

LAND-USE INTENSIFICATION TRENDS IN THE RIO DE LA PLATA REGION OF SOUTH AMERICA: TOWARD SPECIALIZATION OR RECOUPLING CROP AND LIVESTOCK PRODUCTION

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KEYWORDS

grazing, integrated crop-livestock systems, mixed crops-livestock, Pampa

HIGHLIGHTS

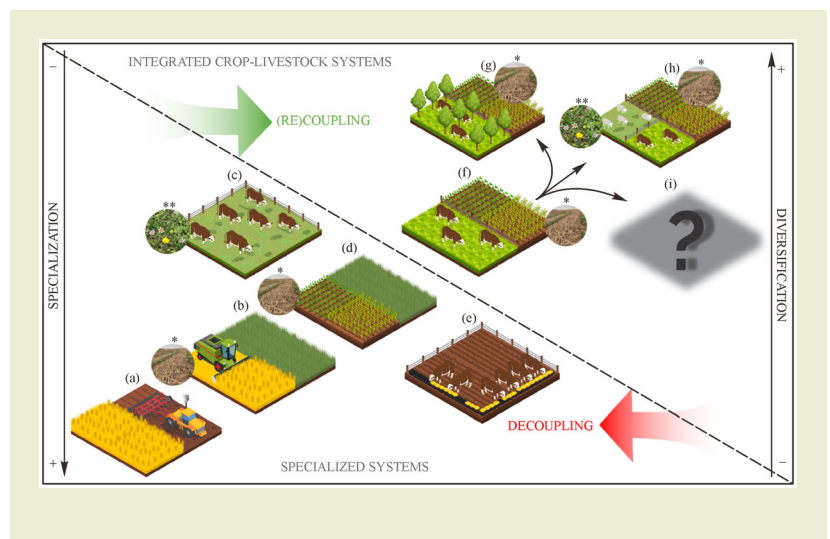
- Current intensification trends in the Rio de la Plata need urgent re-direction.
- Integrated crop-livestock systems reconcile food production with ecosystem services.
- Case studies validate recoupling as a sustainable way to ecological intensification.

Received November 12, 2020;

Accepted January 13, 2021.

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GRAPHICAL ABSTRACT



ABSTRACT

The Rio de la Plata region comprises central Argentina, Uruguay, and southern Brazil. Modern agriculture developed around 1900 with recent decades being characterized by the advance of cropping areas over native grasslands. Highly specialized agriculture has decoupled crop and livestock production but has succeeded in intensifying yields. However, significant losses of ecosystem

services have been reported. Thus, questions have been raised on the sustainability of this pathway. A glance at world regions that have experienced similar trends suggests that an urgent course correction is needed. A major concern has been the lack of diversity in regions with highly specialized agriculture, promoting renewed interest in integrated crop-livestock systems (ICLS), not only because ICLS are more diverse than specialized systems, but also because they are rare examples of reconciliation between agroecosystem intensification and environmental quality. Consequently, this paper discusses alternatives to redesign multifunctional landscapes based on ICLS. Recent data provide evidence that recoupling crop and animal production increases the resilience of nutrient cycling functions and economic indicators to external stressors, enabling these systems to face climate-market uncertainty and reconcile food production with the provision of diverse ecosystem services. Finally, these concepts are exemplified in case studies where this perspective has been successfully applied.

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1 INTRODUCTION: THE CURRENT INTENSIFICATION PATHWAY

The Rio de la Plata region is a grassland ecosystem covering 70 Mha in South America. It covers the great plain of central-eastern Argentina, Uruguay and the extreme south of Brazil^[1]. Extensive cattle grazing of native grasslands has been the main economic activity in the region since Iberian colonization. In addition to providing moderate financial returns it has allowed the conservation of the area and enabled the development of a unique culture with a transnational character represented by the “gaicho” rancher^[2].

In Argentina, native grasslands were predominant until they were replaced by cash crops, sown pastures, and afforestation^[1]. Over past 30 years, large changes have occurred with the intensification of both agriculture and livestock production in the Pampean region^[3,4]. During 1960–1990, agricultural systems were mainly characterized by extensive production of ruminant livestock on native grasslands and annual crop rotations under multi-pass tillage coupled with extensive livestock production^[5]. Annual crops slowly expanded until the 1990s, and a large proportion of the land remained covered by native grasslands and perennial pastures^[6]. However, multi-pass tillage and low crop production triggered high soil organic matter losses^[7]. In the 1990s, agriculturalization resulted in the decoupling of crop and livestock production systems and a rapid expansion of cropping and specialization with the adoption of no-tillage technology and glyphosate-resistant soybean^[8].

In Uruguay, > 85% of the land area of 17.4 Mha is devoted to

agriculture^[9]. Land use by different agricultural sectors depends mostly on soil use capacity, infrastructure and socioeconomic issues. Ruminant livestock production on grasslands occupies 82% of the agricultural area (14.3 Mha); > 80% of this grassland area is covered by native or regenerated pastures and < 20% by improved or cultivated pastures. Although cash crops such as barley (*Hordeum vulgare*), canola (*Brassica napus* subsp. *napus*), maize (*Zea mays*), rice (*Oryza sativa*), soybean (*Glycine max*), and wheat (*Triticum aestivum*) cover a small part of the area, the cropping area since 2000 has increased from 0.6 Mha to a peak of 1.7 Mha in 2014–2015 and later stabilized at 1.3 Mha^[9]. Cropland is concentrated mostly in regions with soils of the highest use capacity (2.4 Mha)^[10], except for irrigated rice (0.2 Mha) which is cultivated mostly in marginal lowland soils (i.e., not suitable for other crops).

