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ABSTRACT

Managing for resilience in agriculture will be required to overcome future challenges such as growing food demand, climatic uncertainty, scarce raw materials and economic instability. Identifying resilience-enhancing practices is therefore fundamental for developing sustainable agroecosystems. We aimed to assess the resilience of two agricultural systems with different levels of diversification in southern Brazil: a specialized soybean (*Glycine max*) system and an integrated soybean-beef cattle system. We assessed the robustness and the adaptive capacity of these systems when facing climate hazards and price volatility. The study was based on a long-term trial that has been carried out since 2001, composed of an annual rotation of no-till soybean production during the summer and grazing of mixed black oat (*Avena strigosa*) and Italian ryegrass (*Lolium multiflorum*) pasture in the winter. Treatments consisted of four grazing intensities in the integrated crop-livestock system (ICLS), defined by sward heights: 10, 20, 30 and 40 cm plus an ungrazed control representing the specialized cropping system (CS). The experiment was carried out using a randomized complete block design with three replicates. We analysed system results over five years using two methods: *i*) a downside risk analysis to estimate the expected losses of yield and gross value added; and *ii*) the Ecological Network Analysis, which was applied to each treatment and year, for the assessment of the resilience of nitrogen (N-R_{flow}) and phosphorus (P-R_{flow}) flows. Both methods showed that co-located crop-livestock production in an ICLS was more resilient than the specialized soybean system and had improved nutrient cycling and resource-use efficiency. The effects of grazing management on system resilience depended on the output: beef yields were more stable under lower grazing intensities, but the risk of falling below a target economic threshold was inversely proportional to grazing intensity and null when the highest grazing intensity was adopted. The ecological network analysis did not reveal differences in resilience of nutrient flows among grazing management treatments. Our study suggests that R_{flow} (N or P) is a useful proxy for assessing the robustness and adaptability of agroecosystems. Our comprehensive resilience analysis of nutrient and economic flows provides evidence that system diversification through the integration of grazing animals into specialized cropping systems is a good strategy towards the sustainable intensification of agriculture. It would be relevant, however, to consider further studies comparing more complex system configurations and levels of diversification.

Keywords: cattle; soybean; nutrient flows; downside risk; Ecological Network Analysis

1. Introduction

Current and future food production must be in accordance with the principles of sustainable agriculture in a manner that is environmentally, economically and socially responsible over time (FAO 2014). Sustainable intensification of agriculture is based on the application of ecological concepts and principles – such as landscape diversity and heterogeneity – to achieve high productivity, efficiency, and resilience. Sustainable intensification also aims to reduce the undesirable socioeconomic conditions and economic and environmental impacts caused by climate change (Bonaudo et al., 2014; Altieri et al., 2015). In this context, resilience in agriculture is an important factor in addressing future challenges, such as food supply for a growing population, climatic hazards, scarce raw materials and economic instability (Altieri et al., 2015; Li, 2011; Fair et al., 2017; Chaudhary et al., 2018).

Beginning with the definition of ecological resilience proposed by Holling (1973), resilience theory has evolved for application to socio-ecological systems (Walker et al., 2004), including farming systems (Darnhofer, 2014). To address the issue of accumulating challenges to agricultural systems, Meuwissen et al. (2019) proposed a framework to assess the resilience of European farming systems by distinguishing three resilience capacities: *i*) Robustness, the capacity to withstand stresses and shocks (e.g., inputs, climate, etc.); *ii*) Adaptability, the capacity to change in response to shocks but without changing the structures and feedback mechanisms of the system; and *iii*) Transformability, the capacity to change the structure and feedback mechanisms of the system when facing shocks or stresses that make business as usual impossible. Multiple attributes (such as agricultural practices or risk management) can enhance one or more resilience capacities (Meuwissen et al., 2019).

Through the use of practices that improve soil physical, chemical, and biological quality and nutrient recycling, diversification of income sources, and regulation of pests and diseases (Morecroft et al., 2012; Altieri et al., 2015; Rapidel et al., 2015; Garrett et al., 2017; Migliorini and Wezel, 2017, Peterson et al., 2018), the integration of crops and livestock has been suggested as a way to enhance the resilience of agricultural systems (Stark et al. 2018). Various types of integrated crop-livestock systems (ICLS) exist worldwide, ranging in scope from farm- to territory-level integration and encompassing both commercial and smallholder operations (Herrero et al., 2010). In addition to the general benefits of crop-livestock integration, identifying the management practices with the greatest potential to improve ICLS resilience and evaluating the extent at which these practices can reinforce one or more resilience capacities will further inform the design of more sustainable agricultural systems. Thus, understanding resilience dynamics is fundamental to achieving sustainable human interactions with their supporting agroecosystems (Mori, 2011; Angeler and Allen, 2016).

Herrera et al. (2012) reported several impact assessment tools for farming system resilience and delivery of public and private goods (Meuwissen et al., 2019). These tools were generally based on dynamic approaches, relying on historical data and dynamic modeling. An alternative to the use of long-term datasets is the Ecological Network Analysis (ENA), which makes use of the information theory proposed by Ulanowicz et al. (2009) to assess agricultural system resilience (Stark et al., 2018; Alomia-Hinojosa, 2020). This method was used by several authors to evaluate the agroecological performance of ICLS in the tropics by modeling nitrogen fluxes at the farm level (Rufino et al., 2009; Alvarez et al., 2013, Stark et al. 2016). The ENA can also be used to analyze ecological interactions within and between ecosystems, identifying holistic properties through the network of flows (Fath et al., 2007). Even though it consists of a static approach (i.e., based on the quantification of flows through system components on an annual basis), Stark et al. (2018) suggested that resilience studies using the ENA should address the interannual effect of environmental factors on agriculture. These are the boundaries within which ENA can address questions and provide a good proxy of agricultural system resilience.

We used data from a long-term experiment started in 2001 (Kunrath et al., 2020) to test the resilience-enhancing potential of system diversification (specialized soybean system *versus* integrated soybean-beef cattle system) and grazing management (ungrazed, specialized soybean system *versus* ICLS under increasing grazing intensities). We studied the field-level resilience of the systems when subjected to different external environmental factors (e.g., climate, input and price variability) over five experimental years, using two approaches: *i*) a dynamic downside risk analysis to estimate the expected losses of yield and gross value added, following Meuwissen et al. (2019); and *ii*) Ecological Network Analysis for the assessment of the resilience of nitrogen (N-R_{flow}) and phosphorus (P-R_{flow}) flows. Ultimately, we aimed to compare both approaches for consistency in outcomes, or complementarity, in the study of agricultural resilience, as well as to highlight potential resilience-enhancing practices involved in ICLS.

2. Materials and methods

2.1 Study Area

This study used data from a long-term ICLS trial that has been carried out since 2001 in Rio Grande do Sul state, Southern Brazil (28°56'14.00"S, 54°20'45.61"W). The soil is a clayey oxisol (Rhodic Hapludox, Soil Survey Staff, 1999), with 540, 270, and 190 g kg^{-1} of clay, silt, and sand, respectively. The region has a humid subtropical climate (Cfa) according to Köppen's classification. From 2009 to 2018, the average maximum monthly temperatures were between 16 °C and 33 °C and the average minimum monthly temperatures were between 6 °C and 21 °C (Fig. 1). Monthly rainfall varied among years: in the summer/autumn of 2011/2012, there was a marked decrease in the amount of monthly rainfall compared to the historical monthly average of the region. The first half of 2011, 2015 and 2016 and the second half of 2009, 2012, 2014 and 2015 were periods of above-average rainfall. Economic conditions, e.g., sale prices of the products (soybean grains and live animals) and input prices (fertilizers, seeds, herbicide, and live animals) also varied widely for the period between 2009 and 2017 (Fig. 1).

The variables described above were considered as sources of variation of the external environment, both climatic and economic, influencing the performance of the studied system.

2.2 Treatments and Experimental Design

The experimental area was managed under no-till soybean (*Glycine max*) production in the summer and black oat (*Avena strigosa*) cover crop in the winter since 1993. From May 2001 on, no-till ICLS was adopted, with soybean production during summer and grazing of mixed black oat and Italian ryegrass (*Lolium multiflorum*) pasture during winter.

The experiment was carried out using a randomized complete block design with three replicates with experimental units ranging from 0.8 to 3.2 ha. Different sizes of experimental units were used to facilitate sward height maintenance using 'put-and-take' animals (Mott and Lucas, 1952). Treatments consisted of four sward heights (or grazing intensities): 10 (ICLS10), 20 (ICLS20), 30 (ICLS30) and 40 cm (ICLS40); plus, an ungrazed control treatment (specialized cropping system - CS) representing the soybean monocrop/winter cover crop system.

In this study, we evaluated the production years 2009/2010, 2011/2012, 2014/2015, 2015/2016, and 2016/2017 due to the occurrence of greater external stresses or nutrient input variability during these years. In 2009/2010, 90 kg ha^{-1} of N were applied in the winter pasture phase and 60 kg ha^{-1} of P_2O_5 and K_2O in the summer soybean phase. In 2011/2012, 90 kg ha^{-1} of N were applied in winter pasture and 60 kg ha^{-1} of P_2O_5 and K_2O in the soybean, however, in the period between November and June there was a drought that affected soybean production. In 2014/2015, 140, 60, and 90 kg ha^{-1} of N, P_2O_5, and K_2O were applied, respectively, in the winter pasture phase. In 2015/2016, only 90 kg of N were applied in the winter pasture phase. In 2016/2017, 115.5, 60 and 90 kg ha^{-1} of N, P_2O_5 and K_2O were applied, respectively, in winter pasture phase (Fig. 1). The fertilizer types were urea, triple superphosphate, and potassium chloride, with urea split-applied in the pasture phase (30 and 60 days after sowing) and the last two applied together with sowing of the soybean or black oat.

