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A conceptual model of cow-calf systems functioning on native grasslands in a subtropical region

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A B S T R A C T

Cow-calf systems utilise grazing of native grasslands for beef cattle propagation and constitute the principal livestock activity in the Pampas and Campos areas. Cow-calf system sustainability is questioned because of their low production levels and negative environmental impact. Ecological intensification has been proposed as a way out that constitutes an alternative to dominant discourses based on increasing external-input use. There is, however, a considerable gap between the availability of scientific knowledge to promote the ecological intensification of cow-calf systems and farmers' practices. This gap between scientific knowledge availability and farmers' practices can be made explicit, and its consequences for systems performance can be explored through a conceptual model. Conceptual models are tools to build a systems view of the interactions among the production system's state variables, farm management, and resulting system performance. In this paper, we develop a conceptual model of cow-calf systems on native grasslands of the Pampas and Campos regions to support the diagnosis and redesign of farm systems towards ecological intensification. We apply the conceptual model to analyse cow-calf systems in Uruguay, drawing on a survey among 250 Uruguayan livestock farmers. Using the model, we show that in Uruguay, the level of implementation of strategic, tactical, and decision-supporting techniques is low. Consequently, most farms have poor control of the grazing intensity and timing of main events in the production cycle. This results in ample room to improve the productive and environmental performance of most cow-calf farms in Uruguay. We distinguished three broad types of cow-calf systems based on the degree of implementation of techniques, the evolution of state variables throughout the year, and productive indicators. These types imply different departure points and strategies for a sustainability transition process. The conceptual model designed in this paper may support the cow-calf systems sustainability transition in the context of co-innovation processes by aiding the interactive diagnosis and redesign of farm systems.

Implications

Cow-calf systems have low production and net income. Ecological intensification has been proposed as an alternative to improve these systems. There is a gap between scientific knowledge and farmers' practices. We demonstrate that the implementation of ecological management techniques is low. Most farms have poor control of grazing intensity and timing of main events in the production cycle. The conceptual model formulated in this study provides a framework for discussing current cow-calf systems functioning and alternative pathways for sustainability transitions. In the context of co-innovation processes, it can aid the diagnosis and redesign steps supporting interactive learning by participant actors.

Introduction

Native grassland constitutes the principal land use in most countries in South America (Baeza and Paruelo, 2020). This native grassland provides ecosystem services related to environmental conservation, such as carbon sequestration and biodiversity maintenance (Modernel et al., 2016). The native grassland is also the

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basis for livestock production with its social, cultural, and economic relevance (Paruelo et al., 2022). Cow-calf systems are the principal livestock activity in southern South America's Pampas and Campos areas, mainly involving family farms (Modernel et al., 2018).

Cow-calf systems on native grasslands are complex systems where interactions between abiotic and biotic components result in a marketable animal product, and the human element has a central and decisive role (Briske et al., 2011; Stuth and Maraschin, 2001).

Although the cow-calf systems have the lowest environmental footprint (Paruelo et al., 2022), their sustainability is questioned because of their low production levels and negative environmental impact due to inadequate grazing management of native grasslands. Average meat production in these systems is low (around 80 kg LW ha^{-1}) (Modernel et al., 2018; Nabinger and Carvalho, 2009). Reproductive efficiency is also low, e.g., 60–65 calves are weaned per year per 100 mating cows (Soca et al., 2007), equivalent to 90 kg of weaned calves per mating cow (Do Carmo et al., 2016). These production levels result in low net farm income and farmer labour productivity (Ruggia et al., 2021). The main causes of low productive and economic results are high grazing intensity and lack of adequate herd management (Claramunt et al., 2020; Nabinger and Carvalho, 2009; Ruggia et al., 2021). High grazing intensity could increase soil erosion rates due to soil cover reduction, plant and animal diversity, and increase greenhouse gas emissions (Modernel et al., 2016), rendering grazing intensity a key lever for change.

