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The application of ecologically intensive principles to the systemic redesign of livestock farms on native grasslands: A case of co-innovation in Rocha, Uruguay

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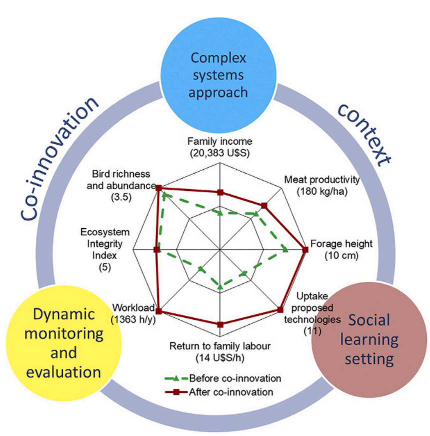
HIGHLIGHTS

- Seven commercial farms were redesigned over three years of co-innovation.
- Ecological intensification improved economic, environmental, and social indicators.
- Spatio-temporal grazing management resulted in enhanced meat productivity.
- Farmers highlighted the different way of working with an advisor.
- Changes in performance of the participant farms exceeded national trends.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Family-run cow-calf farms based on native grasslands exhibit low economic and social sustainability, as reflected in low family incomes and high workloads. Experimental results have shown that pasture–herd interaction management could improve native grasslands and animal productivity.

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OBJECTIVE: This paper analyzes the extent to which the sustainability of family-run livestock farms based on native grasslands could be enhanced by a systemic redesign informed by ecological intensification practices. The research questions address the initial state of farm sustainability, key bottlenecks to improving farm sustainability, and changes in sustainability criteria achieved over three years of farm redesign.
METHODS: The study was executed as part of a multi-level co-innovation project in Uruguay in which a team of scientist-practitioners and seven farm families participated in farm characterization, diagnosis, and redesign. The farm characterization took the form of indicators to describe the farms' management and bio-physical subsystems. Redesign plans were negotiated between the research team and the farmers. Frequent monitoring and evaluation cycles enabled finetuning across the years of implementation.
RESULTS AND CONCLUSION: Improvements were observed in the economic indicators gross margin (+55%), return to labor (+71%), and family income (+53%) and in the social indicator workload (−22%), and the environmental indicators bird diversity and ecosystem integrity index were maintained or increased slightly. These changes were explained by the uptake of coherent sets of ecological intensification practices causing changes in forage height (+30%), forage allowance (+69%), pregnancy (+22), weight of weaning calf per mating cow (+32%), and presence of tussocks (+65%). Ecological intensification principles resulted in synergistic positive effects between productivity–biodiversity tradeoffs and the scope for enhanced farm resilience and stability.
SIGNIFICANCE: Cow-calf family-run farms can be transformed to produce positive environmental and social effects and viable economic results. The implementation of projects in a co-innovation context may be taken as a guide to scaling up and scaling out the ecological intensification of livestock production on native grasslands, contributing to an extension system at the national level with the aim of improving cow-calf systems sustainability.

1. Introduction

Global demand for meat is expected to more than double by 2050 (Godfray et al., 2010), but there is widespread concern about the environmental impacts of current livestock production systems (de Vries et al., 2015; Herrero et al., 2015; Petz et al., 2014; Ran et al., 2016). The development of sustainable grazing systems that promote ecosystem resilience, enhance or maintain plant diversity, increase soil health, and maintain ecosystem multifunctionality through the delivery of multiple ecosystem services is a global concern (Sala et al., 2017; Teague and Barnes, 2017).

The Río de la Plata grasslands, i.e., the grassland biome that covers south Brazil, northeast Argentina, and the whole of Uruguay, is a biodiversity hotspot (Miñarro and Bilenca, 2008; Modernel et al., 2016; Overbeck et al., 2007) that provides provisioning, regulating, and cultural ecosystems services of local and global importance (Modernel et al., 2016). Livestock production in the region is based on native grasslands as the main source of animal nutrition. The farming systems are unique, as they produce beef, sheep meat, wool, and leather with negligible inputs of chemical fertilizers, fossil energy, or pesticides (Picasso et al., 2014; Viglizzo et al., 2001). There are cultural services associated with native grassland as mentioned by rural population (Bindritsch, 2014) such as "tranquility", "rest and walks", "pure air" and "more wild animals". In Uruguay, around 40% of the 27,000 livestock farms operate cow-calf systems, which produce calves for fattening (Modernel et al., 2016; MGAP, 2013), and around 60% of the livestock farms are family-run (Tommasino et al., 2014). A lack of economic prospects (Bervejillo and Tambler, 2014) has contributed to important land-use changes in that native grasslands have been converted to allegedly improved pastures or cropland, threatening various ecosystem services (Modernel et al., 2016). Enhancing economic performance while maintaining or improving environmental and social outcomes of livestock farming is therefore an urgent rural development concern.

Regional experimental research on strengthening the sustainability of native grassland-based livestock systems has highlighted various strategies and measures based on ecological rather than external-input intensification. Ecological intensification involves designing sustainable production systems that save on inputs and are less harmful to the environment (CIRAD, 2008) by focusing on the management of ecological process to increase ecosystem services provision (Tittonell, 2014). In particular, measures have been developed to improve the balance between grassland productivity and animal productivity by maintaining an adequate forage allowance through seasonal adjustments in stocking rates (Nabinger et al., 2011; Soca et al., 2013a). Experimental results have shown how management promoting more productive native species and increasing standing biomass reversed grassland degradation and resulted in greater pasture and animal production (Carriquiry et al., 2012; Do Carmo et al., 2016; Maraschin et al., 1997; Soca et al., 2007). However, these experimental insights at the level of production system components have not been reflected in increases in on-farm sustainability. Between 2010 and 2017, meat productivity at the Uruguayan national level varied between 71 and 80 kg ha^{-1}, without any clear tendency (Aguirre, 2018).

Farmers' failure to adopt ecologically intensive practices has been attributed to a component-based rather than a systems-based approach to extension (Dogliotti et al., 2014) and to a failure of the dominant transfer of technology approach to promoting learning for innovation (Oyhantçabal, 2003). Ecologically intensive changes need to be designed from a whole-farm perspective. The complexity of such changes necessitates deliberate iterative trial and learning cycles in situ (Leeuwis et al., 2002; Dogliotti et al., 2014; Fazey et al., 2018). Combining on-farm actors with those at regional or national level has been found to support the learning cycles and the permanence of the results by 'anchoring' (Elzen et al., 2012). Co-innovation is an approach that has proved successful in supporting learning for change (Rossing et al., 2010; Dogliotti et al., 2014; Albicette et al., 2017; Rossing et al., 2021). Conceptually, the approach combines elements from complex adaptive systems theory (e.g., Douthwaite and Hoffecker, 2017), social learning (e.g., Blackstock et al., 2007), and project monitoring for learning (e.g., Alvarez et al., 2010). We hypothesized that combining farmers' and scientific knowledge on the ecological intensification of native grassland-based livestock production in a farm-level co-innovation process would improve cow-calf farms' sustainability within three years.

