et al., 2012). In fact, the ridge-based systems were able to convert “carbon-emitting lands” into “carbon-uptake lands” as stated by Morse (2010). On the other hand, the rice-based systems presented a negative CO_2-e balance, mainly stemming from large fuel consumption and carbon emission connected to soil preparation, the low amount of plant residues effectively incorporated as soil organic matter, and the emissions of methane from the flooded fields.

Greenhouse gas emissions and the CO_2-e balance, which represents the global warming impact of a production system, are key factors in the evaluation of agricultural sustainability nowadays (Glendining et al., 2009). The four carbon-based footprint indices analysed in this study all presented a similar tendency, with the cropping systems conducted on ridges being less adverse to the environment than the other systems. Within the rice-soybean cropping systems, the carbon-based footprints obtained for minimum-tillage were markedly better than those obtained with conventional tillage. For all four indices assessed, the Rice and Fallow system presented the least favourable profile. This result was partially unexpected, since this cropping system is very simple and consumed the lowest amount of energy. However, apart from energy use, the Rice and Fallow combines a discontinuous and limited production of food and biomass with a nearly continuous emission of GHG, and this is what is reflected in the footprint indices. From this perspective, the ridge-based systems seem to adequately balance food production with environmental preservation.

5. Conclusions

The cropping system based on irrigated rice and fallow requires less energy to run and is one of the simplest production models to be carried out in the lowlands. It is the logical choice for most wetland fields in south Brazil, since rice is adapted to the hydromorphic environment, and beef cattle – an important activity at regional level – can be placed in the paddies during the fallow period. However, this system presented the most adverse results for several indicators, especially for those related to energy use efficiency and ecosystems services, like the carbon-based footprints. For most indicators evaluated, the rice-soybean systems represent an improvement over the Rice-Fallow, particularly if conducted in minimum-tillage. The main advantages of using minimum-tillage instead of conventional tillage in the rice-soybean rotation are related to energy use, carbon emission and carbon sequestration. These desirable outcomes from minimum-tillage in the rice-soybean rotation were accompanied by a similar total biomass production, thus resulting in an improved performance in the carbon-based footprint indicators.

The ridge-based cropping systems are conceptually very different from the systems maintained in flat soils. Besides the technical differences, the ridge systems presented better results than the other production models on important characteristics like soil quality, biomass production, carbon sequestration, GHG emission and water- and PAR use-efficiency. Importantly, as the ridge-based systems neutralize waterlogging, the systems also showed a much higher productivity of maize than the regional benchmarks.

Of the two ridge-based systems evaluated, the Ridges and Cattle often performed slightly better than the Ridges and Cover crops system. This better performance was reflected in a diverse set of indicators, like grain production (+18%), carbon sequestered as soil organic matter (+12%), CO_2-e balance (Global Warming Impact; −46%), P accumulated in soil (+346%), water productivity for maize (+43%), solar radiation productivity for maize (+36%), energy produced in food (+19%) and protein produced in food (+27%). These results confirm the benefits from including pastures and cattle in a well-planned rotation scheme with grain crops. These observations are in line with milestone reports from De Moraes et al. (2014) and Ruviaro et al. (2016) who highlight the importance of crop-livestock integration for the sustainability of several production systems in Brazil and other South-American countries. The current result makes evident that the adoption of large ridge-based cropping systems is a viable alternative to the wetland paddies which are temporarily or permanently not used for irrigated rice cultivation. In our view, the ridge-based concept is a promising route to a diversified and more sustainable agriculture in the lowlands.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2017.07.001.

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