Ecological intensification (Doré et al., 2011; Tittonell, 2014) has been proposed as a pathway to increase cow-calf systems' productivity and net farm income and improve the production and use of native grasslands (Soca et al., 2007). Ecological intensification of livestock production on native grasslands aims to increase meat production per unit area without increasing costs while preserving and improving ecosystem services such as biodiversity, soil and water quality, and soil carbon stocks. Ecological intensification promotes intelligent and intensive use of the ecosystem's natural support and regulation functions through managing biodiversity, solar energy capture, and biogeochemical cycles (Doré et al., 2011; Soca et al., 2007).

In the past three decades, scientific knowledge has been generated for the ecological intensification of cow-calf systems. Studies addressed both native grassland management (Claramunt et al., 2017; Do Carmo et al., 2018; Nabinger and Carvalho, 2009; Da Trindade et al., 2016) and breeding cow management (Claramunt et al., 2020; Do Carmo et al., 2016; Quintans et al., 2010; 2004; Soca and Orcasberro,1992). Results showed that appropriate grazing intensity through monitoring of forage allowance increased forage production and the cows' energy intake (Do Carmo et al., 2021; Da Trindade et al., 2016). Appropriate forage allowance combined with herd management techniques increased reproductive efficiency and meat production without increasing input use or production costs and maintained or increased the provision of ecosystem services by the native grasslands (Do Carmo et al., 2016; Dumont et al., 2020).

There is, however, a considerable gap between the availability of scientific knowledge to promote the ecological intensification of cow-calf systems and farmers' practices (Landais et al., 1988), as shown by the low and partial adoption of scientific results (Ministerio Ganaderia Agricultura Pesca (**MGAP** – OPYPA 2016). One explanation for this gap is that the scientific knowledge developed, presented, and promoted refers to individual techniques aimed at improving specific system components without accounting for the cow-calf systems as a whole. A systemic perspective of the production process at the farm level to enable combining and integrating techniques in terms of coherent farm-specific sets is lacking. To our knowledge, no published studies provide a systemic integration of available scientific knowledge to promote ecological intensification of the cow-calf systems of the Pampas and Campos grasslands. The temporal alignment of the processes of gestation, lactation, and mating with the spatiotemporal alignment of forage production and cows' energy intake across native grassland paddocks (Funston et al., 2016; Soca and Orcasberro, 1992; Duru and Hubert, 2003) is key in cow-calf production systems' management aimed at improving energy intake and transformation of energy by animals for ecological intensification.

Conceptual models (Rapidel et al., 2006) are tools to build a systems view of the interactions among the production system's state variables, farm management, and the resulting system performance. This paper aims to develop a conceptual model of cow-calf systems on native grasslands of the Pampas and Campos regions as a basis for the ecological intensification of production systems. First, we present a conceptual model of cow-calf systems functioning, integrating biophysical and technical components and their relationships. Second, we review scientific knowledge on ecological intensification management options, which we classify as strategic, tactical and decision-support techniques. Third, we apply the conceptual model to analyse cow-calf systems in Uruguay, drawing on a survey among 250 Uruguayan livestock farmers. We end by discussing the usefulness of the proposed conceptual model for fostering ecological intensification of the Pampa and Campos cow-calf systems.

Material and methods

The conceptual model of the cow-calf system

A conceptual model is a representation of a system that is built to address specific questions. The system is defined by its limits, components, environment, relevant state variables and flows of mass and information within the system and exchanged with the environment. In agricultural systems, two sub-systems may be distinguished. The biophysical sub-system comprises a set of components (soil, forage, animals), each represented by one or several state variables. The technical sub-system is a combination of animal management techniques that act individually or interactively on processes (e.g. forage production, animal intake), on state variables (e.g. forage mass, body condition score (**BCS**), or on the flow between components and processes (Rapidel et al., 2006).

Following Rapidel et al. (2006), we considered a cow-calf system as a biophysical sub-system affected by the environment (climate, weather and soil) and by a technical sub-system**.** We built a conceptual model of cow-calf grassland systems by combining different sources of information: analytical research based on factorial experiments in which the effects of different management treatments were tested (Claramunt et al., 2017; Do Carmo et al., 2018; Quintans et al., 2010; Soca et al., 2013); results from regional diagnosis and survey studies (Fernández Rosso et al., 2020; MGAP, 2016; Modernel et al., 2018); and on-farm research and co-innovation projects (Bilotto et al., 2019; Do Carmo et al., 2019; Ruggia et al., 2021).