Therefore, the objective of this study was to analyze the extent to which the sustainability of family-run livestock farms based on native grasslands could be enhanced by a systemic, i.e., whole-farm, redesign based on ecological intensification practices. The objective led to the following research questions: (1) what is the initial state of farm sustainability among the participating farms; (2) what are the key bottlenecks to improving farm sustainability; (3) what are the changes achieved over three years of farm redesign? The study was executed as part of a three-year project in Rocha, Uruguay, in which a team of scientist-practitioners and seven farm families engaged in farm characterization, diagnosis, and redesign. To anchor results at regional and national level, a network of various institutions was formed to communicate and monitor the project's results. The study built on an earlier rapid rural appraisal in the region that revealed the farms' lack of economic prospects, reflected in low farm succession expectations and an increasing rural exodus. The co-innovation-based project governance aspects have been analyzed elsewhere (Albicette et al., 2017; Rossing et al., 2021) and are not part of the results reported here. Co-innovation is described briefly as part of the project context, and its effect on the on-farm sustainability changes is addressed in the discussion section. In this paper, we focus on assessing sustainability in terms of changes in the economic, productive, social, and environmental indicators identified in the co-innovation process. The following sections describe the approach developed in the project, comprising farm characterization and diagnosis, farm redesign, and monitoring and evaluation. Next, we report on the changes in economic, social, and environmental indicators at the seven participating family-run livestock farms by comparing the baseline with results during and after the first three years of implementation of the farm-specific redesigns. We address the underlying causes by presenting results on explanatory intermediary variables. We discuss the significance of the results in relation to productivity–diversity tradeoffs, farm resilience and stability, and the co-innovation project governance context, and we provide suggestions on how to enable changes in a larger farm population by coupling research and development efforts with changes in national-level policies.

2. Materials and methods

2.1. Study area and farm selection

The study was carried out in the Rocha department in the east of Uruguay (34°28′S, 54°21′W). The study region's climate is temperate sub-humid with a mean annual temperature of 16.8 °C, and mean annual precipitation of 1141 mm, fairly evenly distributed throughout the year but with major variations between years (Castaño et al., 2011). Soil water deficits frequently occur between October and March, and water surpluses between May and August.

Seven family-run farms were selected as case studies (Crawford et al., 2007). The number of farms was determined by project resources and the experimental nature of the approach. In line with the study's mission, the farms were selected to reflect the regional agronomic diversity of family-run cow-calf farms. Other selection criteria included the farmers' willingness to discuss strategic choices, act upon jointly identified critical points in their farm management, and participate in local farmer groups to enhance learning and future scaling out. Farm selection resulted from several meetings between the research team, extension agents from two local farmer organizations (SFR-Castillos and SFR-R109), and agronomists of the national farmers' union (CNFR), followed by intake interviews with prospective farm families by the research team. Farm selection took around six months from start to completion.

2.2. Co-innovation approach

The study's approach included on-farm agronomic analyses and interventions, embedded in participatory settings at three levels to enhance learning and anchor project results. The co-innovation governance details are provided by Albicette et al. (2017) as well as the description of the three levels at which activities took place. In this paper, we focus on presenting the farm families' interactions with the research team. Each farm was visited monthly by an advisor who was part of the research team, usually accompanied by one or more researchers. Visits initially served to build trust between the research team and the farmers. Later, the visits were used to collect farm management data, gather field and animal samples to calculate indicators (see Section 2.3), and discuss the research findings and the farmers' management concerns.

Three phases were distinguished in the project's on-farm interventions: (i) farm characterization and diagnosis (April to December 2012), (ii) negotiation of the farm redesign plan (July to December 2012), and (iii) implementation of the agreed plan followed by monitoring and evaluation of sustainability indicators (January 2013 to July 2015). Overlap of the first two phases occurred as a result of the emergence of elements for redesign arising from insights during characterization and of differences between farms in the speed at which agreement on the diagnosis was achieved, e.g., when new analyses and rounds of discussion were needed because the farm family and the research team did not reach agreement on the diagnosis.

2.3. Farm characterization and diagnosis

Characterization involved describing the farms' structure and functioning in terms of two interacting subsystems: the management subsystem and the biophysical subsystem (Dogliotti et al., 2005; Dogliotti et al., 2014). Information on the management subsystem was obtained in several interviews with the farmers and concerned farm history, decision-making procedures, labor force, income sources, succession expectations, support by extension agents or projects, and participation in study groups or unions. Information on the biophysical subsystem was acquired from observations and measurements on the farms and consultation of the farmers and their records. We obtained data on land use in each field of the seven farms over the three years before the project started. Soil properties were assessed in a soil survey. The economic, social, and environmental performance of each farm was described in terms of indicators based on Dogliotti et al.'s (2014) sustainability assessment framework, duly adapted to livestock production (Table 1). Several indicators were calculated or measured to enable the attribution of changes to underlying causes. Indicators in the economic domain included forage height and forage allowance, which were expected to affect pregnancy rate, weight of weaning calf per mating cow, and meat production. In turn, forage height, forage allowance, and tussock cover were affected by sheep-to-cattle ratio and stocking rate. In the social domain, the number of ecologically intensive management principles adopted was recorded to explain changes in workload (see Section 2.4 and Table 2). In the environmental domain, tussock cover was expected to increase and lead to greater values for bird diversity and the ecosystem integrity index, potentially resulting in a tradeoff between meat productivity and the ecosystem integrity index.

Based on each farm's characterization, a diagnosis report was drawn up for the farmers, summarizing the characterization results and assessing the farm's strengths and weaknesses. The research team used problem trees representing core problems, consequences, and root causes (AusAid, 2000) to summarize the diagnosis for discussion with the farmers. Once agreement on the diagnosis was reached, the root causes became the entry points for the redesign proposals.

2.4. Farm system redesign based on ecological intensification practices

Using local experimental (Nabinger et al., 2011; Soca et al., 2013a; Carriquiry et al., 2012; Do Carmo et al., 2016; Maraschin et al., 1997; Soca et al., 2007; Soca and Orcasberro, 1992; Quintans, 2008) and experiential information, a list of strategic and tactical management principles was drawn up to reflect the ecological intensification philosophy (Table 2) (Paparamborda, 2017) The key proposition was better synchronization of native grassland production and animals' feed requirements across the seasons (Fig. 1). Starting from the root causes for each farm and based on available on-farm resources, specific combinations of management options were combined in redesign plans, which were subsequently translated into three-year implementation plans. The research team and each farm family assessed the redesign and implementation plans in terms of their feasibility and likely contribution to increasing and stabilizing family income while preserving the

Table 1
Economic, social, and environmental indicators, measurement protocols, units, and references used during farm system characterization and diagnosis (Initial) and redesign monitoring (Final).