The same basic experimental protocol was carried out uniformly every year. Black oat was seeded in May at a 45 kg ha^{-1} seeding rate, in rows spaced 17 cm apart, and Italian ryegrass was established by natural reseeding. In November, the area was desiccated (glyphosate + chlorimuron-ethyl or saflufenacil) and between November and December soybean was seeded in rows spaced 45 cm apart at a 45 seeds m^{-2} density. Soybean seed inoculation with rhizobium and agronomic management was performed according to the technical recommendations for the crop, and the soybean harvest occurred in April.

The stocking period occurred between July and November of each year and grazing began when herbage mass reached 1500 kg ha^{-1} of DM. The experimental animals were cross-bred Angus x Hereford x Nelore castrated steers with approximately 10 months of age and average initial body weight of 210 kg. Each grazed paddock received three tester animals and a variable number of ‘put-and-take’ animals (Mott and Lucas, 1952) in order to periodically adjust the stocking rate and maintain the sward heights as close as possible to treatment targets.

2.3 Measurements

The monitoring of sward heights was done every 15 days by evaluating 100 points per paddock using a sward stick (Barthram, 1985). To determine total herbage accumulation [kg dry matter (DM) ha^{-1}] during the winter stocking period, we evaluated herbage mass [kg DM ha^{-1}] at the beginning of the stocking period and daily herbage accumulation rates (kg DM ha^{-1} day^{-1}) up to the end of it. Initial herbage mass was estimated in each paddock by the double sampling technique (Wilm et al., 1944). For this purpose, five samples of 0.25 m^2 were taken by clipping above litter level at random locations and then oven dried at 50 °C until reaching constant weight. For the correction of the herbage mass at paddock level, a calibration equation was generated by the linear regression between the herbage mass of the samples and the sward height measured at five points per sample. This equation was then applied to the average paddock sward height to determine the initial herbage mass of the paddock. Herbage accumulation rates were determined every 28 days using three grazing exclosure cages per experimental unit (Klingman et al., 1943). Total herbage accumulation was calculated as the product of the average daily herbage accumulation rate of all 28-day periods and the number of days in the corresponding stocking period, summed to the initial herbage mass of that stocking period.

For the evaluation of animal performance, steers were weighed at the beginning and at the end of the stocking period after 12-hour feed and water restriction. Average daily gain was calculated by dividing total live weight gain of the tester animals by the number of days in the stocking period. To evaluate the productive outputs of the system, we calculated the live animal production (LAP; kg ha^{-1} $year^{-1}$) by multiplying the number of animals per hectare by the average daily gain of the tester animals and by the number of grazing days in the stocking period.

At the end of the stocking period, pasture litter (kg DM ha^{-1}) was sampled using the same methodology described for herbage mass determination. All pasture assessments were also performed in the CS treatment. Soybean grain yield (SGY; kg ha^{-1} $year^{-1}$) was determined at R8 stage (harvest maturity), by sampling five random 2-m transects (0.9 m^2 area per transect, totaling 4.5 m^2 per paddock). The samples were threshed, cleaned, and weighed and the soybean grain yields were to 13% moisture content.

2.4 System conceptualization

A conceptual model of the systems was developed with the purpose of determining all compartments and the biomass and mineral flows among compartments and with the external environment (Fath et al., 2007). For the ICLS, the model was composed of five compartments: Soil, Annual Winter Pasture, Summer Crop, Air, and Animal. For CS, the model was composed of four compartments: Soil, Winter Cover, Summer Crop, and Air. The Air compartment corresponds to the source for atmospheric N uptake by bacteria in the process of symbiosis via biological N-fixation (Fig. 2).

The inflows (from the environment) correspond to the flows of mineral fertilizers and seeds towards the soil compartment and the flows of purchased live animals and mineral salt towards the animal compartment. The productive outflows (to the environment) correspond to animal products (live animal production) and crop products (soybean grain yield). The non-productive outflows (to the environment) correspond to flows that are potential sources of pollution and/or system losses (emissions from animal wastes and mineral fertilizers such as leaching and volatilization), soil nutrient unavailability, and flows that participate in the processes of organic accumulation and mineralization. In this study we did not distinguish between the flow of losses and the accumulation of nutrients in the soil because this process is difficult to quantify and involves biotic and abiotic drivers of soil nutrient dynamics in the soil (Jarvis et al., 1996, Oenema, 2006; Lemaire et al., 2014) in each production system tested.

The assessed models were not considered at steady state and therefore an inflow was added to the system (from the environment) to characterize the supply of minerals “stored” in the soil. Thus, the soil compartment within the system is composed of the elements readily available for the uptake flow towards the winter pasture and summer crop compartments.

From this generic model, all network flows, corresponding to the five treatments, three repetitions, and five years (i.e. 75 networks) were quantified. Data were sourced from the experiment’s long-term database, scientific literature, and derived calculations.

The uptake flows for the Summer Crop compartment were calculated as the difference between estimated values of biological N-fixation (Hungria et al., 2005) and soybean total nutrient requirement (Malavolta et al., 1997; Hungria et al., 2005) as a function of soybean grain yield. Residues and senescent flows from Summer Crop compartment to the Soil compartment were considered as the total amount of above ground soybean biomass, calculated by harvest index (Spaeth et al., 1983; Assmann et al., 2014).

The senescence flow of winter pasture was calculated as the difference between herbage mass, pasture residue, and herbage intake by the animals (Souza Filho et al., 2019). The flow of mineral salt was calculated as the difference between the outflow and inflows of animal, herbage intake, and animal excreta flows. The latter was calculated as the difference between the amount of nutrient exported by the animals and the flow of herbage intake by the animals.

The non-productive outflows are the result of the sum of losses by volatilization when applying fertilizers or depositing excreta and from leaching or storage of elements in the soil as soil organic matter. In 2015/2016 there was no inflow of phosphate fertilizer (Fig. 1), resulting in the negative balance of the system. This means that the flow of phosphorus uptake in the Winter Pasture and Summer Crop compartments for this season came from the stock of phosphorus in the soil.

2.5 Data analysis

2.5.1. Resilience assessment through dynamic downside risk analysis

Adopting the framework proposed by Meuwissen et al. (2019), we answered a list of questions pertaining to the study system. The first question was: *'resilience of what and to what?'*. Here, we considered the resilience of an agricultural system at field level (CS or ICLS) when subjected to climatic oscillations and price volatility of inputs and outputs (Fig.1). The second question was: *'resilience for what purpose?'*. We identified two desired functions of the systems. The first one is the production of commodities, through the delivery of soybean grains and beef. The second function is the creation of wealth to the farmers, by contributing to their livelihoods through better remuneration. We assessed this function through the Gross Value Added (GVA) per ha, as follows:

$$GVA = \sum_i (GPV_i - ICV_i) \qquad (1)$$

where GPV_i is the gross production value of the activity i, and ICV_i is the intermediate consumption value of the activity i. The GPV was calculated as:

$$GPV_i = Q_i \times UP_i \qquad (2)$$

where Q_i is the quantity of product i (kg of soybean grain or kg of live beef steers ha^{-1}) and UP_i is the unit price of product i, corresponding to prices paid to the farmers in Rio Grande do Sul state, Brazil, in May for soybeans (CONAB, 2018d), and in November for live beef steers (CEPEA 2018a). The intermediate consumption is different for soybean and steers, as follows:

$$ICV_{soybean} = \sum_j (QC_j \times UP_j) \qquad (3)$$

$$ICV_{livestock} = \sum_j (QC_j \times UP_j) + Head \times VetCost \qquad (4)$$

where QC_j is the quantity of input j (seeds, fertilizers, and herbicide, for soybean; and steer acquisition and mineral salt, for steers), and UP_j the unit price of input j, Head is the number of steers per ha, and VetCost is the average veterinary cost per animal in the state of Rio Grande do Sul, Brazil (CEPEA, 2018b). For the unit price of inputs, we used the average price paid by farmers in the state of Rio Grande do Sul (CONAB 2018a, 2018b, 2018c and CEPEA, 2018a).

No data were available to quantify the cost of energy used to carry out cropping operations. As these costs were the same for all treatments in a given year, the comparison of the cost values was not biased; we systematically made the same under-estimation of cost values for a given year. Nevertheless, energy costs could vary among years due to price volatility and differences in operations between years. As a result, we underestimated the inter-annual variation of GVA.

All values were obtained in Brazilian national currency (R$) in accordance with domestic market prices for each year studied, and subsequently converted to constant R$ prices using the General Price Index (average of the cities of Brazil and all items as given by the Getúlio Vargas Foundation). To obtain dollar values (US$), the average long-term conversion was made using the current exchange rates between R$ and US$ (BACEN, 2018).

The third question to address in the framework of Meuwissen et al. (2019) was: *'what resilience capacities?'* With data from such an experimental design, we cannot appraise the transformability capacity, because the structure of the five systems (combination of activities), and the feedback mechanisms (as the variation of livestock stocking rates to adjust the observed sward heights to treatment targets) were kept identical throughout the experimental period. Therefore, we focused on only two resilience capacities: the robustness and the adaptability of the systems. We carried out the assessment of these capacities by determining the downside risk (Nawrocki, 1999) for the desired system functions (yield and GVA). We estimated the expected loss, given by the lower partial moment of order one (LPM1), calculated as:

$$\text{LPM1}\ (t) = \frac{1}{n} \sum_{i=1}^{n} \text{Max}\ [0, (t - F_i)] \qquad (5)$$

where n is the number of observations, F_i is the value of the function (yield or GVA) for the year i, and t is the target value, the threshold below which we considered that there is a loss. The expected loss is null when the function never falls below the threshold. The smaller the expected loss, the greater the resilience.

We chose the average of the function over the five studied experimental years as the threshold for yield downside risk. For the GVA, we chose the threshold of US$ 700 per ha for each activity (crop or livestock production). This value corresponded to the average GVA for soybean (US$ 683 +/- 602). We considered that adding livestock into the same plot would at least double the creation of wealth (threshold: US$ 1400). Because the thresholds were different for both systems, we calculated the ratio between the expected loss and the threshold, expressed in percentage, in order to compare the expected losses between systems.