Review and classification of techniques to manage cow-calf systems on Pampas and Campos grasslands

We reviewed the literature on management techniques for the Campos and Pampas region cow-calf systems. Based on the idea that techniques for the management of grazing systems can be classified according to their time horizon and the entity involved (Duru and Hubert, 2003; Funston et al., 2016; Nozières et al., 2011), we classified the techniques into three groups: strategic, tactical, and support for decision-making. We defined strategic techniques as those determining the main events defining the production system. They involve medium to long-term decisions, which structure the system and define the moments at which the main productive events occur throughout the cycle. Tactical techniques comprise decisions within one production year, allowing adaptation to changing circumstances, correcting or mitigating a specific setback, and steering towards the defined productive objectives. Techniques that support decision-making involve monitoring of state variables (forage mass, BCS) to inform tactical management decisions.

Application of the conceptual model to cow-calf systems in Uruguay

To illustrate the heuristic value of the conceptual model, we use it to diagnose cow-calf system functioning and management at family farms in two native grassland regions in Uruguay: Sierras del Este and Cuesta Basáltica.

Data were obtained from a representative survey by the Ministry of Livestock, Agriculture and Fisheries (MGAP, 2021) that was part of the Livestock Family Farmers and Climate Change project. The survey, conducted between May and August 2015 consisted of a face-to-face structured interview conducted by interviewers hired for this task. The interviewers had received training from researchers for the application of the survey. The survey involved 250 farmers in the two regions, selected to represent the diversity of stocking rates. For this purpose, farms in the regions known through the 10-yearly agricultural census were classified into three stocking rate categories: less than 0.6 animal units (**AU**) ha^{-1}, from 0.6 to 0.9 AU ha^{-1}, and over 0.9 AU ha^{-1}. From 1614 farms in the two regions, 250 farms were selected to be interviewed based on Neyman's sample size estimation (Cochran,1977). In the final sample, 48% of farms were from the Cuesta Basáltica and 52% from the Sierras del Este.

The survey format was similar to a model used by the Agricultural Statistics Research of the Ministry of Livestock, Agriculture and Fisheries (MGAP) (https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/tematica/diea). It covered the following topics: general information about the family and the farm; land use; animal stock; breeding management; rearing and wintering management; sheep management; production costs; technical assistance; access to information and networks.

Cow-calf system types

Based on the conceptual model built, the use of strategic, tactical and decision- supporting techniques by the farms surveyed, and published farm case studies (Do Carmo et al., 2019; Ruggia et al., 2021), we proposed the classification of cow-calf systems in Uruguay into three types, contrasting in their degree of control of the production process by the farmer.

Results

This section proposes a conceptual model of the cow-calf system in the Campos and Pampas region of southern South America. From an ecological intensification perspective, we classified techniques available to improve the production, use, and conversion of forage energy into animal products by linking the technical and biophysical sub-systems. We classified these techniques as strategic, tactical and decision-supporting. Then, based on data from a survey on livestock systems in Uruguay, we analysed the level of implementation of strategic, tactical and decision-supporting techniques. Finally, we proposed three possible types of cow-calf systems and described how they work and their results.

A conceptual model of cow-calf systems functioning and management

Cow-calf systems on native grasslands are complex systems where interactions between abiotic and biotic components result in a marketable animal product and where the human element has a central and decisive role (Briske et al., 2011; Stuth and Maraschin, 2001). Outdoor grazing systems with low external inputs convert solar energy, water, and soil nutrients into animal products (Nabinger, 1997; Briske et al., 2011). Forage production and animal energy intake from forage are key processes at the production system level (Hodgson, 1990; Ungar, 2019). Forage production is affected by soil type, botanical composition, soil moisture, temperature, and leaf area index (Nabinger, 1997; da Silva et al., 2015). Animal energy intake is mainly controlled by forage availability and quality (Hodgson, 1990; Da Trindade et al., 2016; Do Carmo et al., 2021) and is used for maintenance, reproduction, lactation, and gestation (Short et al., 1990) and growth (NRC, 2000).