Sustainability domain	Indicator	Measurement or calculation protocol	Unit and reference	Data sources	
				Initial	Final
Economic	Gross margin	Difference between gross product[a] and production costs[b]	US\$ ha^{-1}	Farm data. Average of three years prior to the project (2009–2010, 2010–2011, and 2011–2012)	Farm data. Average of the three years of project implementation (2012–2013, 2013–2014, and 2014–2015)
	Costs	Expenditure on inputs	US\$ ha^{-1}		
	Family income	Difference between gross product and production costs (without valuation of family labor)	US\$		
	Return to labor	Relation between gross margin and labor time dedicated to grassland and herd management	US\$ h^{-1}	Farm data. July 2012–June 2013	Farm data. July 2014–June 2015
	Meat equivalent	Live weight (kg yr^{-1}) of beef and mutton and weight of wool multiplied by a factor 2.48 produced between 1 July and the next 30 June	kg ha^{-1} (Oficialdegui 1985 referenced by Durán, 2008)	Farm data. Average of three years prior to the project (2009–2010, 2010–2011, and 2011–2012)	Farm data. Average of three years of project implementation (2012–2013, 2013–2014 and 2014–2015).
	Stocking rate	Ratio of number of livestock units (LU) and total land area utilized from 1 July to 30 June	LU ha^{-1} (Allen et al., 2011)	Farm data	Farm data
	Sheep-to-cattle ratio	Ratio of total head of sheep and total head of cattle from 1 July to 30 June	–	Farm data	Farm data
	Pregnancy	Ratio of pregnant cows and total number of breeding cows from 1 July to 30 June	%	Farm data	Farm data
	Weight of weaning calf per mating cow	Ratio of the weight of all calves at weaning and the number of breeding cows from 1 July to 30 June	Kg	Farm data	Farm data
	Forage allowance	Ratio of forage mass available (kg of dry matter, DM) and animal live weight (LW) per unit area of the land unit grazed from 1 July to 30 June	kg DM kg^{-1} of LW kg DM kg^{-1} of LW (Allen et al., 2011)	Farm data	Farm data
	Forage height	Average forage height on 55 to 96% of the total area of each farm (average 80% of the area), every 45 days	cm (Barthram, 1986)	Farm data. Autumn 2013	Farm data. Autumn 2014 and 2015
Social	Workload	Work assessment approach	Hours $year^{-1}$ (Dedieu and Servière, 1999)	Farm data. July 2012–June 2013	Farm data. July 2014–June 2015
	Uptake of ecologically intensive management principles	Number of technologies applied over the course of a year (July–June) based on the 11 principles in Table 2	Number (range: 0 to 11)	Farm data. July 2012–June 2013	Farm data. July 2014–June 2015
Environmental	Ecosystem integrity index	Four components (vegetation structure, plant species, soil, and riparian areas) were considered based on qualitative and quantitative visual evaluation	Number (0, low, to 5, high) (Blumetto et al., 2019)	Farm data. Spring 2013	Farm data. Spring 2015
	Bird diversity	Diversity of species (richness) and number of individuals (abundance) measured on three linear transects of 300-m length on reference paddocks during each season. The Shannon index was calculated per farm	Shannon index (Gibbons and Gregory, 2006; Shannon and Weaver, 1949)	Farm data. Average of all seasons in 2013	Farm data. Average of all seasons in 2015
	Tussock cover	Calculated based on 50 to 100 quadrant samples of 1 m^2 per paddock along transects of 100–200 m, depending on the variability of the paddock	% (Mueller-Dombois and Ellenberg, 1974)	Farm data. Autumn 2014	Farm data. Spring 2015

[a] Gross product: sales - purchases + on-farm consumption ± inventory difference.
[b] Production costs: the cost associated with production activities including valuation of family labor, taken from data of the Ministry of Labor and Social Insurance of Uruguay for the livestock sector.

environment without increasing production costs or labor demand.

2.5. Monitoring and evaluation

During the implementation of the redesign plans, we monitored the indicators according to the protocols and the frequency described in Table 1. Given the erratic nature of rainfall in the area, each farm was equipped with a high-resolution rain gauge (ECRN-100, Decagon Devices Inc. USA) to relate forage height results to rainfall. Annually, a progress report was made for each farm showing the main results. These reports were discussed among the field agronomist, researchers, and farmers. Farm redesign plans were adjusted when necessary in light of these discussions.

Table 2
Strategic and tactical management principles used to inform farm redesign plans (based on Paparamborda, 2017).

Category	Ecological intensification management principle	Justification	References
Strategic	Adjusting stocking rate and/or sheep-to-cattle ratio	High grazing pressure and high sheep-to-cattle ratios have led to a series of self-reinforcing negative effects. Photosynthetically active tissues determine forage growth. Animals' forage use efficiency is lower on shorter than on taller swards because of greater animal grazing time and associated loss of energy. Prolonged insufficient forage supply results in low animal reproductive efficiency and, therefore, in low meat productivity. Environmentally, greater forage height contributes to the recovery of native grassland biodiversity and increases soil cover and root biomass.	Scarlato et al., 2012; Claramunt et al., 2017
	Allocation of paddocks according to forage availability and animal requirements	Forage allowance (kg dry matter (DM) per kg of animal live weight (LW) is a key indicator of grazing intensity in livestock systems and the main lever to adjust grazing intensity in cow-calf systems. A forage allowance of 4.9 kg DM per kg LW compared with 2.2 kg DM per kg LW has been shown to improve the quantity, height, forage accumulation, and individual and per area productivity of cow-calf systems in Uruguay.	Do Carmo et al., 2018
	Concentration of the mating period in summer	Concentrating the mating period between December and February means that calving is predominantly in spring (September to November). In this way, the period of the higher cow energy requirements is matched with the period when forage growth is greater, reducing the time between calving and return to estrus. Mating of heifers should take place earlier than mating of cows to allow more time for recovery before their second mating period.	Soca and Orcasberro, 1992; Do Carmo et al., 2016
	Weaning at the end of summer (March) when calves are 6 months old	Weaning at the end of summer allows cows to recover body condition before winter. Forage growth in native grasslands is extremely low in winter (average growth rate of 6 kg DM ha^{-1} day), and cows usually lose one point of body condition during this period. The best chance of pregnancy in summer is achieved when cows have a body condition score (BCS) of 4 at calving, which requires starting winter with a BCS of 5.	Soca and Orcasberro, 1992; Carriquiry et al., 2012
	Preferential feeding of heifers and female calves	Heifers and female calves are fed preferentially to ensure adequate growth after weaning. Loss of body weight during winter in female calves and heifers affects their reproductive success. A high forage allowance and strategic supplementary feeding are offered in winter to growing heifers when necessary.	Quintans, 2008, Quintans et al., 2008; Astessiano et al., 2011
	Forage allowance and feeding according to cows' body condition	To achieve the abovementioned BCS, it might be required to categorize cows according to their BCS and apply differential forage allowances and strategic supplementary feeding (usually in winter) to gestating cows. Differential forage allowances and strategic supplementary feeding might also be required during part of the mating period.	Quintans et al., 2008; Soca et al., 2013a
Tactical	Diagnosis of pregnancy during autumn	Using ultrasound scans, cows are classified as in early or late pregnancy or as non-pregnant. Forage allowances are adjusted accordingly. Non-pregnant cows might be sold or kept, depending on forage availability and replacement options.	
	First mating period when heifers are 2 years old	The age of heifers at first pregnancy is a key determinant of the efficiency of a cow-calf system. The target is first pregnancy at 2 years of age, considering that heifers have reached at least 65% of adult weight. It is important to consider this minimum weight when starting the mating period to ensure a good second pregnancy rate.	Soca et al., 2007
	Diagnosis of cows' ovarian activity	Ovarian activity is diagnosed at the middle of the mating period to enhance pregnancy. If the cow is deeply anestrous, calves may be weaned definitively. If the cow is superficially anestrous,	Quintans, 2016