The last question was: '*what enhances resilience?'*. We tested two agricultural practices for their resilience-enhancing attributes: *i*) system diversification through crop-livestock integration; and *ii*) grazing management, through the use of different grazing intensities in the stocking period of the ICLS. For diversification, we considered the relative weight of livestock activity in each system, by calculating the contribution of livestock to the global GVA of the system, from 0 for the specialized cropping system to 81% for the highest grazing intensity (ICLS10, Table 2). For grazing management, we considered the mean stocking rate of the winter period (kg of live weight ha^{-1}). To test the resilience-enhancing potential of both practices, we calculated the coefficient of determination of linear regressions between expected losses and each of these variables.

2.5.2 Resilience assessment from an ascendency perspective

The capacity of a system to grow and develop (C) depends on its capacity to exercise efficient activity uses (A), while simultaneously keeping a reserve (Φ) of flexible pathways to adapt to uncertainties, such that C = A + Φ (Ulanowicz et al., 2009). We used the ratio between Φ and C as an indicator of the resilience of the system.

For this calculation, all flows were converted into terms of N and P per year, expressed in kg ha^{-1} (Appendix A - Supplementary Data). The choice of the N and P flux resilience for the study was due to the great importance of the cycle of these elements within the context of sustainability in agricultural systems (Galloway et al., 2008; Bouwman et al., 2013; Fowler et al., 2013; Cordell and White, 2014). As in Stark et al., (2018), the resilience of nutrient flows (R_{flow}) in the system was calculated as the ratio between reserve (Φ – equation 6) and development capacity (C - equation 7). For more detailed information on formulas and calculations, see Ulanowicz et al., (2009).

Φ represents the actual reserve capacity of the system formed by the network of flows and C is the maximum potential capacity of the system for all flows that can be achieved. This relationship demonstrates the ability of a system to absorb variations imposed by the external environment of the system.

$$\Phi = -\sum_{i.j} T_{ij} \log\left(T_{ij}^2 / T_{i.} T_{.j}\right) \qquad (6)$$

$$C = -\sum_{i.j} T_{ij} \log\left(T_{ij} / T_{..}\right) \qquad (7)$$

where, $T_{i.}$ is the total inflow for compartment *i*; $T_{.j}$ is the total outflow for compartment *j*; and T_{ij} is the flux between the compartments *i* and *j*.

For R_{flow} calculations, values range from 0 to 1. Values close to 1 mean that the system requires a substantial amount of energy for the transition to an alternative state (Mori, 2011; Briske et al., 2017), i.e., that the system has a greater ability to adapt to environmental disturbances.

To perform the ENA analysis for ascendency calculation, N and P flows matrices were built from the 75 networks obtained by combining all treatments and years, and the indicators *Φ* and *C* were calculated using the software R (R Development Core Team, 2016). Input and output data were processed and calculated using spreadsheets (Microsoft Excel). Data were submitted to analysis of variance (ANOVA) according to the model $R_{ij} = \mu + B_i + T_j + \varepsilon$, where R_{ij} represents the average of flows and resilience of the five years, μ the overall experimental average, B_i the blocks, T_j the treatment effects and Ɛ the experimental error. When significant ($p < 0.05$), the means were compared using the Tukey test, at a 95% confidence level.

3. Results and Discussion

3.1. Resilience of crop and livestock activities measured through yield and GVA

Soybean production was more vulnerable than livestock production when commodity supply functions were analysed separately (Tab. 1). The expected loss of soybean grain yield

(SGY) was 534 kg ha^{-1} for the specialized cropping system (CS) or 17.5 % of the average yield downside threshold (3052 kg ha^{-1}). For live animal production (LAP), the expected losses represented only 2.6 to 8.6 % of the average beef production.

Livestock production in this system occurs over a few months during winter. For reasons that include the sensitivity of processes during the soybean cycle, from germination to maturation of beans during summer, as well as the length of the cycle itself, the animal growing operation is less vulnerable to climatic hazards when compared to soybean production. Raising animals presents some flexibility, such as the classic process of compensatory growth, to cope with forage shortage, so that animal production exhibits some adaptive capacities to cope with climatic oscillations. Additionally, as the main climatic hazard observed was a long drought during summer (year 2011/2012) (Fig. 1), winter forage production, on which animal feeding depended entirely, was less exposed to the risk. Thus, the production of the forage biomass was not as impacted as that of the soybean. Pasture biomass production in the year 2011/2012 was on average 6000 kg ha^{-1}, versus 600 kg ha^{-1} for soybean, the latter representing only 10% of soybean biomass production in the other years.

For the wealth creation function (Tab. 2), the specialized soybean system (CS) was the riskiest. Considering the threshold of US$ 700 for the downside risk, the expected loss (US$ 215) represented 30.1% of this amount. The livestock activity, embedded in the integrated crop-livestock system (ICLS), was less risky, regardless of the grazing intensity. For the same threshold, the expected losses for livestock GVA ranged from US$ 0 to 78. Raising cattle during the winter months was not a risky operation and was typically above the expected threshold, except for the lowest grazing intensity (ICLS40), which was close to the threshold ($GVA_{livestock}$ = US$ 777). Inherently, animal production was highly dependent on the purchase of animals, but even with the exposure to external price volatility, crop-livestock operations were more resilient than specialized soybean production. These results show that there is not a direct link between the level of dependency, evaluated for instance through the economic value of the intermediate consumptions, and the level of resilience.

3.2. Two attributes enhancing the resilience of the ICLS

The first attribute we considered was system diversification through the integration with livestock. The expected losses decreased as the relative weight of the livestock activity increased ($r^2 = 0.98$, Fig. 3a), meaning that diversification enhanced the resilience of the wealth creation function. When one production activity faces disturbances, the other activity might not be affected. Indeed, the second activity could be less exposed to the disturbances or less sensitive to the disturbances than the first one, as previously suggested. We saw that the animal operation was less sensitive to climatic hazards with more stable outputs over time than the soybean production. This interpretation is linked to diversity as an underlying mechanism of resilience (Meuwissen et al., 2019). Beyond the system diversification, the integration of livestock with cropping was a good way to improve economic resilience. For instance, there was no feed purchase, except for mineral salt, since animal production was pasture-based. This enabled a reduced dependency of the animal operation on external inputs, making it less exposed to price volatility of feed resources. This model of integration fits to the resilience concept of modularity, where ecological systems are compartmentalized into smaller units managed independently (here crop and livestock phases), and the connectivity between these subsystems plays the role of promoting resilience (Carpenter et al., 2012). However, practices such as diversification may enhance agricultural resilience in several ways. Therefore, in addition to quantifying the relative weight of each activity within the system as a whole, the characterization of each diversification practice (i.e., each compartment) in relation to its processes is essential to understand where the resilience-enhancing mechanisms of the system reside.

It is noticeable that there was no trade-off between income per ha and risk: risk decreased as GVA_{system} increased (r^2=0.87, Fig. 3b). Livestock integration with increasing animal density per ha was related to increased GVA_{system} and also to decreased expected loss. The addition of the livestock activity into the same unit of land used to produce crops enhanced the efficiency of use of this resource, which, in turn, increased the income per land unit. This result contradicts the general assumption that there is a trade-off between diversity and resource-use efficiency in farms (Kahiluoto and Kaseva, 2016). In addition, the exposure to the risk of falling prices between buying and selling operations was low in our system due to the short duration of the livestock operation (only 5 months). As this event did not occur in the studied years, the expected losses for the highest level of cattle stocking were null.

The second resilience-enhancing attribute we analysed was grazing management. The expected loss for beef production decreased with the stocking rate (r^2=0.88, Fig. 3c), with the lowest grazing intensity (ICLS40) presenting the lowest risk. As animal density was the lowest, higher forage availability enabled individuals to acquire an adequate daily diet, so that the animal–vegetation system exhibited a buffering capacity to cope with hazards. This effect of lower animal densities has already been shown by Lurette et al. (2013) for dairy farms. It corresponds to the resilience principle of reserve (Meuwissen et al., 2019), and the buffering capacity of the plant-animal biological system when there are few animals. Considering the wealth creation function, the ICLS40 system is no more the less risky (Fig. 3d), because we chose the same threshold (700 US$) for calculation of the expected loss for the four ICLS. The systems with higher stocking rate (ICLS20 and ICLS10) had a better capacity to provide each year a GVA above this threshold, because of their higher resource-use efficiency per land unit. This result shows that the effect of an attribute on enhancement of resilience and the generality of findings must be interpreted with caution. We showed that the low stocking rate enabled buffering capacity when we considered the beef yield function, enhancing resilience towards climatic hazards. But this buffering capacity is no longer at play when we consider the wealth creation function (GVA).

3.3. The resilience of the N and P flows

From the ascendancy perspective (R_{flow}), ICLS (at any grazing intensity) were significantly more resilient, in terms of N-R_{flow} ($p < 0.001$, Fig. 4) and P-R_{flow} ($p < 0.001$, Fig. 5), than CS in the face of climatic, management, and input variations. This conclusion can also be drawn for N-R_{flow} and P-R_{flow} over time (data not shown in the study). Similar responses were observed under annual and multiyear analyses, i.e., higher values of R_{flow} (N and P) for ICLS in comparison to CS in each year. Stark et al. (2018) observed similar results for different productive systems, showing that the N-R_{flow} is linked to the diversity of flows of the system, which improves the adaptive capacity of the system through alternative flow pathways.