The initial increase in cropping area in Uruguay (mainly driven by the economic benefit of soybean production between 2003 and 2015) was based on rotation intensification (double cropping and conversion of pastures to no-till cropping in integrated crop-livestock systems; ICLS) and expansion into new areas^[11]. However, the drop in international grain prices, in addition to soil degradation in poorly designed rotation systems^[12–15] and soil use and management regulations^[16], stabilized the cropping area and favored ICLS expansion over the last five years. For example, the area under soybean cultivation decreased by 30% between 2013/2014 and 2019/2020 while the area of cultivated pastures increased^[9]. As ruminant livestock production (mainly beef cattle and sheep) is predominantly conducted on native grasslands, ICLS has been adopted by only a few farmers representing 18% of the total land used for livestock production^[9].

The terrestrial biomes in Brazil have lost about 50 Mha of their natural cover over the last two decades and the Pampas had the most substantial loss of all the Brazilian biomes (16.8%)^[17]. The area of native grasslands decreased by 1.6 Mha between 2000 and 2018, with 58% being converted to cropland and 19% to silviculture^[17]. Several studies have identified the role of temporary crops (mainly soybean) and cultivated forests (mainly eucalypts; *Eucalyptus* spp.) driving the rapid and progressive degradation of natural landscapes^[18–22]. Estimates of habitat loss show that only 41% of the original area of native vegetation of the Brazilian Pampa biome remained in 2002 and only 36% in 2008^[23]. In regions where soybean expansion was more important, the remaining areas of native grasslands are now < 10% of their original area^[22].

The Brazilian Pampas is the northernmost area of the Rio de la Plata region^[1]. Currently there are about 9 Mha used for grain cropping in this region, mainly soybean (~ 5.9 Mha), rice (~ 1 Mha), and maize (~ 0.8 Mha) in the summer^[24]. In the winter only about 1.3 Mha are used for grain crops including barley, canola, oat (*Avena sativa*), rye (*Secale cereale*), triticale (\times *Triticosecale*) and wheat^[24]. About 20% of the total agricultural land area is integrated with livestock production according to the latest census^[25], making this the region with the largest percentage area under ICLS in Brazil. The remaining area (~ 66% of the total agricultural land, i.e., 6 Mha) is covered with winter service crops in no-till systems, mainly grass species such as black oat (*Avena strigosa*) and Italian ryegrass (*Lolium multiflorum*), or fallow in systems managed under multi-pass tillage practices. Those areas represent an opportunity for the coupling of crop and livestock production to provide additional provisioning services. Service crops are planted to restore deteriorated ecosystem services and include cover crops, green manures, catch crops and other types of crops.

Although agricultural intensification (genetic modification, high-technology machinery and increases in agrochemical inputs) has resulted in substantial yield increases, the decoupling of crop and livestock production along with landscape homogenization has led to losses of ecosystem services^[4]. Livestock production has been intensified in feedlots or displaced to marginal areas, especially in Argentina^[26]. The use of grains as feed in feedlots has increased particularly in areas with < 60% native grassland cover, whereas stocking rates have increased in subregions dominated by native grasslands. The latter have aggravated overgrazing of native grasslands with negative impacts on aboveground net primary production and meat production. Side effects include negative impacts on the diversity of plants, birds and mammal species, as well as on soil organic carbon content and increased soil erosion^[4].

Ecological intensification of agricultural systems has been proposed as a pathway to solving many of these problems in the Rio de la Plata region. These problems arise mainly from the homogenization of agroecosystems with low crop diversity and long fallow periods in addition to the decoupling of crop and livestock production^[27]. Including service crops during fallow periods increases biodiversity and channels the energy not intercepted by cash crops toward the restoration of deteriorated ecosystem services^[27–29]. Ecological intensification aimed at mimicking the functioning and structure of natural systems is proposed to maintain or increase soil organic carbon and nitrogen stocks, improve soil physical properties, reduce weed populations, control soil erosion and reduce nutrient losses, among other functions^[30–33]. Also, some service crops produce forage biomass during the winter when forage production from native grasslands is usually insufficient. Therefore, there is a huge opportunity for complementarity, with service crops producing provisioning services such as animal protein in periods of forage scarcity in the native grasslands. In addition to the opportunity for the redesign of ICLS in those agricultural areas, grazing livestock mimic the herbivory of natural systems and restore this pathway of nutrient cycling^[34].

The purpose of this paper is to review the opportunities for and the research on developing ICLS in the Rio de la Plata region. First, we discuss the opportunities and challenges for establishing ICLS. Second, we summarize results of some long-term field experiments related to ICLS. Third, we discuss the results of some case-studies in the three countries.

2 OPPORTUNITIES AND CHALLENGES IN RECOUPLING CASH CROPS, SERVICE CROPS AND LIVESTOCK PRODUCTION

The range of possible crop-livestock combinations is as large as the number of domesticated plant and animal species multiplied by almost unlimited spatio-temporal designs. In the Rio de la Plata region, temperate and subtropical climates allow for a unique availability of annual and perennial C3 and C4 crop and forage plants to design very diverse production systems. Also, cattle and sheep are widely distributed across the region making the coupling of crop and grazing animal production a realistic option. Currently, there are some 43 million cattle grazing on the native grasslands of Rio de la Plata^[4], and crop-livestock integration can be performed on-farm or at the territory level. The latest model is more complex and integrates specialized crop and livestock enterprises within a region through the exchange of resources (e.g., conserved forage) or seasonal displacement of

livestock between farms^[35]. ICLS are commonly implemented as annual rotations of summer cash crops (mainly maize, rice and soybean) succeeded by winter pastures grazed by beef cattle or sheep^[36], or grazing of rice crop residues and volunteer plant stands in fallow periods in paddy fields, usually by cattle categories with lower nutritional requirements^[37].