(continued on next page)

Table 2 (*continued*)

Category	Ecological intensification management principle	Justification	References
		temporary weaning may be applied.	
	Temporary or early weaning	Temporary weaning with nose flaps for calves over 5–14 days or early weaning in which calves are separated from the cows definitively may be used depending on their ovarian activity to advance estrus in postpartum cows. Strategic supplementary feeding to both cows and calves is applied along with temporary or early weaning.	Quintans et al., 2009; Soca et al., 2013b
	Checking fertility status of bulls two months before the breeding period	A basic fertility status evaluation of bulls consists of a physical examination of the animal and its reproductive organs, measurement of scrotal size, and evaluation of semen.	Viñoles et al., 2009

3. Results

3.1. Farm characterization and diagnosis

The characteristics of the farms' management subsystems at the start of the redesign phase are shown in Table 3 ('Management subsystem') and Table 4 ('Initial'). On five of the seven farms, the management team was composed of the male farmer and his wife. Two farms were managed by female farmers. Farms were in various life stages. A successor was not available on all farms, and land ownership varied greatly. Labor was predominantly provided by the family, except for Farm 2, and off-farm labor was important in Farms 3 and 4. All farmers had finished primary school, participated in farmers groups, and received some technical assistance.

In terms of biophysical characteristics, farm size varied from 61 to 364 ha (Table 3). Between 51 and 96% of the farm area was under native grasslands, and the remaining area comprised native grasslands with sown species (*Lotus pedunculatus* and *Lotus subbiflorus*), fertilized annual crops, or artificial pastures. The number of paddocks per farm ranged from 9 to 21. Predominant soils in the farms were Typic Argiudoll and Vertic Argiudoll (FAO, 2006). Soil organic matter values (SOM, %) ranged from 2.4 to 5.1 in line with the national soil-specific reference values (Durán and García Préchac, 2007) except for Farm 3, which had lower SOM values (1.0%) than the national soil-specific reference value (3.3%) (Durán and García Préchac, 2007).

At the start of the project, the farms applied only a few ecologically intensive technologies (Table 4, Initial). Allocation of cattle to paddocks according to forage height and animal requirements, a key strategic management principle, was applied only by Farm 7. Forage allowance and supplementary feeding according to cow body condition were adjusted only partially by Farms 1 and 7. First mating of heifers at 2 years of age was applied by five of the seven farms, and ovarian activity diagnosis in cows was not practiced at any farm. Few farmers kept records of management activities or purchases and sales.

The economic, social, and environmental performance of the farms at the start of the redesign is shown in Table 5. Averaged over the three years before redesign, family income was 11,586 ± 5411 U$S, substantially lower than the average family income in rural areas of 15,918 U$S (INE, 2009-2015). The lowest family income was observed in Farm 5 (−223 U$S), and this forced the farmer to sell some animal stock to survive. In the social domain, workload ranged from a 789- to a 2665-h year^{-1} (Table 5). Return to labor was highly variable, ranging from −2

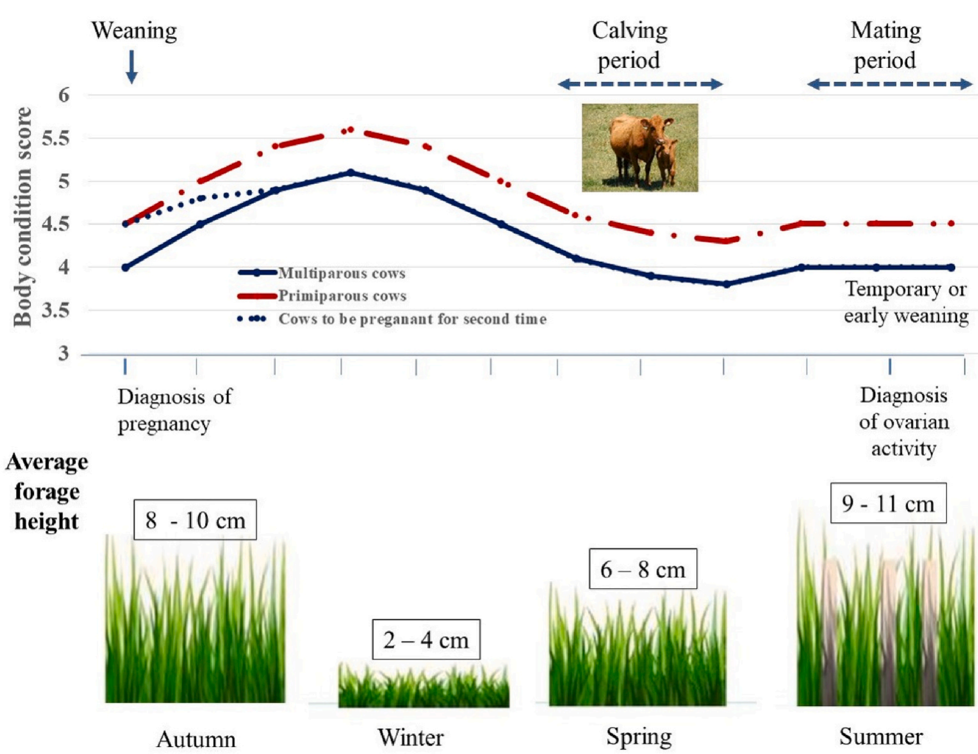

Fig. 1. Main strategic and tactical management options for ecological intensification of cow-calf systems based on native grasslands in Uruguay. Based on Soca and Orcasberro (1992), Quintans et al. (2008), and Soca et al. (2013a).

Table 3
Characteristics of the farms' management and biophysical subsystems at the start of the redesign phase.