Campos grasslands are dominated by C4 species (Lezama et al., 2019). Their growth rate is affected by seasonal variation in radiation, temperature, water availability, and leaf area index controlled by grazing intensity (da Silva et al., 2015). Depending on soil moisture, most forage accumulation typically occurs between September and March (spring and summer). In contrast, forage accumulation rates are limited during winter (May to August), tending to zero (Royo Pallarés et al., 2005). Depending on the type of soil and the vegetation, the aboveground productivity of native grassland varies from 2 500 to 4 500 kg DM ha^{-1} per year, but production values differ depending on grazing intensity (Do Carmo et al., 2018). In an average year, a farm with good control of the grazing intensity can achieve an available forage mass per hectare of 2 500 kg DM ha^{-1} or about 8 cm of sward height in autumn (March), around 1 200 kg DM ha^{-1} or 3–4 cm in late winter (August), and 1 800–2 000 DM ha^{-1} or 6 cm in mid-spring (November) (Do Carmo et al., 2016; Ruggia et al., 2021). Such levels of available forage mass are necessary but not enough to obtain animal production greater than the current average. Another relevant factor is the utilisation of energy by animals. The timing of the main events of the beef cow productive cycle – mating, calving, and weaning - should be planned when they are most appropriate from the point of view of forage availability (Funston et al., 2016). Concentrating the calving period in early spring, and therefore the mating in late summer, ensures that most of the breeding cows' energy requirements for lactation and the return to ovarian activity after calving can be met. Weaning at the end of summer reduces the energy requirements of breeding cows, allowing them enough time to recover body condition before the onset of winter (Soca and Orcasberro, 1992). The biophysical sub-system comprises paddocks and animals, each represented by several state variables (available forage and animal body condition). The technical sub-system is a combination of strategic, tactical, and decision-supporting techniques that define the flows among the state variables within the biophysical sub-system and the system's performance. As productive performance indicators, we propose the pregnancy rate, the weight of calves at weaning, and the weight of cows sold in autumn. The product of the first two indicators is the weight of weaned calves per mating cow (Fig. 1). Below, we describe the various system components and their interactions in more detail, starting a production year in autumn.

Autumn is a key moment in Pampas and Campos grazing systems. Net forage accumulation during spring, summer, and early autumn defines forage availability until the next spring (Do Carmo et al., 2018). The forage availability in the winter is the lowest of the entire cycle (Bilotto et al., 2019; Do Carmo et al., 2018). Weaning in March will allow the cows to increase their body condition (measured by the body condition score BCS) by benefiting from available forage before winter and not having to spend energy on milk production anymore (Trujillo et al., 1996). During winter, the cows'