The highest level of synergies and stability arise from diverse agricultural systems that mimic natural systems by coupling varied plant functional types with multispecies herbivory on-farm and no-till ICLS designs (Fig. 1).

Gordon et al.^[38] stressed that agricultural production in the early days of agriculture was closely connected to nature. The contemporary specialization trend has progressively promoted the disconnection of agriculture and nature, creating uniform

agricultural landscapes. This decoupling process constrains the natural biogeochemical cycles, and pollution becomes a problem. It is noteworthy that agricultural intensification per se is not the origin of decreasing sustainability, but rather the intensification pathway associated with decreasing diversity^[34].

Diverse ICLS contributions to productivity, resource use efficiency, stability and sustainability have been demonstrated in some regional studies^[12,39–42]. Cultivated pastures in rotation with crops complement the lower productivity and quality of native pastures, reduce the need for pesticides, increase biodiversity, fix biological nitrogen, improve soil quality, sequester soil carbon and control soil erosion, determining higher crop productivity^[14,39,43–45]. For example, shifting crop-pasture rotations to no-till continuous annual cropping reduced soil quality and wheat yield in Uruguay^[14]. In turn, rice-pasture

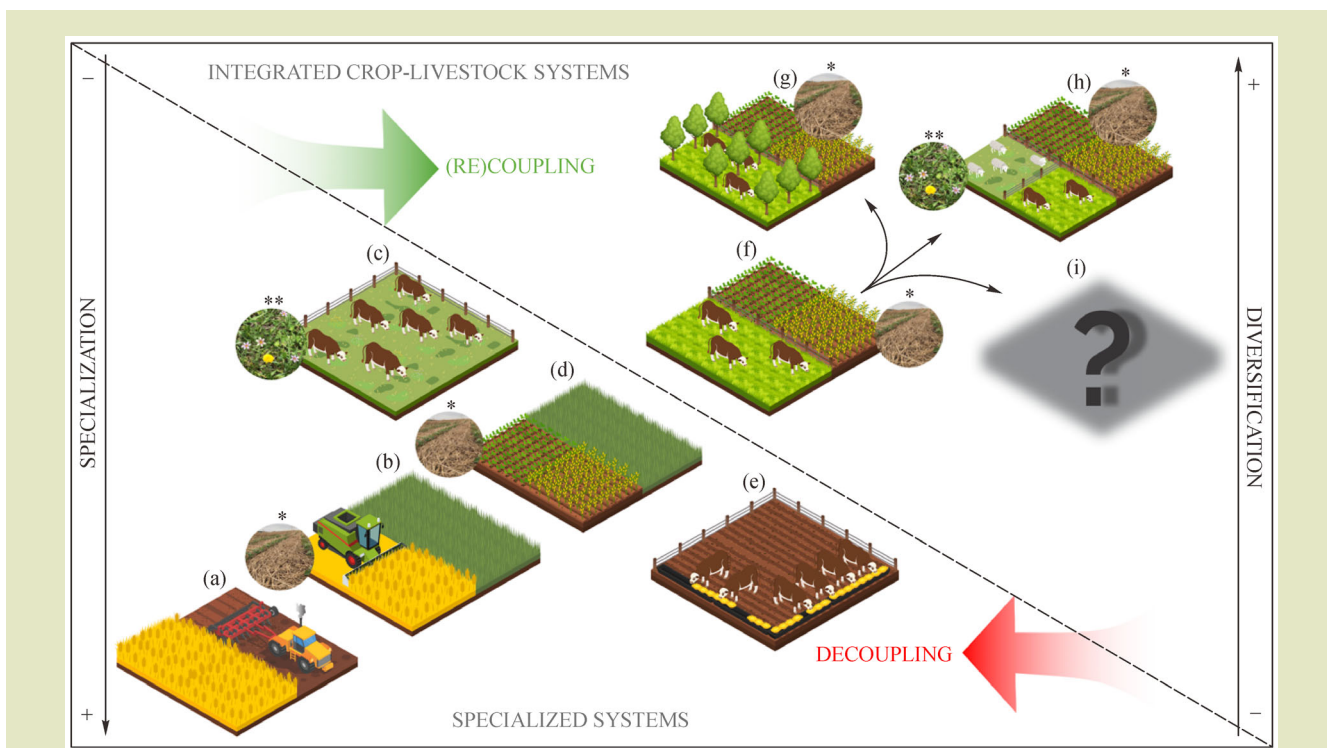


Fig. 1 Conceptual model for decoupling and (re)coupling of crop and livestock production across a range of possible specialization/diversification scenarios. Coupling of crop and livestock production can be done at any system level and at different spatio-temporal scales (i.e., at field, farm or landscape scale). The probability of synergies and complementarities occurring between system components is higher as system diversification increases. The same applies to the complexity and magnitude of biogeochemical cycles. System representations correspond to: (a) monocropping system under multi-pass tillage, (b) specialized cash crop production under no-till (*) plus cover crops, (c) extensive livestock production on native grasslands (**), (d) specialized cash crop production under no-till (*) plus cover crops plus crop rotation, (e) intensive livestock production in feedlots, (f) integrated system with livestock grazing cover crops plus cash crops under no-till (*) plus crop rotation, (g) integrated system with livestock grazing cover crops plus cash crops under no-till (*) plus crop rotation plus trees, (h) integrated system with different livestock species grazing cover crops and native grasslands (**) plus cash crops under no-till (*) plus crop rotation, and (i) any other crop-livestock combination not represented previously (could include silvopastoral systems with native grassland species and trees, livestock integration into perennial systems such as orchards and vineyards, or even mixed grazing).

systems were one of the keys to the sustainable increase in rice productivity with higher ecological efficiency and environmental performance indicators^[46,47]. Despite this, when livestock was integrated into the flooded rice system, nutrient use efficiency also increased^[48,49].