Farm	Management subsystem							Biophysical subsystem						
	Management team [a]	Life cycle stage [b]	Farm succession [c]	Ownership land (%)	Family labor availability (PE) [d]	Family labor/Total labor	Off-farm labor (PE) [d]	Area (ha)	Native grassland area (%)	Number of paddocks	Bovine stock (number)	Ovine stock (number)	Dominant soil type	Soil organic matter (%)
1	1 WF	3	1	100	1	0.96	0	316	55	21	226	117	Typic Argiudoll/ Vertic Argiudoll	2.4–4.7
2	1 WF	3	1	100	1	0.14	0	319	91	14	338	388	Typic Argiudoll/ Vertic Argiudoll	3.2–3.5
3	2C	3	1	72	2	0.90	0.5	61	77	14	63	246	Typic Argiudoll	1.0–1.2
4	2C	4	2	56	2	1.00	1.25	92	75	13	42	263	Typic Arigiudoll/ Typic Hapludolf	2.4–4.8
5	2C	3	1	48	2.25	0.96	0	364	88	15	197	0	Typic Argiudoll/ Entic Hapludoll	3.3–4.1
6	2C	4	0	0	2	0.93	0	291	96	9	188	410	Typic Argiudoll	3.0–5.1
7	2C	2	1	100	2	0.97	0	231	92	17	170	265	Typic Argiudoll/ Entic Hapludoll	2.6–3.1

[a] Management team composition: number of members of the management team, WF = woman farmer, C = couple.
[b] Life cycle stage, 1 = entry or establishment, 2 = expansion, 3 = consolidation or stabilization, 4 = exit.
[c] Farm succession, 0 = no succession expected or possible, 1 = possible but not defined yet, 2 = defined or in transition to next generation.
[d] PE = 1 person equivalent represents 2400 labor hours per year.

to 13 U$S h^{-1} (Table 5). Statistical information on specialized rural workers' salary provided a reference value for return to labor of 3 U$S h^{-1} (INE, 2009-2015).

Regarding environmental performance, the average initial ecosystem integrity index value was 3.6 (Table 5), representing an acceptable to good environmental status (Blumetto et al., 2019). In most of the farms, no signals of severe soil erosion or loss of botanic biodiversity were found, and, when they appeared, they were observed only on small areas of the farms. However, in Farm 3, soil erosion and overgrazing were observed on almost 50% of the area, with poor soil cover, loss of botanic diversity, and the presence of species indicative of degradation, such as dwarf herbs and *Cynodon dactylon*. The average Shannon index for birds was 3.2 (Table 5).

Inspection of the intermediary variables (Table 6) showed that average equivalent meat productivity was 100 kg ha^{-1}, ranging from 64 to 151 kg ha^{-1}. The average pregnancy percentage on the seven farms was 76%, ranging from 63 to 89%. The weight of weaning calf per mating cow, an indicator of efficiency on cow-calf farms, was 107 $\pm$ 29 kg. Farm 3 achieved the highest equivalent meat productivity despite the low weight of weaning calf per mating cow (74 kg), high stocking rate (1.3 LU (livestock unit) ha^{-1}), and high sheep-to-cattle ratio (3.96), explained by the use of high levels of feed supplementation (mostly produced on-farm). This resulted in a high workload and high production costs (Table 5).

Most farms had a low forage allowance, ranging from 1.3 to 4.6 kg DM (dry matter) kg^{-1} BW (body weight) (average 3.3 $\pm$ 1.2 kg DM kg^{-1} BW, Table 6), considerably lower than the values of 4.9 to 6 kg DM kg^{-1} BW suggested by experiments (Soca et al., 2013a). The low forage allowance was explained by a combination of high stocking rate and/or high sheep-to-cattle ratios (Table 6) and low forage availability, caused by the impact of low average sward height on forage growth rates. The initial forage height in autumn 2013 was on average 6.5 $\pm$ 1.0 cm, ranging from 4.6 to 10.6 cm (Fig. 2), compared to the 9 cm suggested by Soca and Orcasberro (1992) (Fig. 1). Extremely low forage heights were found on Farms 3 and 5, with values of 3 and 4 cm in summer, respectively, and 2 and 3 cm in autumn, respectively. The lowest forage allowance value (in Farm 3) was associated with the highest stocking rate and highest sheep-to-cattle ratio (Table 6).

A problem tree summarizing the diagnoses for the seven farms identified low family income as the main economic weakness and connected it with the underlying causes (Fig. 3). Low family income, which was found on all farms, was caused by the low number and weight of weaning calves per mating cow, the low weight of sold cows, and/or in some cases high production costs. The low number and weight of weaned calves were caused by both a low pregnancy percentage and a low forage allowance before weaning. Some farms used early weaning and feed supplementation to increase pregnancy percentage, thereby increasing production costs and workload. A low cow body condition score (BCS) at calving was caused by low forage availability during most of the year, and particularly during autumn and winter, and on two farms also by late weaning in autumn. The combination of low forage allowance and late weaning did not allow cows to recover body condition before winter. Low forage availability and allowance during most of the year were caused by high stocking rates, high sheep-to-cattle ratios, and the low growth rates of native grasslands that resulted from a suboptimal leaf area.

3.2. Farm redesign

Common elements of the seven farms' redesign plans were reducing the stocking rate and/or sheep-to-cattle ratio and planning the monthly re-allocation of animals to paddocks depending on forage height and animal forage requirements derived from individual cow BCS. No changes were made to the areas of native grasslands or to the layout of the paddocks. Herd management plans were tailored to farmers' preferences and technologies with which farmers were familiar. In addition,

Table 4
Use of ecologically intensive principles (Table 2) and farm records per farm at the start (Initial) and the end (Final) of the project. A value of 0 indicates the principle was not applied, 1 indicates the principle was applied but needed adjustments, and 2 indicates the principle was applied adequately.

	Farm 1		Farm 2		Farm 3		Farm 4		Farm 5		Farm 6		Farm 7	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Adjusting stocking rate and/or sheep-to-cattle ratio	2	2	0	2	0	2	0	2	0	2	0	2	2	2
Allocation of paddocks according to forage height and animal forage requirements	0	2	0	2	0	2	0	2	0	2	0	2	1	2
Concentration of the mating period in summer	2	2	0	2	0	2	0	2	2	2	0	2	2	2
Weaning in March when calves are 6 months old	2	2	2	2	0	2	0	2	2	2	0	2	2	2
Preferential feeding of heifers and female calves	2	2	0	2	0	2	0	2	0	2	0	2	2	2
Forage allowance and feeding according to cows' body condition	1	2	0	2	0	2	0	2	0	2	0	2	1	2
Diagnosis of pregnancy during autumn	2	2	0	2	0	2	0	2	2	2	0	2	2	2
First mating period when heifers are 2 years old	2	2	2	2	2	2	2	2	2	2	0	2	2	2
Diagnosis of cows' ovarian activity	0	2	0	2	0	2	0	2	0	2	0	2	0	2
Temporary or early weaning	2	2	0	2	0	2	2	2	0	2	0	2	1	2
Checking fertility status of bulls two months before starting the breeding period	2	2	0	2	0	2	0	2	0	2	0	2	2	2
Use of economic and management records	1	2	0	0	0	0	0	2	2	2	1	2	1	2

Table 5
Main economic, social, and environmental indicators for the seven farms. Average and standard deviation of gross margin, costs, family income, return to labor, average workload, average ecosystem integrity index, and the Shannon index for birds per farm at the beginning (Initial) and the end of the project (Final). Indicator calculation procedures are described in Table 1. References values for the economic and social indicators were derived from Instituto Plan Agropecuario (2017) for gross margin and costs, and INE (2009-2015) for family income, return to labor, and workload.