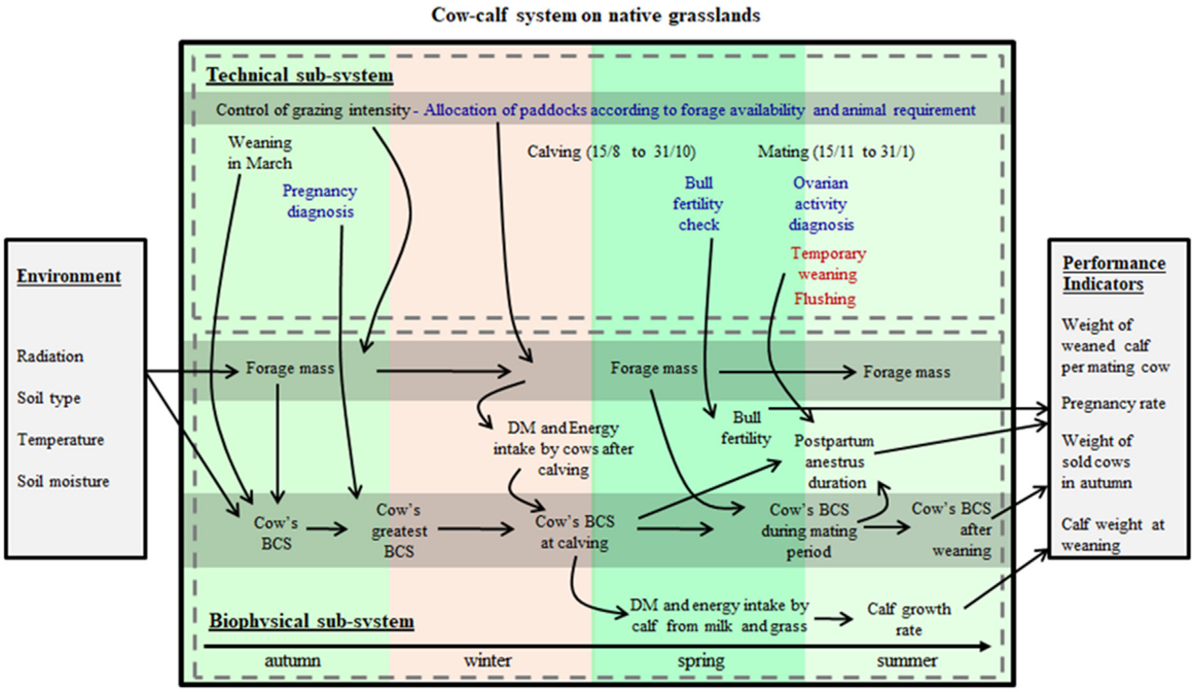

Fig. 1. Conceptual model of cow-calf systems on Pampas and Campos grasslands. The system comprises a technical and a biophysical sub-system and their interactions. Three state variables describe the system status: grazing intensity control, forage mass, and cow body condition score (BCS), indicated in dark shading. Inputs from the environment and performance indicators are shown in grey boxes. In the technical sub-system, strategic techniques are represented in black font, tactical techniques in red, and decision-supporting techniques in blue. For further explanation, see the main text.

BCS will generally decrease due to low forage availability and increasing energy requirements from the advancing gestation. BCS at calving and forage intake after calving (Do Carmo et al., 2021) determine the evolution of postpartum BCS, which significantly affects the return to ovarian cyclicity (Soca et al., 2013; Claramunt et al., 2017) and the level of milk production and thus the development of the calf (Gutiérrez et al., 2013; Iewdiukow et al., 2020).

From September, temperature and soil moisture allow high forage growth rates until November, when water stress becomes more frequent (Carvalho et al., 2006; Do Carmo et al., 2018). Control of grazing intensity during this period is essential to maintain a leaf area index value in the paddocks ensuring high biomass accumulation before summer droughts start. Pasture height is generally used as a proxy indicator for leaf area index and biomass accumulation (da Silva et al., 2015).

At the start of the mating period (mid-November), some cows may still be in anoestrus depending on the calving date and the evolution of their BCS (Quintans et al., 2004; Soca et al., 2013). Suckling control by a calf nasal splint during 14 days (temporary weaning) at the time of mating can stimulate the cow's return to the oestrous cycle (Quintans et al. 2010), which, together with adequate forage allowance, facilitates pregnancy. The weight of the weaned calf is co-determined by the cow's milk production and the availability of forage for the calf (Claramunt et al., 2020). The pregnancy rate and weight of calves at weaning determine the weight of calves weaned per mating cow, a herd-level performance indicator. Control of the cow's BCS is also useful to achieve good selling weights of the cows leaving the herd to be fattened.

Ecological intensification techniques to improve cow-calf system performance on Pampas and Campos grasslands

The techniques, classified into three groups: strategic, tactical, and support for decision-making, are presented in the following sections (Table 1).

Strategic techniques

Adjusting the annual stocking rate to match the carrying capacity of the farm. The carrying capacity is defined by Allen et al. (2011) as the maximum stocking rate, i.e. the number of animal units or amount of forage intake units per unit area and year that will achieve a target level of animal performance in a specified grazing system that can be applied over a defined time without deterioration of the grazing land. Carrying capacity may also be defined from different perspectives (e.g. resource, animal, welfare, systems or environment perspective) (Ungar, 2019). Here, we opt for the systems perspective. From this perspective, the stocking rate should allow a high intake for as long as possible in the annual production cycle (Ungar, 2019). Defining a stocking rate adjusted to the carrying capacity has implications for herd structure and size and is livestock farmers' major decision. To match a farm's carrying capacity, the stocking rate should be adjusted to the natural variation in forage availability across paddocks (Nozières et al., 2011) and throughout the year (Do Carmo et al., 2018). This can be achieved by planning the timing of animal sales (male and female calves, replacement cows) and, occasionally, buying animals to fatten in years with high forage availability.