Likewise, crop-livestock integration at farm and landscape scales can be an ally to livestock production on native grasslands, mainly due to the provision of high-quality pastures in winter, when native pastures have low productivity. In this case, the use of well-managed grazed pastures such as Italian ryegrass, tall fescue and white clover in cropping systems is a good option to improve the ecological indicators toward sustainable intensification^[50]. Also, the provision of high-quality, well-managed pastures in ICLS can help farmers to increase turnoff weight and reduce turnoff age of beef cattle, which has the potential to mitigate emissions of greenhouse gases such as methane from enteric fermentation^[51] and carbon losses to the atmosphere^[52].

Another possible ICLS model is the integration of livestock with trees. Integrated production of beef cattle and eucalypts has been shown to be profitable and to provide ecological benefits^[53]. In addition, integration of cash crops and livestock with trees can be an effective way to diversify production and income, which could be important to the Rio de la Plata region considering that commercial wood plantations (mainly eucalypts) have been increasing in the region^[54]. The integration of animals (mainly sheep) grazing interrow/undercanopy vegetation in vineyards and orchards has been a trend in other parts of the world^[55], but the existence of this ICLS model remains anecdotal in Rio de la Plata and consists of an opportunity for research and development. Therefore, farm designs integrating ruminants and trees such as eucalypts, or with horticultural production such as grapes, olives and walnuts, if well planned and managed can be a way to increase farmer livelihoods in the region.

ICLS is an important way to increase the sustainability and the profitability of food production and the efficiency of land use^[40–42,45,47,56]. However, there are many challenges in the adoption of ICLS, including the implementation of commercial-scale ICLS in specialized farms. Paradigms associated with the use of areas under conservation agricultural practices (e.g., potential soil compaction by animal trampling or the consumption of forage material that would otherwise cover the soil) and a higher degree of managerial complexity remain barriers to ICLS adoption in southern Brazil^[36,57]. Also, specialized farmers (those producing one or two commercial cash crops only) have 38% less probability to couple crops with livestock compared to those with a higher degree of on-farm diversification (at least three different crops)^[58]. Aging is another issue since there has

been an upward trend in farmers' ages and ICLS adoption decreases by 33% when farmers are older than 60 years^[58].

ICLS are more complex to manage than specialized systems, thereby posing a challenge for advisors to develop coordinated actions^[59]. ICLS design requires a holistic approach to be able to deal with system biophysical issues and human psychological barriers (not only owners but also farm staff, their families and other stakeholders). A co-design approach toward ICLS implementation has been proposed, by setting transition strategies to help farmers to move forward to a mindset open to reimagine their production system. Advisors with a holistic approach are rare and this is recognized as an important limitation in ICLS adoption. Both the production systems and advising have become more specialized.

Another recognized challenge is the need to increase research on ICLS in the Rio de la Plata region, which is necessary to generate reliable knowledge of the benefits of animal grazing well-managed pastures in the cash-crop areas^[36,50] and then provide support for farmers to use that information on their farms. Also, government actions based on public policies and research funding are needed to promote ecological intensification, which should be based on more ICLS research generated by research agencies and the national universities.

3 LONG-TERM RESEARCH ON RECOUPLING CROP AND LIVESTOCK PRODUCTION

To address concerns about the recoupling of crop and grazing animal production in cropping areas, three long-term ICLS experiments with increasing levels of plant species diversity and system complexity were designed in southern Brazil, each aiming to answer emerging questions regarding the impacts of reintroducing grazing animals in pure cropping systems. The first experiment was established in the municipality of São Miguel das Missões (28° 56' S, 54° 20' W, 465 m.a.s.l.) in the *Planalto* region (i.e., highlands dominated by specialized soybean/maize farms) in 2001. The experiment consists of yearly no-till soybean-pasture (mixed black oat and Italian ryegrass) rotations designed to study the effects of beef cattle integration under different winter grazing intensities on the plant (forage and soybean) and animal yields and soil attributes compared to the same rotation without grazing^[51,60,61]. The second experiment was established in the municipality of Eldorado do Sul (30° 05' S, 51° 39' W, 46 m.a.s.l.) in the *Central* region (i.e., a mix of lowlands and highlands where rice and

soybean cultivation prevail over other crops, and where native Pampa grasslands have been increasingly converted to soybean cropland) in 2003. This experiment adds maize (alternating with soybean in the summer) into the yearly no-till crop-pasture (ryegrass) rotation, and was designed to study the effect of crop rotation, grazing intensity (sheep) and stocking method (continuous vs rotational) on system attributes^[62]. The third experiment was established in the municipality of Cristal (31° 37' S, 52° 35' W, 28 m.a.s.l.) in the *Inner Coastal Plains* region in 2013, and represents the greatest biological diversity and design complexity of the three experiments. This experiment includes five systems with increasing levels of spatio-temporal diversity (Fig. 2). It was designed to evaluate alternatives for the diversification of fields dominated by rice monocropping under multi-pass tillage practices^[48]. The existence and degree of synergistic interactions is expected to increase with system complexity in terms of diversity, temporality and spatiality^[63].

The most common concern among those considering implementing ICLS at the field scale is animal hoof action compacting the soil and negatively affecting subsequent crop yields^[50]. However, international literature has reported potential decreases^[64], absence of effect^[65] or even increases in subsequent crop yields resulting from livestock integration^[66]. Indeed, increased soil density and reduced total porosity were observed

as a result of grazing one year after the first experiment was established^[60] and confirmed seven years later^[61], but these changes were reversed with each soybean cycle. Generally, grazing intensity did not affect these soil attributes, except for one study^[67]. In this study, increased soil bulk density and decreased macro porosity and total porosity were detected in the top 5 cm of soil under intense and moderate grazing intensities (10 and 20 cm sward height, respectively) compared to lighter grazing intensities (30 and 40 cm sward height) and the ungrazed treatment. Soil water retention was also affected by grazing (~ 9% lower compared to the ungrazed control in the top 20 cm of soil) during the fifteenth soybean season as a result of contrasting amounts of forage residue on the soil surface, but this decrease was not large enough to compromise grain yield^[68]. In fact, soybean yields were never affected by grazing or grazing intensity in that experiment^[52,60,68,69].