In the ICLS, the animal compartment acts as a promoter of nutrient cycling through manure and urine, as a small amount of the nutrient intake during the grazing phase is exported out of the system (Sneessens et al., 2016). In addition, under grazing there is an increase in availability as well as a more gradual release of nutrients over time, and greater soil exploration by belowground pasture biomass, contributing to greater nutrient recycling (Assmann et al., 2015; Deiss et al., 2016; Assmann et al., 2017). This process, in turn, promotes a more homogeneous distribution of flows between all compartments within the system. Martins et al. (2016) demonstrated that under crop-livestock integration soil reacidification over time after lime application was lower compared to ungrazed systems due to less non-productive losses of calcium (Ca) and magnesium (Mg) and greater nutrient recycling, suggesting that the presence of grazing animals promotes chemical resilience on a medium-term timescale in agricultural soils.

3.4. Comparison of the two methods for assessing resilience-enhancing attributes

The combination of the two methods described here demonstrated the value of crop-livestock integration for agricultural resilience. Using the downside risk analysis method, we found that the expected losses are lower in the ICLS. Using the ascendency method, N and P flows kept a higher reserve capacity for recovering from disturbances. Thus, the greater diversity of activities promotes greater efficiency in land use (two production activities are co-located on the same plot), contributing to increased resilience.

Regarding grazing management as a resilience-enhancing attribute, our analysis did not reveal any differences among the R_{flow} values of the four grazing intensities (Fig. 4). The system with the lowest stocking rate (ICLS40) exhibited greater buffering capacity to face climate stresses, and the lowest downside risk, considering the average beef production expected for such system. But the systems with higher stocking rate were less vulnerable in terms of economic return, with a lower risk, if any, of falling below a target Gross Value Added (Fig. 3d).

Both methods yielded consistent results. The N, or the P, R_{flow} was a good proxy for assessing the impact of system diversification through crop-livestock integration to enhance robustness and adaptability (assuming that there was no change in transformability, i.e., structure and high variation in animal load during the grazing period), and to do so from a biophysical perspective rather than an economic one. Indeed, a system with several activities, with possible compensations between various outputs, has more capacity to face the effects of climatic hazards but also exposure to price volatilities of each activity. The N or P flows analysis takes into account this diversity, which enables the system to develop higher capacity to face various hazards.

The R_{flow} is calculated from a static depiction of the annual flows in a given year. The organization of the flows is sufficient to assess the robustness and adaptability of the system.

This observation has two implications: first, this assessment is independent of the environmental context of the system and of the disturbances. It enables assessing resilience within a context of uncertainty, with regard to future unknown disturbances. Second, there is no need for multi-year data on the behavior of the system in order to carry out this assessment. Thus, it can be used, for instance, in an *ex ante* evaluation of systems to design more resilient and innovative farming systems.

On the other hand, the downside risk analysis does require multi-year data. Long-term experiments, such as the one examined in this study, provide such data at plot scale. Long-term farm monitoring also provide data for resilience analysis (see for instance Martin et al., 2017, who analyzed farm vulnerability to climatic and economic variability from a sample of 19 cattle farms in a French department, monitored during 4 to 6 years). These dynamic analyses allow identifying the desired functions of the farming system; and assessing the attributes enhancing the capacities of the system to fulfill those functions facing uncertainties. This allows the research to make various assessments for the same attribute (here, grazing management), considering various functions (capacity to produce a stable amount of meat *versus* capacity to exceed a minimum income). Nevertheless, in contrast to the flow-based method, these longitudinal analyses depend on the actual disturbances observed throughout the study period. This requirement may be an obstacle to assessment of overall resilience if the systems have not been exposed to some disturbances during the observation period.

Therefore, further investigations are needed before making generalize conclusions about the relevance of R_{flow} as a proxy for the resilience capacities of a system. The use of dynamic whole-farm simulation models is a way to assess the sensitivity of various system configurations to a large range of external conditions (climatic, sanitary, prices, etc.). Thus, broader downside risk analysis may be carried out and the results compared with the assessment of resilience via N or P flows of each system configuration. However, this approach is only relevant for assessing the robustness and adaptability capacities, because all the possibilities for transforming the system, which are under the control of the farmer, are not captured in the organization of flows in the system.

3.5. Crop-livestock integration to enhance farming system resilience

This study addressed an interpretative analysis of the ecological and economic processes of agricultural systems, thus contributing to a better understanding of the synergisms and emergent properties of a diversity of functional traits (i.e., crop-livestock integration, see Moraes et al., 2014 for consideration of various ICLS in Brazil). Other diversification practices besides animal integration into cropping systems are also relevant, such as increasing plant species diversity in space and time (Schaub et al., 2020). We did not explore, however, any aspect of the mixture of pasture species (black oat + Italian ryegrass, used for winter grazing in our study) *per se*, since our interest resided on livestock as the agent of system diversification.

We showed that ICLS are interesting alternatives to promote resilience and support the sustainable intensification of agriculture. Nevertheless, this statement is based only on the comparison of two systems, a specialized soybean system with cover crops in the winter and an integrated soybean-beef cattle system with grazing of cover crops in the winter period. To generalize this result, it would be relevant to compare a broader diversity of farming systems with more complex animal production operations, such as cow-calf operations, and more diversified cropping systems, alongside extremely specialized, continuous crop production systems such as annual grain crop rotations.

In addition, this finding is dependent on the particular configuration of the integrated system in this study. Here, crop and livestock are integrated on the same plot, successively through a whole year. It enables a very efficient use of land, and recycling of nutrients, which explained the robustness and the adaptability of this ICLS. Other temporal and spatial configurations of integration are possible, however. On the same plot, crop and livestock may be integrated simultaneously, such as with silvo-agropastoral systems, or multiyear successions of crops and fodder crops, grazed or not (Carvalho et al., 2018). At the farm or territory scale, livestock and crops may occupy separate lands, with only exchanges of matter (fodder, manure) integrating the two activities (Moraine et al., 2016). The interests of these various configurations should be assessed with consideration of the underlying processes enhancing the robustness and the adaptability of each system.

We carried out this study at the field scale, as necessitated by the experimental design underlying the data used. However, higher-level organizational structures also must be considered to achieve a broader assessment of the value of ICLS. First, at the farm scale, the technical operation of the system studied here required other grazing lands for maintaining animals during the summer season (if growing animals are kept the whole year), as well as to provide animals for adjustment of the stocking rate during winter. At this scale, we also have to take in account the workload and the labor organization. Even if diversification enhances resilience, labor and management may be factors contributing to low overall level of ICLS adoption, as showed by Bendahan et al. (2018) in Brazilian Amazonia. If we consider cow-calf operations, which produce animals for growing and finishing, regional farming systems with exchanges among farms have also to be taken in account. Other possible resilience-enhancing attributes emerge at the farming system scale, such as landscape heterogeneity, which supports crop and forage diversity (Di Falco et al., 2010), or enabling environments such as insurance institutions for risk management, or market structuration (Valencia et al., 2019). At these scales, transformability of the farms and of the farming systems also has to be appraised in order to assess overall resilience (Meuwissen and al., 2019).

4. Conclusion

Downside risk analysis showed that integrated crop-livestock systems (ICLS) are more resilient than specialized cropping systems (CS). The integration of summer crops with winter grazing of cover crops, on the same plot, during an annual production cycle, represented the addition of a less risky activity (livestock) with regard to climate hazards and increased the land-use efficiency of the operation. The impacts of grazing management were different according to the outputs of the system. The lowest grazing intensity was more stable for beef yields, with the lowest expected loss in terms of average live weight production, but overall production was rather low. Thus, the systems with higher stocking rate were more important for buffering climate hazards and price volatility, with fewer expected losses per unit of gross value added. Systems with higher resource-use efficiency were more effective from a sustainable intensification perspective, combining higher mean outputs with increased overall resilience. The same conclusion emerged when using an ascendancy perspective to assess resilience of network flows: ICLS were more resilient than CS. However, this analysis did not detect any differences associated with grazing management. Thus, the resilience of the network of nutrient flows, R_{flow} (N or P) appears to be a useful proxy for assessing robustness and adaptability capacities of an agroecosystem, but further investigations are needed in order to generalize this finding to other system configurations.

Acknowledgments

We thank Caitlin A. Peterson for her helpful comments and grammar checking on the manuscript. We also thank the anonymous reviewers for their valuable contributions. This work was supported by the International Cooperation Program CAPES/COFECUB [88887.140961/2017-1] from Coordination for the Improvement of Higher Education Personnel (CAPES) of the Brazilian Ministry of Education.

Appendix A. Supplementary data

References

Alomia-Hinojosa, V., Groot, J.C.J., Speelman, E.N., Bettinelli, C., McDonald, A.J., Alvarez, S., Tittonel, P., 2020. Operationalizing the concept of robustness of nitrogen networks in mixed smallholder systems: A pilot study in the mid-hills and lowlands of Nepal. Ecological Indicators 110, 105883. DOI: https://doi.org/10.1016/j.ecolind.2019.105883

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agron. Sustain. Dev. 35, 869–890. DOI: 10.1007/s13593-015-0285-2

Alvarez, S., Rufino, M.C., Vayssières, J., Salgado, P., Tittonell, P., Tillard, E., Bocquier, F., 2013. Whole-farm nitrogen cycling and intensification of crop-livestock systems in the highlands of Madagascar: an application of network analysis. Agric. Syst., 126, 25-37. DOI: http://dx.doi.org/10.1016/j.agsy.2013.03.005.

Angeler, D.G., Allen C.R., 2016. Quantifying resilience. Journal of Applied Ecology. 53, 617–624. DOI: 10.1111/1365-2664.12649

BACEN, Central Bank of Brazil (Banco Central do Brasil), 2018. Dolar (Dólar, Série Histórica, 2000-2018). Available in: <www3.bcb.gov.br>. (accessed 02.02.2018).

Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.V.G.A., Cecagno, D., Carlos, F.S., Carvalho, P.C.F., 2014. Soil carbon and nitrogen stocks and fractions in a long-termintegrated crop–livestock system under no-tillage in southern Brazil. Agric. Ecosyst. Environ. 190, 52–59. DOI: http://dx.doi.org/10.1016/j.agee.2013.12.003

Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.G.A., Kunrath, T.R., Bayer, C., Carvalho, P.C.F., Franzluebbers, A.J., 2015. Carbon and nitrogen cycling in an integrated soybean-beef cattle production system under different grazing intensities. Pesq. agropec. bras., Brasília. 50, 967-978. DOI: 10.1590/S0100-204X2015001000013

Assmann, J.M., Martins, A.P., Anghinoni, I., Denardin, L.G.O., Nichel, G.H. Costa, S.E.V.G.A., Rodrigo Silva, A.P., Balerini, F., Carvalho, P.C.F., Franzluebbers, A.J., 2017. Phosphorus and potassium cycling in a long-term no-till integrated soybean-beef cattle production system under different grazing intensities in subtropics. Nutr Cycl Agroecosyst. 108, 21. DOI: https://doi.org/10.1007/s10705-016-9818-6

Barthram, G.T., 1985. Experimental techniques: the HFRO sward stick. The Hill Farm-ing Research Organization/Biennial Report. HFRO, Penicuik.

Bendahan, A.B., Poccard-Chapuis, R., Dantas de Medeiros, R., de Lucena Costa, N., Tourrand, J.F., 2018. Management and labour in an integrated crop-livestock-forestry system in Roraima, Brazilian Amazonia. Cah. Agric. 27, 25005. DOI: https://doi.org/10.1051/cagri/2018014

Bonaudo, T., Bendahan, A.B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., Tichit, M. 2014., Agroecological principles for the redesign of integrated crop–livestock systems. Europ. J. Agronomy. 57, 43-51. http://dx.doi.org/10.1016/j.eja.2013.09.010

Bouwman, L., Goldewijk, K.K., Van Der Hoek, K.W., Beusen, A.H.W., Vuuren, D.P.V., Willems, J., Rufino M.C., Stehfest, E., 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. PNAS. 52, 20882-20887. https://doi.org/10.1073/pnas.1012878108

Briske, D.D., Illius, A.W., Anderies, J.M., 2017. Nonequilibrium Ecology and Resilience Theory. In: Briske, D.D. Rangeland Systems: Processes, Management and Challenges, Texas, pp.197-227.

Carvalho, P.C.F., Barro, R.S., Neto, A.B., Nunes, P.A.A., Moraes, A., Anghinoni, I., Bredemeier, C., Bayer, C., Martins, A.P., Kunrath, T.R., Santos, D.T., Carmona, F.C., Barros, T., Filho, W.S., Almeida, G.M., Caetano, L.A.M., Cecagno, D., Arnuti, F., Denardin, L.G.O., Bonetti, J.A., Toni, C.A.G., Borin, J.B.M. 2018. Integrating the pastoral component in agricultural systems. R. Bras. Zootec., 47, e20170001. https://doi.org/10.1590/rbz4720170001

Carpenter, S.R., Arrow, K., Barrett, S., Biggs, R., Brock, W.A., Crépin, A.S., Engström, G., Folke, C., Hughes, T.P., Kautsky, N., Li, C.Z., McCarney, G., Meng, K., Mäler, K.G., Polasky, S., Scheffer, M., Shogren, J., Sterner, T., Vincent, J.R., Walker, B., Xepapadeas, A., de Zeeuw, A., 2012. General Resilience to Cope with Extreme Events. Sustainability. 4, 3248-3259. doi:10.3390/su4123248

CEPEA, Center for Advanced Studies in Applied Economics of ESALQ, State University of São Paulo (Centro de Estudos Avançados em Economia Aplicada da ESALQ, Universidade Estadual de São Paulo), 2018a. Beef and calf price (Preço mensais do boi gordo e do bezerro para o estado do Rio Grande do Sul, ano 2000 à 2017). Available in: <https://www.cepea.esalq.usp.br/br> (accessed 07.02.2018).

CEPEA, Center for Advanced Studies in Applied Economics of ESALQ, State University of São Paulo (Centro de Estudos Avançados em Economia Aplicada da ESALQ, Universidade Estadual de São Paulo), 2018b. Livestock reports (Relatório pecuário, bovinos, ano 2009 à 2017). Available in: <https://www.cepea.esalq.usp.br/br> (accessed 07.02.2018).

Chaudhary, A., Gustafson, D., Mathys, A., 2018. Multi-indicator sustainability assessment of global food systems. Nature Communications. 9, 848. DOI: 10.1038/s41467-018-03308-7

Cordell, D., White. S., 2014. Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future. Annu. Rev. Environ. Resour. 39, 161–88. DOI: 10.1146/annurev-environ-010213-113300.

CONAB, Nacional Supply Company (Companhia Nacional de Abastecimento), 2018a. Crop and livestock input price (Preços mensais de fertilizantes, 2009-2017 – Rio Grande do Sul). Available in: <www.conab.gov.br> (accessed 05.02.2018).

CONAB, Nacional Supply Company (Companhia Nacional de Abastecimento), 2018b. Crop and livestock price (Preços mensais de herbicidas, 2009-2017 – Rio Grande do Sul). Available in: <www.conab.gov.br> (accessed 05.02.2018).

CONAB, Nacional Supply Company (Companhia Nacional de Abastecimento), 2018c. Crop and livestock input price (Preços mensais de sementes, 2009-2017 – Rio Grande do Sul). Available in: <www.conab.gov.br> (accessed 05.02.2018).

CONAB, Nacional Supply Company (Companhia Nacional de Abastecimento), 2018d. Crop and livestock price (Preços mensais da soja, 2009-2017 – Rio Grande do Sul). Available in: <www.conab.gov.br> (accessed 05.02.2018).

Darnhofer, I., 2014. Resilience and why it matters for farm management. European Review of Agricultural Economics. 41, 461–484. DOI: doi:10.1093/erae/jbu012

Deiss, L., Moraes, A., Dieckow, J., Franzluebbers, A.J., Gatiboni, L.C., Sassaki, G.I., Carvalho, P.C.F., 2016. Soil phosphorus compounds in integrated crop-livestock systems of subtropical Brazil. Geoderma. 274, 88–96. DOI: http://dx.doi.org/10.1016/j.geoderma.2016.03.028

Fair, K.F., Bauch, C.T., Anand, M., 2017. Dynamics of the Global Wheat Trade Network and Resilience to Shocks. Scientific Reports. 7, 1-14. DOI: 10.1038/s41598-017-07202-y

Di Falco, S., Penov, I., b, Aleksiev, A., van Rensburg, T.M., 2010. Agrobiodiversity, farm profits and land fragmentation: Evidence from Bulgaria. Land Use Policy. 27, 763-771. DOI: https://doi.org/10.1016/j.landusepol.2009.10.007

Fath, B.D., Scharler U.M., Ulanowicz R.E., Hannon B., 2007. Ecological network analysis: network construction. Ecological Modelling. 208.49–55.

FAO., 2014. Building a common vision for sustainable food and agriculture. Principles and approaches, Rome.

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A., Grizzetti, B., Galloway, J.N., Vitousek, P., Leach, A., Bouwman, A.F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., Voss, M., 2013. The global nitrogen cycle in the twenty- first century. Phil Trans R Soc B. 368, 1-13. DOI: http://dx.doi.org/10.1098/rstb.2013.0164

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. Science. 320, 889-892.

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

Herrera, H., Kopainsky, B., Appel, F., Balmann, A., Accatino, F., Tichit, M., Antoniolo, F., Severini, S., Paas, W., Reidsma, P., 2018. D5.1 Impact assessment tool to assess the Sustainable and resilient EU farming systems (SURE-Farm) project report. Horizon2020 Grant Agreement No. 727520. Available at: https://surefarmproject.eu/wordpress/wp-content/uploads/2018/12/SURE-Farm-D5_1-Impact-assessment-tool.pdf.

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Sere, C., Rosegrant, M., 2010. Smart investments in sustainable food: revisiting mixed crop-livestock systems. Science. 327(5967), 822–825. DOI: https://doi.org/10.1126/science.1183725

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics. 4, 1-23. DOI: https://doi.org/10.1146/annurev.es.04.110173.000245

Hungria M., Franchini J.C., Campo R.J., Graham P.H., 2005. The Importance of Nitrogen Fixation to Soybean Cropping in South America. In: Werner D., Newton W.E. (Eds), Nitrogen Fixation in Agriculture, Forestry, Ecology, and the Environment. Nitrogen Fixation: Origins, Applications, and Research Progress, Dordrecht, pp. 27-42.

INMET, National Institute of Meteorology (Instituto Nacional de Meteorologia), 2018. Stations and Data (Estações Automáticas, Cruz Alta – Rio Grande do Sul, 2001-2017). Available in: <http://www.inmet.gov.br> (accessed 20.03.2018).

Jarvis, S.C., Stockdale, E.A., Shepherd, M.A., Powlson, D.S., 1996. Nitrogen Mineralization in Temperate Agricultural Soils: Processes and Measurement. Advances in Agronomy. 57, 187-235.

Kahiluoto, H., Kaseva, J., 2016. No Evidence of Trade-Off between Farm Efficiency and Resilience: Dependence of Resource-Use Efficiency on Land-Use Diversity. PLoS ONE. 11, e0162736. https://doi.org/10.1371/journal.pone.0162736

Kunrath, T.R., Nunes, P.A.A., Souza Filho, W., Cadenazzi, M.C., Bremm, C., Martins, A.P., Carvalho, P.C.F. 2020. Sward height determines pasture production and animal performance in a long-term soybean-beef cattle integrated system. Agricultural Systems 177, 102716. https://doi.org/10.1016/j.agsy.2019.102716

Lemaire, G., Franzluebbers, A., Carvalho, P.C.F. Dedieu, B., 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agric. Ecosyst. Environ. 190, 4–8. DOI: http://dx.doi.org/10.1016/j.agee.2013.08.009.

Lurette A., Aubron C., Moulin C.H., 2013. A simple model to assess the sensitivity of grassland dairy systems to scenarios of seasonal biomass production variability. Computers and Electronics in Agriculture, 93 : 27–36.