Determining mating season start and length. In systems on native grasslands, the calving date has been reported to influence the productive and economic results of the cow-calf system (Funston et al., 2016). For the Pampas and Campos grasslands' climate, late winter and early spring calving (from 15 August to 31 October) allow the highest energy availability in the forage to coincide with the highest energy demand from the cows, thus ensuring high milk production and a fast return to ovarian cyclicity (Soca et al., 2013; Soca and Orcasberro, 1992). The mating season should start in mid-November to last a maximum of three months to ensure energy supply–demand matching, aiming for most cows to become pregnant within 60 days. In mid-November, the cows will have had a calf on average 2.5 months earlier and, if provided with sufficient

Table 1
Strategic, tactical, and decision-supporting techniques underpinning ecological intensification of cow-calf systems in southern South America.

Category	Technique	Reference
Strategic	Adjusting the annual stocking rate to match the carrying capacity of the farm	Briske and Heitschmidt (1991), Ungar (2019), Torell et al. (2010)
	Determining mating season start and length	Soca and Orcasberro (1992), Do Carmo et al. (2016), Funston et al. (2016), NRC (2000)
	Determining lactation period length	Soca and Orcasberro (1992), Trujillo et al. (1996), NRC (2000)
	Supporting energy intake of primiparous cows after calving	Soca et al. (2013), Astessiano et al. (2012)
	First pregnancy of heifers at two years of age	Quintans et al. (2008), Soca et al. (2013), Meikle et al. (2018)
Tactical	Applying temporary weaning: suckling restriction for two weeks during the mating season	Soca et al. (2007), Quintans et al. (2010)
	Applying temporary weaning combined with dietary flushing	Soca et al. (2013), Astessiano et al. (2012)
Decision-support	Testing bulls' fertility before the mating season	Viñoles et al. (2009)
	Monitoring Body Condition Score (BCS)	Vizcarra et al. (1986), Soca and Orcasberro. (1992), Trujillo et al. (1996)
	Monitoring forage height and biomass	Do Carmo et al. (2020)
	Ovarian activity diagnosis	Perry et al. (2016), Quintans et al. (2010)
	Pregnancy diagnosis	Beal et al. (1992)

forage, will have recovered BCS after calving. Such concentrated mating will also contribute to more uniform calf weights at weaning, which can be financially advantageous at the time of sale.

Determining lactation period length. Weaning the calves at the end of summer (March) reduces the cows' energy requirements (NRC, 2000). In combination with the cows' yet low gestation energy requirements (the cow is only three months pregnant) allows them time to increase their BCS before winter, benefiting from forage availability during autumn (Claramunt et al., 2017; Soca and Orcasberro, 1992).

Supporting energy intake of primiparous cows after calving. A negative energy balance due to lactation has more impact on primiparous than on multiparous beef cows (Soca et al., 2013). The postpartum anoestrus interval is longer in primiparous cows, and the reproductive efficiency is lower than in multiparous cows (Soca et al., 2013). Consequently, primiparous cows get pregnant less quickly than multiparous cows (Soca et al., 2007). Adequate energy intake by primiparous cows after calving is essential to ensure they continue their body development, improve their BCS, and produce milk. Energy intake can be supported by allocating them to a dedicated paddock with a high forage allowance. Overseeding native grasslands with legumes (e.g. *Lotus* spp.) or other species has been proposed as an effective method to improve forage quality and quantity during early spring (Carámbula et al., 1994; Soca et al., 2002). However, if grazing intensity on such paddocks is not carefully controlled, this technique may cause biodiversity loss and degradation of the natural grasslands (Jaurena et al., 2016).