Additionally, livestock integration improves land-use efficiency and, by adding a less risky activity into specialized cropping systems, works as a buffer to climate hazards and price volatility, and thereby increases system economic resilience^[42]. Developing high yielding food systems that are also resilient to multiple disturbances (i.e., have high capacity to recover after disturbances) is crucial to future food security in the face of increasing weather variability and uncertainties resulting from climate

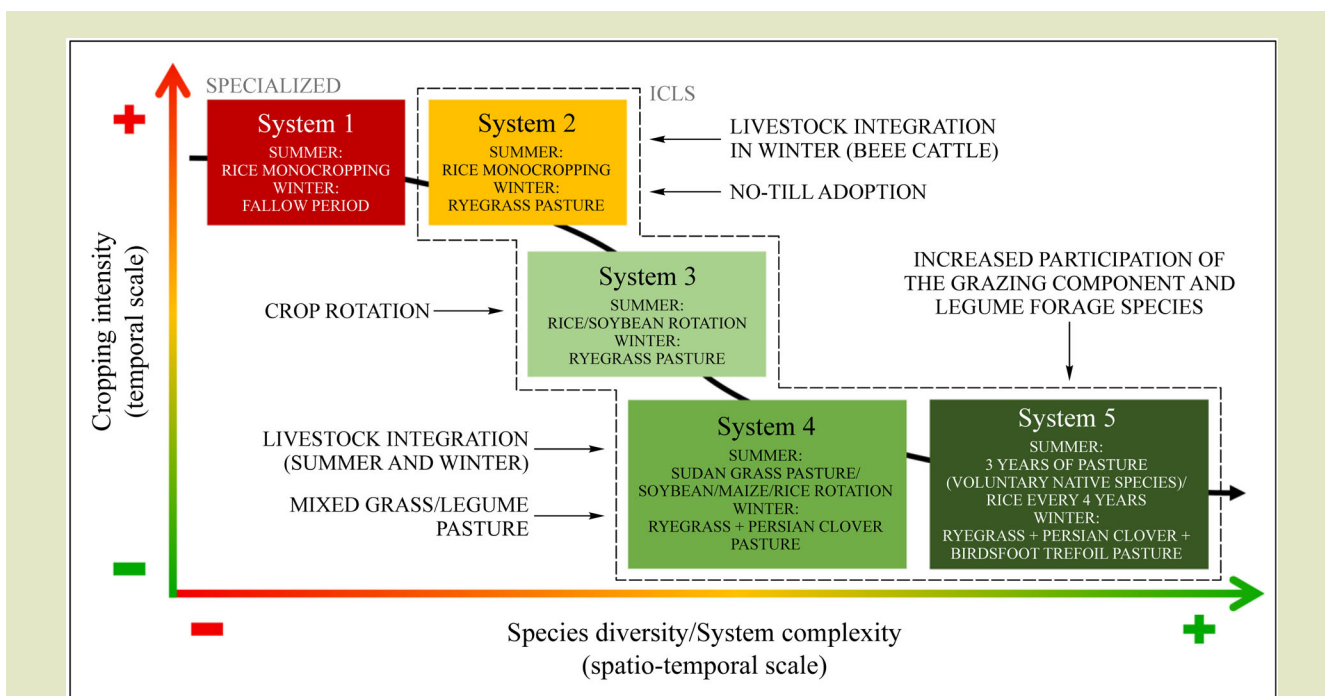


Fig. 2 Conceptual model of the experiment in the municipality of Cristal, Rio Grande do Sul, Brazil. Sustainability of lowland agroecosystems hypothetically increases from System 1 (specialized cropping system using multi-pass tillage practices) to System 5 (biodiverse, complex agroecosystem under no-till) as a result of increasing species diversity and spatio-temporal complexity. The arrows indicate important additions of complexity to the systems.

change^[70,71]. Moreover, there is a need for cleaner food systems, as farming is increasingly under pressure from society for its environmental footprint^[34], especially those systems including livestock^[72]. In this sense, it is possible to reduce the trade-off between animal production and enteric methane emissions by using the best grazing management practices. It was observed in the São Miguel das Missões experiment that individual live weight gain of beef cattle is maximized when pastures are managed at 30 cm height, while methane emission per unit of live weight gain (i.e., emission intensity) is minimized at 23 cm height, indicating that grazing management targets in mixed ryegrass and black oat should stay within this range^[51].

Other concerns preventing the adoption of ICLS refer to the nutrient export from ICLS areas in livestock carcasses and the uneven distribution of nutrients in dung and urine deposited by grazing animals both of which could potentially reduce subsequent crop yields. The effect of livestock integration on subsequent crop yields has been indicated previously in this text not to be a reason for concern if conservation agriculture and sound grazing management practices are adopted. Nutrient export was shown to be controlled by harvested grain crops rather than livestock^[62]. Up to 95% of P and K and 99% of Ca and Mg exported from the ICLS area in the Eldorado do Sul experiment occurred through the removal of grain produced during crop harvest, while contribution of livestock was of minor importance. Instead, animals returned the nutrients ingested almost entirely in dung and urine^[62]. Nutrient redistribution by grazing animals, as well as the act of grazing itself, are indeed sources of variability in the vegetation, creating patterns of waste deposition^[73] and of tall and short patches^[74] as the stocking period progresses. However, heterogeneity in nutrient distribution did not affect subsequent field-scale grain yields, likely because of places with dung deposition present above-average soybean yields that compensate for eventual areas with a nutrient deficit^[52]. Furthermore, for whole-system functioning and performance, sward heterogeneity may be beneficial as it may increase intake and live weight gains of grazing animals^[75].