Malavolta, E., Vitti, G.C., Oliveira, S.A., 1997. Avaliação do estado nutricional das plantas, princípios e aplicações, second ed. Piracicaba, pp.319.

Martin, G., Magne, M.A., San Cristobal, M., 2017. An integrated method to analyze farm vulnerability to climatic and economic variability according to farm configurations and farmers' adaptations. Frontiers in Plant Science. 8, 1-16. https://doi.org/10.3389/fpls.2017.01483

Martins, A.P., Cecagno, D., Borin, J.B.M., Arnuti, F., Lochmann, S.H., Anghinoni, I., Bissani, C.A., Bayer, C., Carvalho, P.C.F., 2016. Long-, medium- and short-term dynamics of soil acidity in an integrated crop–livestock system under different grazing intensities. Nutr Cycl Agroecosyst. 104, 67–77. DOI: 10.1007/s10705-015-9759-5.

Meuwissen, M.P.M., Feindt, P.H., Spiegel, A., Termeer, C.J.A.M., Mathijs, E., de Mey, Y., Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M, Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., Ciechomska, A., Accatino, F., Kopainsky, B., Poortvliet, P.M., Candel, J.J.L., Maye, D., Severini, S., Senni, S., Soriano, B., Lagerkvist, C.J., Peneva, M., Gavrilescu, C., Reidsman, P., 2019.A framework to assess the resilience of farming systems. Agricultural Systems. 176, 102656. DOI: https://doi.org/10.1016/j.agsy.2019.102656

Migliorini, P., Wezel, A., 2017. Converging and diverging principles and practices of organic agriculture regulations and agroecology. A review. Agron. Sustain. Dev. 37, 63. https://doi.org/10.1007/s13593-017-0472-4

Moraes, A., Carvalho, P. C. F., Anghinoni, I., Lustosa, S. B. C., Costa, S. E. V. G. A., Kunrath, T. R., 2014. Integrated crop–livestock systems in the Brazilian subtropics. Europ. J. Agronomy. 57, 4–9. DOI: http://dx.doi.org/10.1016/j.eja.2013.10.004

Moraine, M., Duru, M., Therond, O. A social-ecological framework for analyzing and designing integrated crop–livestock systems from farm to territory levels. Renewable Agriculture and Food Systems. 32, 1-14. DOI:10.1017/S1742170515000526

Mori, A.S., 2011. Ecosystem management based on natural disturbances: hierarchical context and non-equilibrium paradigm. Journal of Applied Ecology. 49, 547–551. DOI: 10.1111/j.1365-2664.2010.01956.x

Morecroft, M.D., Crick, H.Q.P., Duffield, S.J., Macgregor N.A., 2012. Resilience to climate change: translating principles into practice. Journal of Applied Ecology. 49, 547–551. DOI: 10.1111/j.1365-2664.2012.02136.x

Mott, G.O., Lucas, H.L., 1952. The design, conduct and interpretation of grazing trialson cultivated and improved pastures. In: International Grassland Congress, Pensylvania, pp. 1380–1395

Nawrocki, D.N., 1999. A Brief History of Downside Risk Measures. The Journal of Investing. 8, 9-25. DOI: 10.3905/joi.1999.319365

NRC. Nutrient Requirements of Dairy Cattle. Minerals, 2001, seventh ed. Washington.

Oenema, O., 2006. Nitrogen budgets and losses in livestock systems. International Congress Series. 1293, 262–271. DOI:10.1016/j.ics.2006.02.040.

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

Rapidel, B., Ripoche, A., Allinne, C., Metay, A., Deheuvels, O., Lamanda, N., Blazy, J.M., Valdés-Gómez, H., Gary, C., 2015. Analysis of ecosystem services trade-offs to design agroecosystems with perennial crops. Agron. Sustain. Dev. 35, 1373–1390. DOI: 10.1007/s13593-015-0317-y.

Rufino, M.C., Tittonell, P., Reidsma, P., Lopez-Ridaura, S., Hengsdijk, H., Giller, K.E., Verhagen, A., 2009. Network analysis of N flows and food self-sufficiency-a comparative study of crop-livestock systems of the highlands of East and southern Africa. Nutr. Cycl. Agroecosyst. 85, 169–186, http://dx.doi.org/10.1007/s10705-009-9256-9

Schaub, S., Finger, R., Leiber, F., Probst S., Kreuzer, M., Weigelt, A., Buchmann, N., Scherer-Lorenzen, M., 2020. Plant diversity effects on forage quality, yield and revenues of semi-natural grasslands. Nature Communications. 11, 768. DOI: https://doi.org/10.1038/s41467-020-14541-4

Sneessens, I., Veysset, P., Benoit, M., Lamadon, A., Brunschwig, G., 2016. Direct and indirect impacts of crop-livestock organization on mixed crop-livestock systems sustainability: a model-based study. Animal. 10, 1911-1922. DOI:10.1017/S1751731116000720

Soil Survey Staff. 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. USDA Natural Resource Conservation Service Agriculture Handbook # 436, Washington.

Souza Filho, W., Nunes, P. A. A., Barro, R. S., Kunrath, T. R., Almeida, G. M., Genro, T. C. M., Bayer, C., Carvalho, P. C. F., 2019. Mitigation of enteric methane emissions through pasture management in integrated crop-livestock systems: Trade-offs between animal performance and environmental impacts. Journal of Cleaner Production 213, 968-975. DOI: https://doi.org/10.1016/j.jclepro.2018.12.245

Spaeth, S. C., Randall, H.C., Sinclair, T.R., Vendeland, J.S., 1983. Stability of Soybean Harvest Index. Agronomy Journal. 76, 482-486. DOI: 10.2134/agronj1984.00021962007600030028x

Stark, F., Fanchone, A., Semjen, I., Moulin, C. H., Archimède, H., 2016. Crop-livestock integration, from single practice to global functioning in the tropics: Case studies in Guadeloupe. Europ. J. Agronomy. 80, 9–20. http://dx.doi.org/10.1016/j.eja.2016.06.004

Stark, F., González-García, E., Navegantes, L., Miranda, T., Poccard-Chapuis, R., Archimède, H., Moulin, C. H., 2018. Crop-livestock integration determines the agroecological performance of mixed farming systems in Latino-Caribbean farms. Agron. Sustain. Dev. 38, 4. https://doi.org/10.1007/s13593-017-0479-x

Ulanowicz, R.E., Goerner, S.J., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: Resilience, efficiency and the return of information theory. Ecological Complexity. 6, 2 7–36. DOI:10.1016/j.ecocom.2008.10.005.

Valencia, V., Wittman, H., Blesh, J., 2019. Structuring Markets for Resilient Farming Systems. Agron. Sustain. Dev. 39, 25. DOI: https://doi.org/10.1007/s13593-019-0572-4

Walker, B., C. S. Holling, S. R., Carpenter, Kinzig, A., 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society. 9, 5. URL:http://www.ecologyandsociety.org/vol9/iss2/art5

Table 1 Soybean grain yield (SGY), live animal production (LAP), and stocking rate as a function of integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a specialized crop system (CS).

	ICLS10[d]	ICLS20[d]	ICLS30[d]	ICLS40[d]	CS
SGY (kg ha^{-1})					
Mean[a]	2845	3014	2996	3163	3052
Standard deviation[b]	1498	1545	1557	1607	1513
Expected loss[c]	524	543	548	565	534
Expected loss / Mean (%)	18.4	18.0	18.3	17.9	17.5
LAP (kg ha^{-1})					
Mean	1152	1156	873	528	
Standard deviation	355	112	114	35	
Expected loss	134	41	45	14	
Expected loss / Mean (%)	8.6	3.5	5.1	2.6	
Stocking rate (kg ha^{-1})	1369	934	715	418	0

[a] Average value for years 2009/2010, 2011/2012, 2014/2015, 2015/2016, and 2016/2017.

[b] Standard error for years 2009/2010, 2011/2012, 2014/2015, 2015/2016, and 2016/2017.

[c] Lower partial moment of order one for the estimation of downside risk, with mean as the threshold.

[d] Grazing intensities in the stocking period of the integrated crop-livestock system (ICLS), corresponding to 10, 20, 30 and 40 cm sward heights, respectively.

Table 2 Goss values added of the system (GVA$_{system}$), of the livestock operation (GVA$_{livestock}$) and livestock contribution to the whole system in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a specialized cropping system (CS).

	ICLS10[e]	ICLS20[e]	ICLS30[e]	ICLS40[e]	CS
GVA$_{system}$ (US\$ ha^{-1})					
Mean[a]	3233	2329	1992	1498	683
Standard deviation[b]	1285	1061	770	637	602
Threshold for downside risk	1400	1400	1400	1400	700
Expected loss[c]	0	97	73	194	215
Expected loss / threshold (%)	0	6.9	5.2	13.9	30.7
GVA$_{livestock}$ (US\$ ha^{-1})					
Mean[a]	2634	1667	1337	777	-
Standard deviation[b]	1899	859	674	333	-
Threshold for downside risk	700	700	700	700	
Expected loss[c]	0	0	7	78	-
Expected loss / threshold (%)	0	0	1.0	11.1	-
Livestock contribution[d] (%)	81	72	67	52	0

[a] Average value for years 2009/2010, 2011/2012, 2014/2015, 2015/2016, and 2016/2017.

[b] Standard error for years 2009/2010, 2011/2012, 2014/2015, 2015/2016, and 2016/2017.

[c] Lower partial moment of order one for the estimation of downside risk, with mean as the threshold.

[d] Livestock contribution to the whole system, calculated as GVA$_{livestock}$ / GVA$_{system}$, expressed in percentage.

[e] Grazing intensities in the stocking period of the integrated crop-livestock system (ICLS), corresponding to 10, 20, 30 and 40 cm sward heights, respectively.