Farm	Economic indicators								Social indicator		Environmental indicators			
	Gross margin (U$S ha^{-1})		Costs (U$S ha^{-1})		Family income (U$S)		Return to family labor (U $S h^{-1})		Workload (h yr^{-1})		Ecosystem integrity index (0 (low) to 5 (high))		Bird richness and abundance (Shannon index)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
1	60 ± 24	57 ± 16	63 ± 24	63 ± 18	24,984 ± 9021	25,481 ± 5036	13	26	1793	921	3.3	3.5	3.1	3.0
2	22 ± 40	45 ± 20	120 ± 13	136 ± 9	13,203 ± 15,096	21,740 ± 6465	8	12	2134	1867	3.4	3.6	2.9	3.2
3	89 ± 53	146 ± 56	55 ± 8	76 ± 10	8466 ± 3607	14,260 ± 1988	9	19	1156	617	3.0	3.2	3.2	3.7
4	−8 ± 14	42 ± 10	106 ± 33	116 ± 2	2297 ± 1885	7580 ± 904	5	8	789	649	3.8	3.7	3.3	3.6
5	−18 ± 14	9 ± 7	66 ± 19	88 ± 6	−223 ± 5245	9087 ± 2572	−2	5	1643	1319	3.9	3.9	3.5	3.5
6	46 ± 15	70 ± 16	60 ± 20	85 ± 15	19,475 ± 5519	27,908 ± 4717	8	8	2665	2545	3.7	4	2.9	3.5
7	29 ± 15	48 ± 15	110 ± 27	142 ± 12	12,900 ± 4848	18,682 ± 3560	7	8	2074	1625	3.6	3.7	3.3	3.4
Average	31 ± 43	60 ± 46	83 ± 32	101 ± 31	11,586 ± 5411	17,820 ± 2744	7	12	1750	1363	3.6	3.7	3.2	3.4
Reference	36 ± 26	35 ± 19	109 ± 15	105 ± 4	15,918	20,383	3	5	2400	2400	5	5	3.5	3.5

a number of specific adjustments were proposed and discussed.

On Farms 2, 3, 4, and 6, the mating period was concentrated in summer to replace continuous mating or double mating seasons. Temporary weaning of calves was suggested for the start of the mating period, and calves were to be weaned by the end of summer. Pregnancy diagnosis was scheduled in autumn. Strategic supplementation during winter was suggested to strengthen the BCS of female calves and heifers. Bulls' fertility status was scheduled to be checked before the start of the mating period. On all farms, a diagnosis of cow ovarian activity was proposed. For Farms 2, 3, and 4, the fattening of culled cows was suggested to increase the selling price. Low-cost practices proposed and implemented in the farms were the same. However, the way and moment of implementing them presented some differences between farms, according to the farm base line and available resources, together with the farmer's objectives.

Sheep management proposals differed according to farmers' preferences, but, at all farms, the number of head was reduced, and the mating period was adjusted to meet market demand for sold lambs.

3.3. Impacts of the redesign on farm sustainability

The proposed changes were fully adopted in all farms, except for the use of farm records, which were kept by only five farmers (Table 4, Final). Regarding farm performance, family income and its variability and gross margin increased from 11,586 ± 5411 U$S to 17,820 ± 2744 U$S and from 31 to 60 US$ ha^{-1}, respectively (Table 5, Final). Average production costs increased from 83 to 101 US$ ha^{-1}. Family income and gross margin improved on six of the seven farms. Average workload decreased by 22% (Table 5) thanks to concentrating mating, calving, and weaning periods, combined with improved animal BCS, thereby reducing the need for farmer interventions. The ecosystem integrity index increased slightly on five farms, decreased on Farm 4, and remained constant on Farm 5 (Table 5). Improvements were observed mainly in paddocks with native grassland. The vegetation's structural aspects, like tussock cover and shrubberies (Table 6, Final) were improved, and annual crops were replaced by multi-species pastures. The Shannon index for birds increased or was maintained (Table 5).

Productive changes explained the economic changes. Equivalent meat production per ha increased on average from 100 to 122 kg ha^{-1} (Table 6). Average pregnancy percentages for the seven farms increased from 76 to 91% (Table 6). Farms 1 and 6 had high pregnancy percentages at the start of the project (89 and 79%, respectively), but at a high cost and with a high workload, by applying technologies such as early weaning to all cows and feed supplementation. Attention to individual

Table 6
Indicators affecting economic, social, and environmental performance. Average and standard deviation of the economic indicators were calculated over the three years preceding the project (Initial) and across the three project years (Final) to stabilize variation caused by price and weather fluctuations. The number of applied ecologically intensive management options was obtained from interview data at the start and at the end of the redesign. Tussock cover was obtained by sampling at the start and at the end of the redesign. Reference values were derived from Instituto Plan Agropecuario (2017) for equivalent meat and Instituto Nacional de Investigación Agropecuaria (2010, 2011, 2012, 2013, 2014, 2015) for pregnancy percentage. Nd indicates no data.

Farm	Economic indicator												Social indicator		Environmental indicator	
	Stocking rate (LU ha^{-1})		Sheep-to-cattle ratio		Forage allowance (kg DM kg^{-1} BW)		Pregnancy (%)		Weight of weaning calf per mating cow (kg)		Equivalent meat (kg ha^{-1})		Number of ecologically intensive management options applied		Tussock cover (%)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
1	0.7 ± 0.1	0.7 ± 0.1	0.9 ± 0.1	0.4 ± 0.4	Nd	7.3 ± 2.3	89 ± 3	86 ± 9	137 ± 2	141 ± 18	92 ± 14	91 ± 5	18	24	4	10
2	1.0 ± 0.1	0.9 ± 0.1	1.2 ± 0.1	0.9 ± 0.1	3.1 ± 0.6	4.8 ± 1.8	66 ± 11	92 ± 9	97 ± 20	124 ± 28	104 ± 14	130 ± 5	4	22	6	27
3	1.3 ± 0.1	1.1 ± 0.1	4.0 ± 0.5	1.4 ± 0.1	1.2 ± 0.7	3.2 ± 1.9	63 ± 6	95 ± 3	74 ± 9	142 ± 41	151 ± 16	168 ± 13	2	22	3	3
4	0.8 ± 0.0	0.8 ± 0.0	6.0 ± 1	3.3 ± 1.6	4.1 ± 0.5	7.5 ± 1.8	84 ± 17	94 ± 1	111 ± 47	151 ± 21	83 ± 16	129 ± 7	4	24	11	15
5	1.1 ± 0.2	0.7 ± 0.0	0.2 ± 0.4	0	3.0 ± 0.6	5.9 ± 1.0	70 ± 14	83 ± 12	83 ± 9	103 ± 23	64 ± 10	84 ± 6	10	24	19	24
6	0.7 ± 0.1	0.8 ± 0.0	2.3 ± 0.2	1.8 ± 0.3	4.6 ± 0.9	5.6 ± 2.3	79 ± 9	94 ± 3	116 ± 25	148 ± 16	88 ± 10	110 ± 3	1	24	16	15
7	0.9 ± 0.1	0.9 ± 0.0	1.9 ± 0.1	1.1 ± 0.4	3.8 ± 0.3	4.8 ± 1.1	80 ± 2	96 ± 1	128 ± 20	171 ± 12	115 ± 3	138 ± 5	18	24	10	13
Average	0.9 ± 0.2	0.8 ± 0.0	2.3 ± 0.2	1.5 ± 0.5	3.3 ± 1.2	5.6 ± 1.5	76 ± 3	92 ± 5	106 ± 30	140 ± 29	100 ± 28	122 ± 28	8.1	23.4	10	15
Reference	Nd	Nd	Nd	Nd	Nd	Nd	78 ± 3	82 ± 2	Nd	Nd	96 ± 6	101 ± 5	Nd	Nd	Nd	Nd