As the role of livestock as the nutrient recycling component of ICLS became clear, the Eldorado do Sul experiment was redesigned in 2017 to answer an emerging question^[76], namely “Are system resource use efficiency and yields increased by changing the fertilization logic from a per crop approach (i.e., focused on fertilizing the crop, so applied previously to crop seeding) to a system approach (i.e., focused on the replenishment of soil nutrient pools that were depleted with grain harvest/export, so applied previous to pasture sowing) that aims to increase nutrient recycling via grazing animals”? The authors

compared a soybean-cover crop rotation with an integrated soybean-sheep system where the same cover crops were grazed in winter, and the two previously described fertilization strategies. System fertilization increased herbage yields compared to crop fertilization [8.6 vs. 7.3 t of dry matter (DM) ha⁻¹ on average] without compromising subsequent soybean yields. Also, livestock integration increased herbage yields in comparison to the specialized cropping system (8.7 vs. 7.3 t·ha⁻¹ DM on average), so that the greatest forage production was achieved when both strategies were combined (9.4 t·ha⁻¹ DM). Pasture-based sheep production in the winter increased overall food production through increased resource use efficiency, without expanding agricultural frontiers or increasing the use of external inputs^[76].

Increasing resource use efficiency is important in addressing the rising global demand for food sustainably^[77]. Much can be done through agroecosystem diversification, since complementary patterns of resource use and different responses to environmental disturbances in biodiverse ecosystems can increase ecosystem productivity and stability^[78]. Conservation agricultural practices such as cover crops and reduced tillage are also acknowledged for increasing nutrient and water use efficiencies due to improved soil structure, water retention and organic matter levels^[77]. Soil disturbance has been considered to be the main cause of soil degradation worldwide^[79]. In southern Brazil, rice paddies have been commonly managed with intensive multi-pass tillage^[80]. Soil degradation in flooded rice systems leads to lower yields over time due to decreased pH, cation exchange capacity and nutrient use efficiency^[81], requiring higher levels of fertilization to sustain rice yields^[82]. In this sense, it was observed in the Cristal experiment that combined adoption of no-till and crop-livestock integration (see System 2 in Fig. 2) increased nutrient use efficiency, which in turn increased rice yields for the same amount of N, P and K fertilizer compared to multi-pass tillage (see System 1 in Fig. 2)^[49]. In the ICLS, rice yields did not respond to P and K fertilizer application, contrary to what was observed in the multi-pass tillage system. Similarly, soybean yields in ICLS (see System 3 in Fig. 2) were not affected by P and K fertilizer rates (i.e., fertilization rates were based on different soybean yield expectations according to CQFS-RS/SC^[83] guidelines)^[48]. Although individual effects of no-till adoption and crop-livestock integration could not be distinguished in these studies, their results consistently indicated that reliance of crop yields on mineral fertilizers decreased when both practices were combined, likely due to increased nutrient recycling in ICLS under no-till^[84]. Further studies are needed to understand the effects of increased rotation diversity on rice production system attributes such as resource use efficiency, productivity and stability, and

some are already on course in the Cristal experiment. Although there are some long-term crop-pasture rotation experiments being conducted at INIA (*Instituto Nacional de Investigación Agropecuaria*) and UdelaR (*Universidad de la República*) in Uruguay^[39,43,44,47], perhaps the only experiment at farmlet scale is the Palo a Pique (see details in Rovira et al.^[40]). This experiment was established in 1995 on an undisturbed Vertic Argiudoll with the aim of evaluating the impacts of different pasture-crop rotation intensities (long and short rotations with grain and forage crops under no-till and grazed perennial pastures, no-till continuous forage and grain cropping, and permanent grazed improved perennial pastures) on system productivity (crop, forage and animal) and soil quality and biodiversity indicators^[13,39,56]. Lessons learned from the first 25 years of this experiment highlighted the impact of combining ICLS and no-tillage in fragile, erodible soils to improve feed quality and quantity for livestock. Complementing native grasslands with ICLS significantly increased meat production and diversified incomes with grain production, contributing to the development of strategic agricultural regions of Uruguay^[40]. The results also demonstrated that cropping systems reduced soil organic carbon (SOC) compared with permanent pastures. Continuous non-integrated cropping reduced SOC in the top 15 cm of soil by 17%^[40]. Perennial pastures rotating with crops were critical to mitigate SOC losses, and yet produced 338 to 527 kg of live weight per ha per year.

4 RECOUPLING CROP AND LIVESTOCK PRODUCTION IN PRACTICE: CASE STUDIES FROM ARGENTINA, BRAZIL AND URUGUAY

4.1 Argentina

Evidence suggests that ICLS contribute to improving ecosystem services and economic stability of farms in the Rio de la Plata region. A study conducted in south-western Buenos Aires province in Argentina analyzed the impact of diversification and selection of activities on the economic stability of farms with different degrees of diversification^[41]. At the landscape scale the region naturally shows an integration of crop and livestock activities since the lowlands are generally devoted to cow-calf production due to edaphic constraints, and the uplands are devoted to livestock fattening on pastures or annual cash crop production. The analysis covered seven years of production and financial results on 82 farms managed on a business-as-usual basis and evaluated their susceptibility to weather, pests, markets and policy changes, and a different degree of integration between crops and livestock. Results show that greater diversification of

activities, by coupling crop and livestock production, increased interannual stability of farms through an increase in mean return on capital, with no changes in standard deviation^[41]. Crop production was generally more profitable whereas livestock production offered greater stability over time. ICLS (considering cow-calf, fattening and crop production) reduced the variability in return on capital by 30% to 50% in comparison to single crop production systems [maize, soybean, sunflower (*Helianthus annuus*) or wheat].