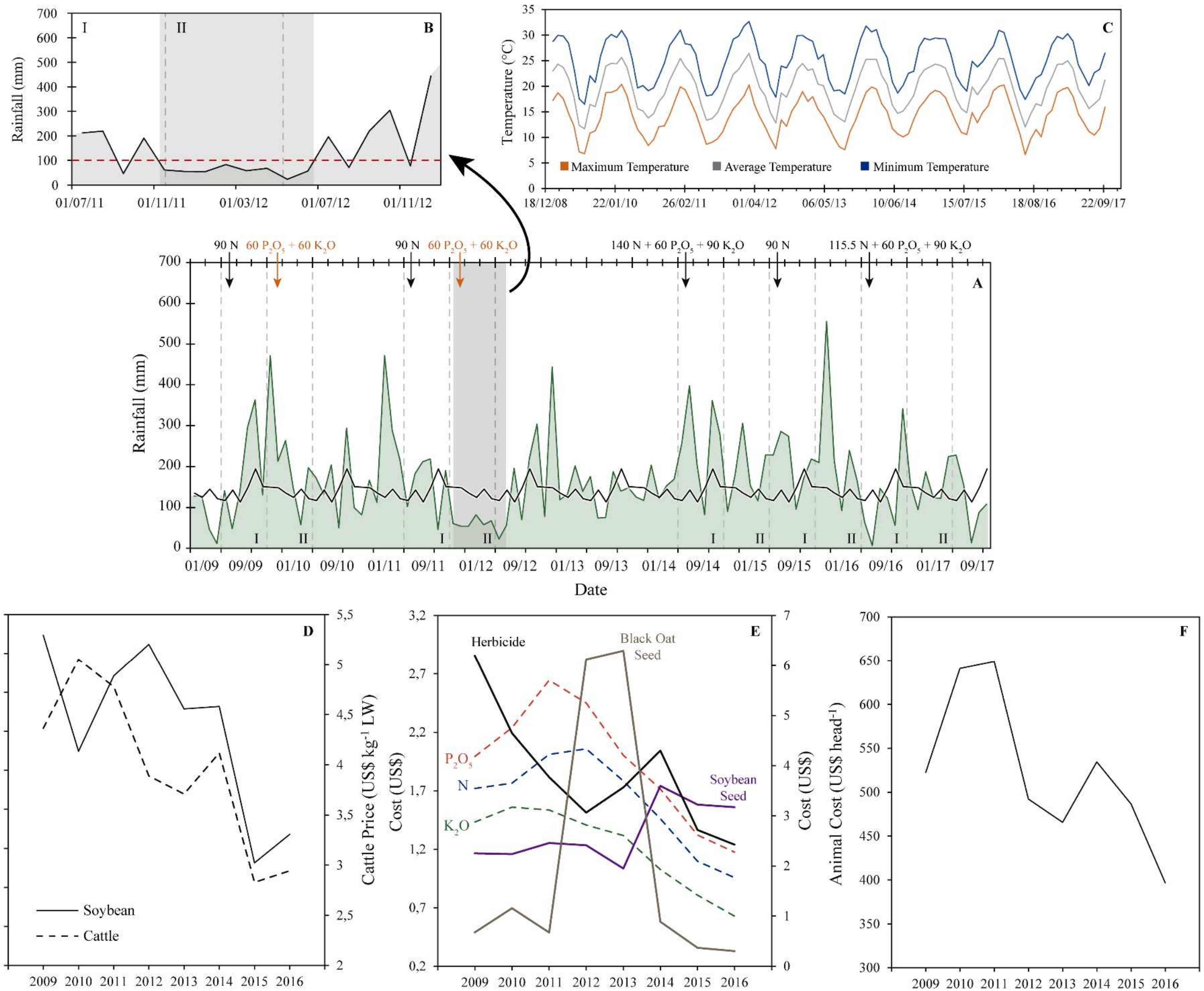
B
I
II
Rainfall (mm)
700
600
500
400
300
200
100
0
01/07/11
01/11/11
01/03/12
01/07/12
01/11/12
C
Temperature (°C)
35
30
25
20
15
10
5
0
Maximum Temperature
Average Temperature
Minimum Temperature
18/12/08
22/01/10
26/02/11
01/04/12
06/05/13
10/06/14
15/07/15
18/08/16
22/09/17
90 N
60 P2O5 + 60 K2O
90 N
60 P2O5 + 60 K2O
140 N + 60 P2O5 + 90 K2O
90 N
115.5 N + 60 P2O5 + 90 K2O
A
Rainfall (mm)
I
II
I
II
I
II
I
II
I
II
01/09
09/09
01/10
09/10
01/11
09/11
01/12
09/12
01/13
09/13
01/14
09/14
01/15
09/15
01/16
09/16
01/17
09/17
Date
D
Soybean Price (US$ kg-1)
Cattle Price (US$ kg-1 LW)
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
5,5
5
4,5
4
3,5
3
2,5
2
Soybean
Cattle
2009
2010
2011
2012
2013
2014
2015
2016
E
Herbicide
Black Oat Seed
P2O5
N
K2O
Soybean Seed
Cost (US$)
Cost (US$)
3,2
2,7
2,2
1,7
1,2
0,7
0,2
7
6
5
4
3
2
1
0
2009
2010
2011
2012
2013
2014
2015
2016
F
Animal Cost (US$ head-1)
700
650
600
550
500
450
400
350
300
2009
2010
2011
2012
2013
2014
2015
2016

Fig 1. The central graph (*A*) shows the cumulative monthly rainfall (mm) from January 2009 to September 2017 (green line) and the average cumulative monthly average from the last 56 years (black line). The gray dashed lines delimit the period of cultivation of the winter pasture (I) and soybean (II) during the evaluated periods. The arrows at the top of graph *A* demonstrate the amounts of N, P_2O_5, and K_2O fertilizer (kg ha^{-1}) applied to winter pasture (black) and soybean (orange). The drought period between November 2011 and June 2012 is represented by the gray bands in graphs *A* and *B*. Graph *C* shows the average monthly temperatures (°C) between 2009 and 2017. Rainfall and temperature data were provided by INMET (2018). Graph *D* shows the average prices of soybeans (US$ kg^{-1} of grain) and animals (US$ kg^{-1} of live weight) paid to the farmer at the time of sale by year. Graph *E* shows the prices of nitrogen (US$ kg^{-1} of N), phosphorus (US$ kg^{-1} of P_2O_5), potassium (US$ kg^{-1} of K_2O), soybean seeds (US$ kg^{-1} of seed), black oat seeds (US$ kg^{-1} of seed), and herbicides (US$ 100 g^{-1} of active ingredient) paid by the farmer each year. Graph *F* shows the cost of the animals (US$ $head^{-1}$) paid by the farmers by year. Prices for agricultural products were obtained from CONAB and CEPEA.

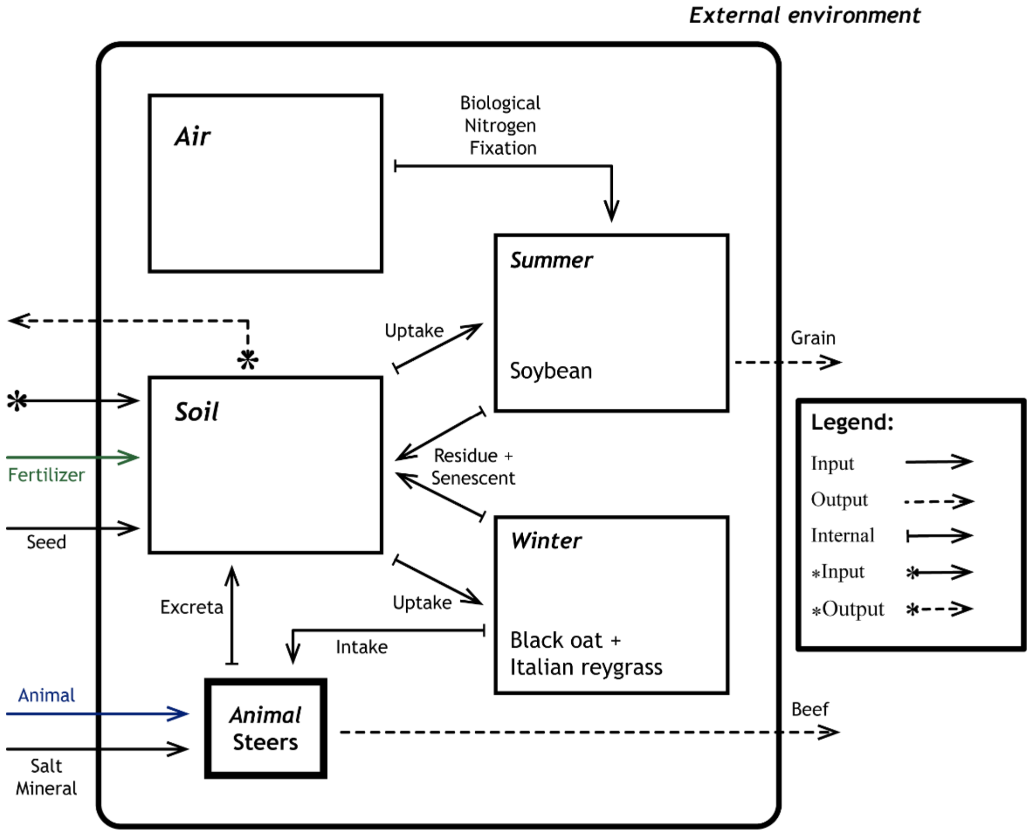

Fig 2. Conceptual model proposed for the ENA analysis applied in an integrated crop–livestock system with different grazing intensities (ICLS10, ICLS20, ICLS30 and ICLS40, corresponding to 10, 20, 30 and 40 cm sward heights) and in a specialized cropping system (CS). The variation factors of the systems (treatments) are represented by the blue and green colorations, which represent the animal stocking (heights of pasture management) and different fertilization strategies over the years, respectively. The larger rectangle represents the boundary between the system and the external environment. The rectangles within the systems represent the compartments air, soil, animals, summer crop (soybean), and winter pasture (black oat + Italian ryegrass).