LU = livestock unit; 1 LU is a cow weighing 380 kg that gestates and weans a calf.

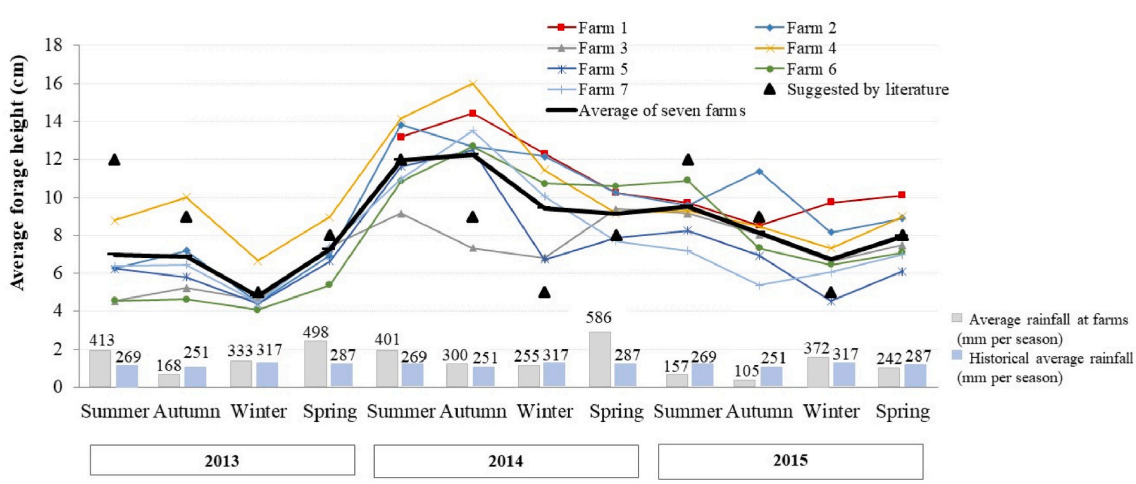

Fig. 2. Progress of average forage height (cm) per season per farm and average of the seven farms throughout the implementation of the redesign plans starting in summer 2013. Reference values suggested by Soca and Orcasberro (1992) are represented by black triangles. Average rainfall at farms per season per year (mm) is represented by grey bars and historical (1986–2011) average rainfall for the study region (Instituto Uruguayo de Meteorología, 2021) by blue bars, with total precipitation values at the top.

cow BCS reduced the number of cows requiring early weaning, and monitoring ovarian activity during the mating period allowed the few cows that required early or temporary weaning to be identified, thus reducing costs and workload. The weight of weaning calves per breeding cow increased throughout the project on all farms (Table 6).

Over the course of the project, we observed an increase in average forage height at all farms up to the target values suggested in the literature (Soca and Orcasberro, 1992), and, in some cases, even higher (Fig. 2). During summer and autumn 2015, a drought occurred (Fig. 2), and forage height values were reduced but did not decrease to as low as the initial values of summer 2012–2013 and autumn 2013. The average stocking rate and the sheep-to-cattle ratio decreased from 0.92 LU ha^{-1} to 0.85 LU ha^{-1} and from 2:3 to 1:5, respectively (Table 6). However, not all farms decreased both variables. Farm 1 maintained the total stocking rate and decreased its sheep-to-cattle ratio, whereas Farms 6 and 7 increased their total stocking rate and decreased their sheep-to-cattle ratio. The changes resulted in an increase in average forage allowance from 3.3 ± 1.2 kg DM kg^{-1} BW to 5.6 ± 1.5 kg DM kg^{-1} BW (Table 6).

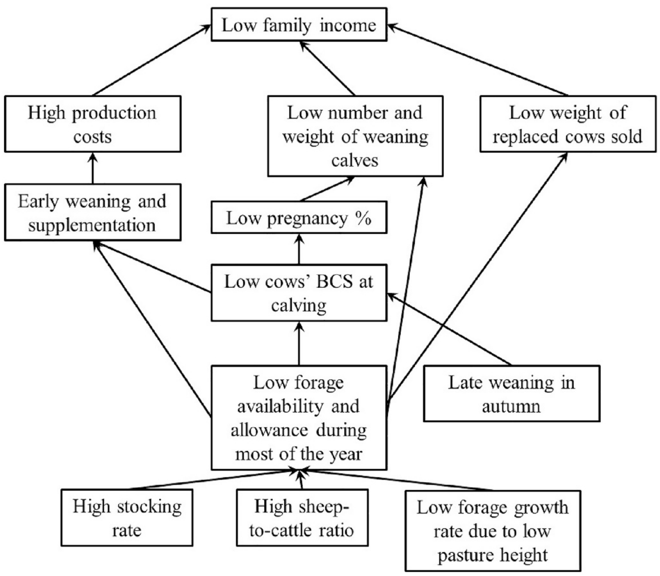

Fig. 3. Problem tree summarizing the diagnosis of the seven farms. BCS = body condition score.

4. Discussion

This study provides the first proof that coherent strategic and tactical adjustments based on ecological intensification principles can considerably improve the sustainability performance of family-run farms on the Rio de la Plata native grasslands. Over three years, six out of seven participating farms were able to substantially improve family income to levels comparable to average family income in rural areas. On all farms, workload decreased, return to family labor increased, and environmental performance was maintained at the relatively high initial levels or increased slightly. The root causes of low initial farm sustainability were addressed by adopting a whole-farm perspective and implementing a coherent set of low-cost practices by which animal requirements were better matched to native grassland productivity. The efficacy of the proposed changes was demonstrated by the increase in sward height, which is a proxy for sward biomass (Do Carmo et al., 2019) and by the increase in forage allowance. The consequent greater herd well-being was reflected in higher pregnancy rates, higher calf weight at weaning, and greater meat equivalent.

This section discusses the results regarding productivity–biodiversity synergies and tradeoffs, farm resilience and stability, and the importance of embedding the co-innovation approach for scaling up and scaling out.