Research on service crops and ICLS has become a priority in the region with several new challenges such as co-innovation and participatory research. Although ICLS research has been strong in the past^[85] the expansion of croplands over recent decades (mainly soybean monoculture) has overshadowed the importance of ICLS. Intense interactions between agricultural research agencies such as INTA (*Instituto Nacional de Tecnología Agropecuaria*) and universities, farmer associations, private companies and local governments has generated a strong social system that has been able to promote the recoupling of crop and livestock production systems and has highlighted the importance of including environmental targets in redesigning farm solutions.

More recently the rapid and ongoing adoption of service crops in the region has also triggered the recoupling of crop and livestock production systems, with beneficial environmental effects. The concept of service crops as crops planted to restore deteriorated ecosystem services has replaced the classical concepts of cover crops, green manures and catch crops and is now widely understood by farmers^[86]. For example, the farmer association AAPRESID has installed a national Service Crops Network to extend this technology and help include environmental targets in farmer decisions^[87]. The adoption of service crops has been fueled in many regions by the possibility of including livestock grazing during certain periods, which has increased revenue on many farms, making the investment in service crops an even easier choice for many farmers.

4.2 Brazil

The philosophy of PISA (*Produção Integrada de Sistemas Agropecuários*) was first based on the general postulation of ecological intensification, meaning intensifying the functionalities of natural processes that agricultural ecosystems provide^[88]. PISA is a reconciliatory solution model of blended good farming practices applied in a context-specific and holistic way aiming at agricultural development and sustainability. Integrated crop-livestock systems^[34], conservation agriculture^[89], climate-smart agriculture^[90], ecological intensification^[88], farm system

design^[91], and the Rotatinoous stocking concept^[92] are examples of technological frameworks that PISA promotes to accomplish parallel goals if saving land, reducing family workloads, producing more nutritious food and increasing farm profitability, in a customized site-by-site context. PISA is inspired by nature and aims to be flexible and adaptable to any food production system in any part of the world. All pillars and technologies converge into actions to reconcile production and sustainability, while addressing the trade-offs between the need to intensify production for food security and the need to protect and restore environmental quality.

PISA has already been applied to ~ 1600 farms in 113 municipalities in southern Brazil. There is a huge diversity in PISA farms in terms of soil characteristics, area, production focus, crop-livestock diversity, family ethnic origins and machinery structure. Most PISA farms are smallholdings of 15–20 ha. The main revenue comes from 13 to 14 lactating cows. The current production systems are vulnerable and highly dependent on external inputs, trending to specialization. Most cattle feed is silage and concentrates, so the costs and the family workload are high. There is a trend toward decoupling crop and animal production from increasing external pressures for the adoption of more intensive, technological pathways such as compost barns and free stalls. The number of dairy farmers decreased by 12% in 2018–2019, so the situation is problematic.

PISA aims at increasing the resilience of farming and improving risk management in these vulnerable systems. Consultants propose the diversification of crops, recoupling crop and livestock production using low cost pasture-based diets, and the recovery of soil health extenuated by poor farming practices. The PISA model is applied by consultants trained by universities and funded by the private sector. The program includes a preset framework including diagnosis, co-design and implementation of best farming practices; the advisory services last four years with six farm visits per year. Farmers volunteer to PISA and receive no aid except for the advisory services provided by consultants, which is covered by the private sector. Complex systems require an innovative approach to extension, moving from a prescriptive specialized expert approach to a holistic co-developer model^[93]. Advisors must share a similar vision of agriculture (focused on sustainable intensification, ICLS, pasture-based systems, no-till, Rotatinoous stocking as the stocking management concept and a holistic approach) and must have a strong connection with research to be able to create a cohesion of technical principles.

After four years of consulting, the main outcomes resulting from the transition from the existing farming methods to the PISA

model are summarized as follows: (1) increased soil organic matter contents; (2) increased milk yields per cow and per unit area; (3) changed cattle diet from > 60% silage plus concentrate to > 60% pasture intake through grazing; (4) decreased production costs of > 30%; (5) enhanced milk quality; (6) decreased workloads; (7) improved spatio-temporal planning of pasture-crop rotations; (8) diversified family activities including orchards and vegetable gardens. Cascade effects toward sustainability were captured by an assessment proposed by the FAO SAFA tool^[94] (Fig. 3).

The transition from current farming practices to ecological intensification is mediated through a strategic first step, which must be an intervention of no-cost, and at the same time, one that deeply affects all system functioning. The adoption of the Rotatinoous stocking concept^[92,95] is a first step that enhances nutrient gathering from pasture and decreases the need for silage and concentrates, thus decreasing costs and family workloads. Milk production and quality increase in the short term. As an indirect result, the family gets confidence and a new mindset opens to more long-term structural interventions (e.g., adoption of no-till, integration with trees, investments in soil health and reorganization of facilities). In the end, all four dimensions of sustainability scored good or best (Fig. 3), indicating that PISA was successful in enhancing environmental integrity and economical resilience, at the same time contributing to the social wellbeing and the governance of smallholders in southern Brazil.

4.3 Uruguay

Soil erosion and soil carbon losses are the main environmental problems threatening soil quality and productivity in Uruguayan croplands^[16,39]. Between 2008 and 2013, legal regulations were updated and soil use and management plans covering the entire rotation became mandatory for all cropping areas > 50 ha. The plan has to be established by a certified agronomist and has to be presented by the farmer and landowner to the Ministry of Agriculture. The USLE/RUSLE (Universal Soil Loss Equation/ Revised Universal Soil Loss Equation) models have to be used to demonstrate that the estimated annual erosion rate in the rotation systems is below the erosion threshold values established for the cultivated soil. Violations and unaccomplished plans of farmers are subject to penalties and fines.