Input represents the inflow from the external environment to the system. *Output* represents the productive outflows from the system to the external environment. *Internal* represents the flows among compartments within the system. ∗*Input* represents the inflows of supply of minerals "stored" in the soil (unavailable nutrients) to the soil of the system (available nutrients). ∗*Output* represents non-productive outflows from the system to the external environment.

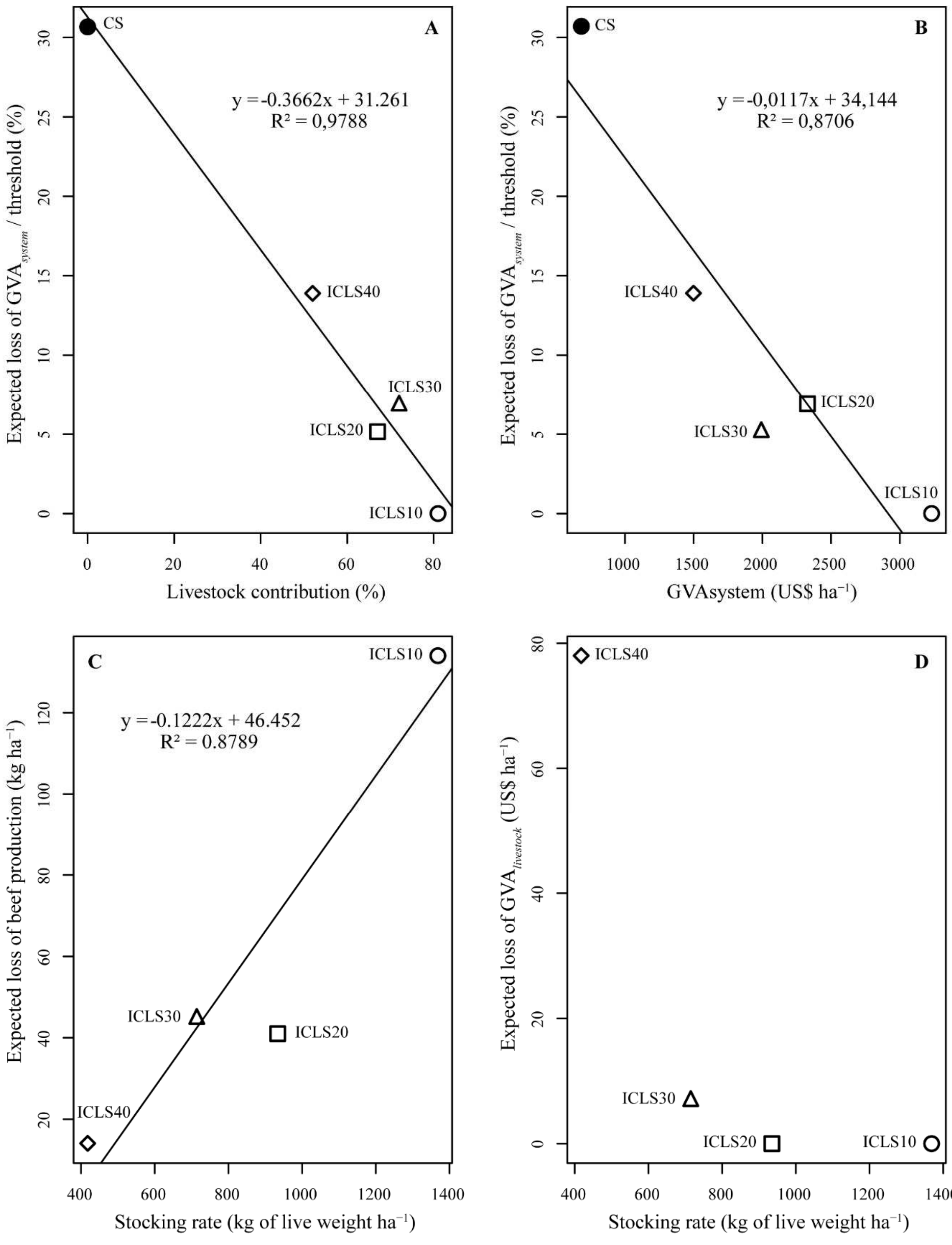

Fig. 3. Expected losses as function of resilience-enhancing attributes (3A, 3C and 3D) and trade-off between risk and productivity (3B) in an integrated crop–livestock system with different grazing intensities (ICLS10, ICLS20, ICLS30 and ICLS40, corresponding to 10, 20, 30 and 40 cm sward heights) and in a specialized cropping system (CS). 3A. Expected loss of beef yield as function of the stocking rate. 3B. Expected loss of the Gross Value Added of the system as function of the GVA_{system}. 3C. Expected loss of beef production as function of the stocking rate, for four ICLS. 3D. Expected loss of livestock operation Gross Value Added ($GVA_{livestock}$) as function of the stocking rate, for four ICLS.

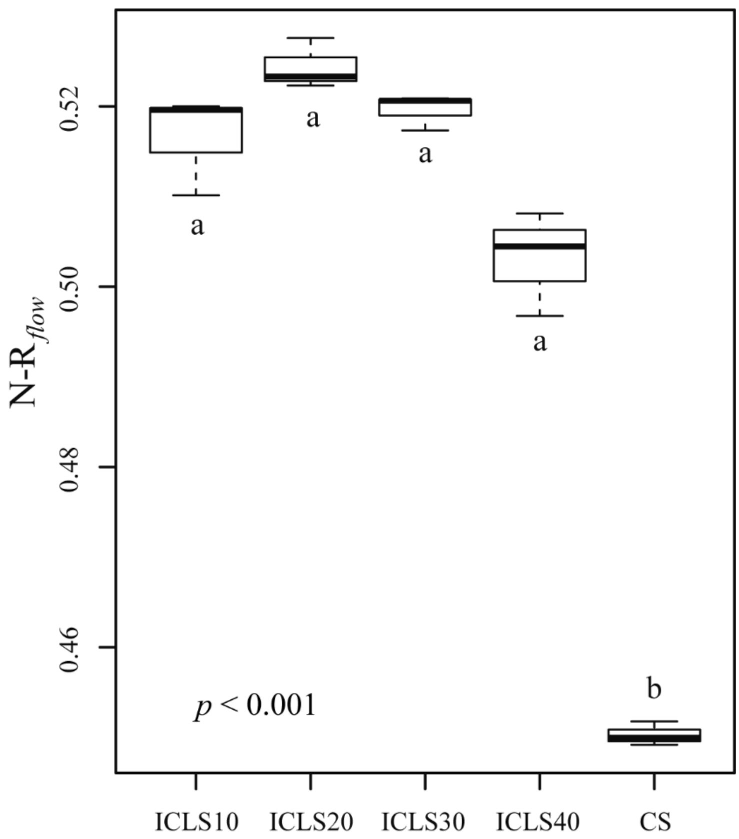

Fig. 4. Nitrogen resilience (N-R$_{flow}$) in an integrated crop–livestock system with different grazing intensities in the winter stocking period (ICLS10, ICLS20, ICLS30 and ICLS40, corresponding to 10, 20, 30 and 40 cm sward heights) and in a specialized cropping system (CS). Different lowercase letters represent a significant difference among treatments (Tukey test, $p < 0.05$). For each treatment, horizontal lines indicate the median values, boxes include the central 50% of the distribution, and vertical dashed lines the central 95% of the distribution.

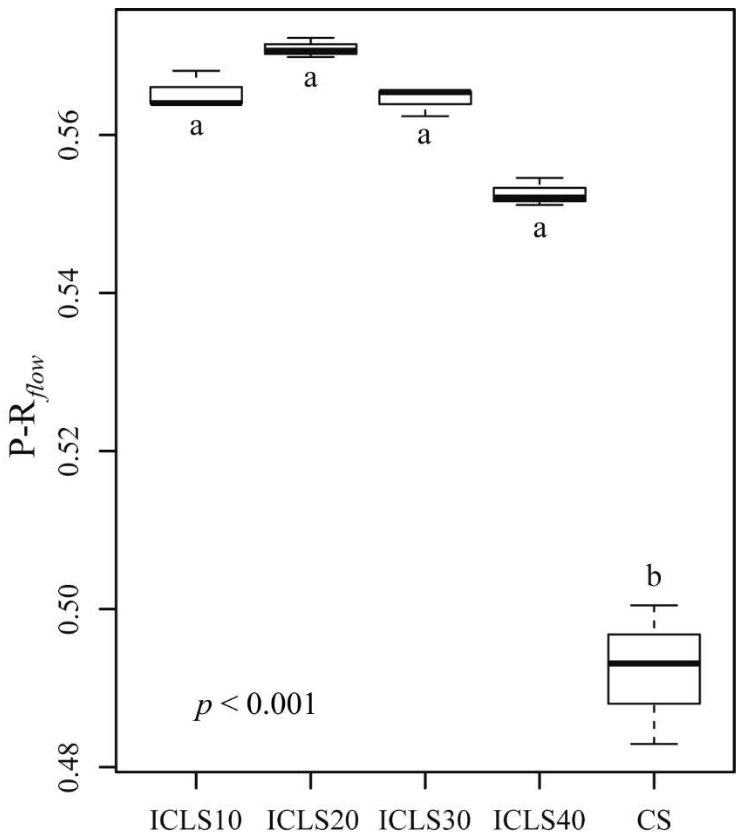

Fig. 5. Phosphorus resilience (P-R_{flow}) in an integrated crop–livestock system with different grazing intensities in the winter stocking period (ICLS10, ICLS20, ICLS30 and ICLS40, corresponding to 10, 20, 30 and 40 cm sward heights) and in a specialized cropping system (CS). Different lowercase letters represent a significant difference among treatments (Tukey test, $p < 0.05$). For each treatment, horizontal lines indicate the median values, boxes include the central 50% of the distribution, and vertical dashed lines the central 95% of the distribution.