4.1. *Productivity–biodiversity synergies and tradeoffs*

Like other native grassland areas of the world, the Pampas and Campos biomes are subject to human-driven intensification based on external inputs (Baldi and Paruelo, 2008; Overbeck et al., 2007). In rethinks about livestock production systems, tradeoffs among the various grassland ecosystem services are usually highlighted (MEA, 2005; Briske et al., 2011; Maestre et al., 2012; Jing et al., 2015), contributing to polarized debates. Here, we have demonstrated how ecological intensification principles could result in synergistic positive effects rather than tradeoffs among provisioning and regulating services and their accompanying cultural services. These changes were realized on commercial farms over three years and send a hopeful message for the sustainability changes possible in other native grassland production systems.

Complexification of the vegetation structure by greater tussock cover has been reported to provide a better environment for fauna, particularly for birds (Garden et al., 2007; Di Giulio et al., 2001). In our study, the Shannon index (H) for bird diversity was 3.4 at the end of the project (Table 6), which may be considered a good value even compared with reference values for the north of Uruguay, where grasslands are considered to be very well preserved (H = 2.6; Tosi et al., 2013), or elsewhere in the Campos region where values of 3.0 and 2.6 were found for native grasslands and revegetated areas, respectively (Becker et al., 2019). The occurrence of synergies is contingent on the amount of tussock cover. We found the increase in forage height from 2 to 4 cm to 12 cm to be associated with an increase in the presence of tussocks to 15% on average, with a maximum of 27% on Farm 2 (Table 6). Da Trindade et al. (2012) reported decreased meat productivity at a tussock cover above 35%. Most farms in the study were still far from this threshold. More research is needed to reveal the nature of the relations between tussock cover, the ecosystem integrity index, bird diversity, and native grassland productivity in the long term.

4.2. *Farm resilience and stability*

In South America, weather records for the past 50 years reveal increased variability in rainfall patterns (Marengo et al., 2012). During the three project years, periods with rainfall exceeding the historical average and periods with rainfall below average were observed. During 2013 and 2014, spring rainfall amounts were almost double the historical average (450 mm vs 280 mm, respectively), whereas in summer 2014–2015 and autumn 2015 amounts were only half of the historical average (157 mm vs 269 mm for summer and 105 mm vs 251 mm for autumn, respectively). Comparing gross margin and equivalent meat obtained by the seven case study farms during the three years before the project started with national averages in the same period revealed no differences (Tables 5 and 6). However, the average gross margin for the case study farms was almost double the national average across the three redesign years, and average equivalent meat was 22% higher than the national average (Tables 5 and 6). Furthermore, the standard deviations of the economic indicators decreased on all farms during the redesign period, indicating greater stability. Although a conclusion on greater farm resilience is premature given the short period of evaluation, the results agree with experimental data that show that appropriate grazing management offers an opportunity to decrease the effect of droughts on grasslands by stimulating deeper and denser rooting systems (Cobon et al., 2009; Modernel et al., 2019; Norton et al., 2016). The consequent greater herbage allowances enable animal body condition to be preserved during drought, reducing the reliance on external, high-cost feed purchases (FAO, 2013).

4.3. *Co-innovation and its options for scaling out and scaling up*

The results presented here have focused on the changes in sustainability indicators in the context of project governance based on co-innovation. As shown elsewhere (Albicette et al., 2017; Dogliotti et al., 2014; Rossing et al., 2021), this context was key to achieving the sustainability changes by fostering a systems perspective that enabled the problem situation to be addressed at the appropriate whole-farm scale and a setting to be created that invited learning and consequent action among all participants. This allowed the divide between generic and actionable knowledge to be overcome (Geertsema et al., 2016) by connecting suggestions on ecologically intensive practices (Nabinger et al., 2011; Soca et al., 2013a; Do Carmo et al., 2016)) to a whole-farm perspective. Different from other alternative approaches to traditional linear extension, such as Farming Farmers Schools (Khatam et al., 2010), the co-innovation approach considers farm sustainability problems from a whole systems perspective. Quotes from interviews in the last project year show the relevance of the approach for farmer learning: "*now we have clearer production objectives, we know when to do things*", "*we are working with more forage, and the animals are in a better condition*", "*the management is easier, we have time to do other things*", "*we now know how to* *manage pastures and cattle*", "*with less we can do things in a better way*."

All the farmers received technical assistance before the start of the project. The extension service work, however, was usually targeted at isolated components, pushing input-based technologies such as adding new species and fertilizing the native grasslands or creating artificial pastures in some paddocks without an assessment of the impacts on the farm system as a whole, and without the farmers' active involvement in adapting the changes to their management systems. The farmers acknowledged the different way of working in the project and the quality of interactions with the research team advisor, as shown by quotes from the end-of-project interviews: "*the technician comes every month, support is more frequent than in previous projects*", "*he is a technician that manages many components on the farm, not only pastures or animals. He is someone who does not impose his own ideas, he helps me to think and I take the decisions. So far, everything we have done has been by consensus. That really seems good to me*", "*I have told the field technician on many occasions that I was not willing to make some changes. It has been difficult for me to decide to make changes, it was not from one day to the other, but he was supporting me all the time during the process*."

The co-innovation approach was costly when calculated per farm because of the time involved in the frequent interactions and the detailed analyses of the state of the farms. The alternative, business-as-usual approach also comes at a cost and appears to be much less effective, given the differences between the project results and national average reference values (Tables 5 and 6). The question, nevertheless, is how to scale out the approach to the entire population of native grassland livestock farmers. One means to this end is the inter-institutional interactions established as part of the co-innovation approach to raise awareness and support among actors operating at regional and national level (Albicette et al., 2017). Such embedding of local innovations in overarching actor networks has been described for other approaches to innovation management (Bos et al., 2009; Bos and Grin, 2008) as part of anchoring the new way of working in existing structures (Elzen et al., 2012). Since the end of the project, the co-innovation approach has been adopted in projects involving 120 livestock farms on almost 50,000 ha, supported by national governmental services, farmers' organizations, educational institutions, and national and international donors (Rossing et al., 2021). Scaling out will involve training both researchers and extension agents in the co-innovation approach. It will also involve reviewing institutional impediments to the way of working at different levels, from the individual level to the entire agricultural innovation system (Klerkx et al., 2017). This study's results warrant such analysis to enable the scaling up of the co-innovation approach and to contribute to a national extension system in which livestock production can be transformed to contribute to multiple ecosystem services.

5. Conclusions

The implementation of a coherent set of ecological intensification practices, jointly designed by farmers and researchers in a co-innovation approach, improved all three dimensions of the sustainability of the cow-calf grazing system in Uruguay, without changing prevailing resource endowments and the socio-economic context. The key systems change involved farmers applying strategic and tactical management options following principles of ecological intensification, supported by a participatory approach. The strategies for change needed farm-specific adaptation across multi-year learning cycles. The results of this work show that cow-calf family-run farms can be transformed to produce positive environmental and social effects and viable economic results. The results and the way of working may be taken as a guide to scaling up and scaling out the ecological intensification of livestock production on native grasslands.

Declaration of Competing Interest

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

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