The validation and calibration of the USLE/RUSLE models to estimate erosion under different soil uses and management systems were done by interdisciplinary teams of the Ministry of Agriculture, UdelaR and INIA over two decades in the 80s and 90s at three sites using Wischmeier runoff plots^[16]. Also,

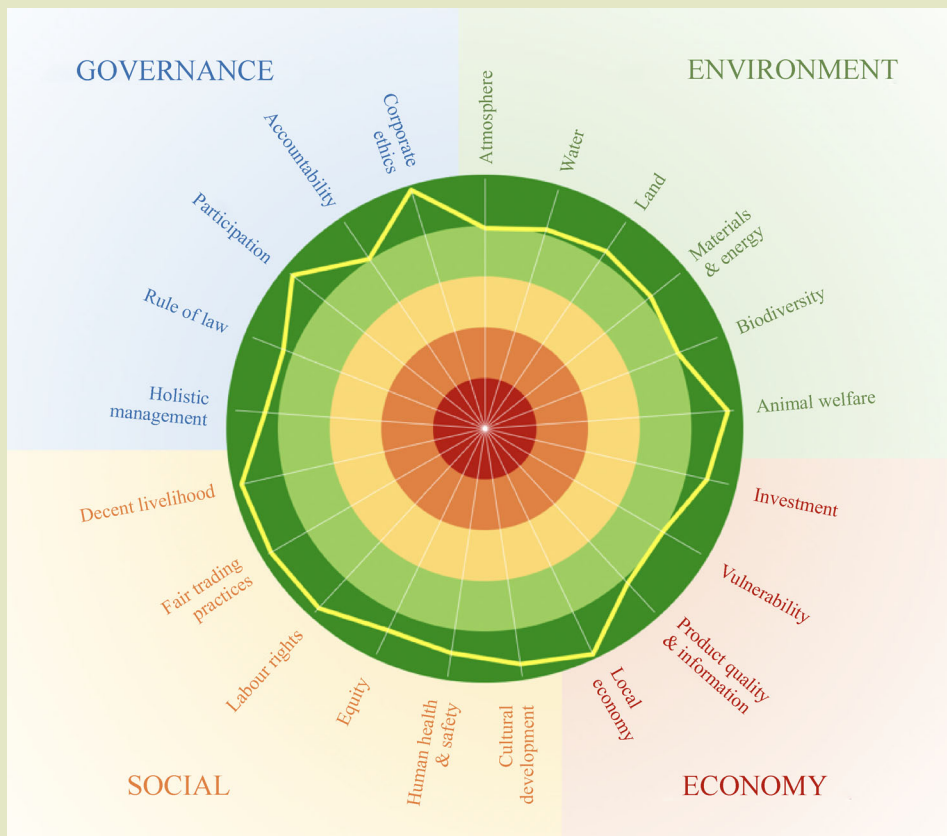


Fig. 3 Performance of PISA farms according to the Sustainability Assessment of Food and Agriculture Systems (SAFA) proposed by FAO (n = 65 farms). Red, orange, yellow, light green and green indicate scores of unacceptable, limited, moderate, good and best, respectively^[94].

long-term experiments allowed for assessing the impacts of crop rotations and soil management systems on soil quality, environmental indicators and productivity^[40,43,45]. Farmers and agronomists were trained each year by specialists in the use of USLE/RUSLE models with a software application developed to facilitate erosion estimations, and online submission of plans by users. The implementation of this policy was articulated with the agricultural sector and covered more than 95% of the cropping area. It was useful to promote ICLS, reduce soil erosion and mitigate other externalities and environmental impacts associated with runoff^[13,15,16]. This policy is consistent with the sustainable soil management application guidelines proposed by FAO and the Global Soil Partnership and with the UN sustainable development goals 2 and 15^[16].

5 CONCLUSIONS

The current trajectory of agricultural intensification in the Rio de la Plata region has increased food production per unit area of

land but has also increased environmental side effects. The latter are mainly a consequence of the specialization toward low diversity systems and to the decoupling of crop and livestock production systems, which have replaced native grasslands and previously established crop-pasture rotations. This intensification pathway must be reconsidered. Instead, ecological intensification based on diverse and multi-functional agricultural landscapes is the way forward. This includes integrated crop-livestock systems.

Based on recent research findings, we argue that ICLS can be seen and used as an innovative concept for producing diverse ecosystem services for billions of people. Regional data provide evidence that recoupling specialized crop and grazing animal production systems improves the long-term resilience of the whole system in terms of nutrient cycling functions, economic performance, and adaptation to climatic variation. This new vision of long-term resilient systems to face climate-market uncertainty is pivotal to facing climate change, so crucial to the future of the Rio de la Plata region.

Acknowledgements

We thank China Agricultural University for the organization of the workshop “Integrated animal-crop production systems”. We also thank Thainá Freitas for her valuable support in the preparation of Fig. 1. This work was supported by CAPES—Coordination for the Improvement of Higher Education Personnel within the Ministry of Education of Brazil, and financial support from the Brazilian National Research Council and from ANII-Uruguay projects FSA-PP-2018-148651, FSA-PI-2018-148819 and FSA-PP-2018-1-148336.

Compliance with ethics guidelines

Paulo César de Faccio Carvalho, Jean Víctor Savian, Tomas Della Chiesa, William de Souza Filho, José Alfredo Terra, Priscila Pinto, Amanda Posselt Martins, Sebastian Villarino, Júlio Kuhn Da Trindade, Pedro Arthur de Albuquerque Nunes, and Gervasio Piñeiro declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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