First pregnancy of heifers at two years of age. The cows' age at first pregnancy substantially impacts the production systems' efficiency (Meikle et al., 2018). The best results for Pampas and Campos grasslands were achieved when heifers got pregnant at two years of age (Quintans et al., 2008). On many Campos farms, however, a significant portion of heifers get pregnant at three years of age (Quintans, 2016). Delay of first pregnancy may be caused by BW loss in female calves and heifers during winter, affecting their reproductive success. In winter, increased forage allowance for heifers (Soca et al., 2013) combined with supplementary feeding constitute strategic decisions for a target BW over 300 kg at two years.

Tactical techniques

Applying temporary weaning: suckling restriction for two weeks during the mating season. Temporary weaning consists of placing a nasal splint on 50- to 70-day-old calves of at least 60 kg of live weight for 11–14 days (Quintans et al., 2010). Temporary weaning reduces milk intake by the calf and milk production by the cow for a short period, improving the cows' energy balance and increasing glucose, insulin and IGF 1 levels. As a result, postpartum anoestrus is reduced, and the overall pregnancy rate is increased. This response to temporary weaning is affected by the cow's BCS at calving and its evolution during mating (Quintans et al., 2010; Soca et al., 2013). Cows with a BCS of 3.5–4 at the beginning of suckling restriction have the highest response to temporary weaning. For this category, an early pregnancy rate of 80% can be obtained (Soca et al., 2007), around 30% more than those without temporary weaning.

Appling temporary weaning combined with dietary flushing. Temporary weaning can be combined with flushing by providing the cows with energy-rich feed for 21–25 days. Increased energy intake for a short period does not change the BCS but increases metabolic hormones improving the energy balance and the pregnancy probability (Soca et al., 2013).

Decision-supporting techniques

Testing bulls' fertility before the mating season. Assessing bulls' reproductive aptitude before the breeding season is a technique to avoid reproductive losses due to unfit bulls (Viñoleset al., 2009). Reproductive problems of the bull directly affect the reproduction of the breeding herd and, therefore, the system's productivity. 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).

Monitoring body condition score. Visual inspection of a cow's BCS ascertains its nutritional status, which predicts reproductive efficiency. The BCS scale for beef cows developed in Uruguay (Vizcarra et al., 1986) has eight levels ranging from very skinny to very fat. BCS is a variable that can be controlled through herbage allowance (Trujillo et al., 1996; Do Carmo et al., 2018; Claramunt et al., 2017). Although BCS monitoring may be carried out systematically throughout the year, it is particularly relevant from weaning to calving since BCS at calving impacts the duration of the postpartum anoestrum and the pregnancy probability during the following mating period. Primiparous and multiparous cows should reach a BCS of 4.5 and 4 points at calving, respectively, for high pregnancy probability, i.e. 80% or more (Do Carmo et al., 2016).

Monitoring forage height and biomass. Monitoring forage height and biomass and estimating forage allowance in each paddock enable allocating animals to paddocks according to their energy requirements and BCS level. Forage height and allowance strongly impact pasture growth rate and, consequently, forage accumulation (or decumulation) (Do Carmo et al., 2018). Soca and Orcasberro (1992) proposed forage height thresholds for the cow-calf system at weaning of 8 and 10 cm and 8 and 6 cm at lactation and mating, which were found to be effective at the farm scale by Ruggia et al. (2021).

Ovarian activity diagnosis. Diagnosing ovarian activity in the middle of the mating season involves determining a cow's reproductive status regarding follicular size and uterine tone, identifying pregnant cows, cows cycling normally, and cows in superficial and deep anoestrus. This information is relevant for implementing tactical techniques (temporary weaning and dietary flushing) to improve pregnancy (Quintans, 2016).

Pregnancy diagnosis. Pregnancy diagnosis (Beal et al., 1992) carried out one to two months after the end of the mating period identifies pregnant and non-pregnant cows. Separating pregnant from empty cows early after weaning enables differential forage allocation in early autumn to recover 1–1.5 points of BCS before winter. It also supports decisions concerning non-pregnant cows: immediate selling, fattening to sale in spring, or keeping them on the farm until the next mating season at a lower-than-standard forage allowance. These decisions contribute to stocking rate control.

Application of the conceptual model to cow-calf systems in Uruguay

Here, we use the representative survey results to assess the use of the conceptual model's strategic, tactical, and decision-supporting techniques for ecological intensification in the two Uruguayan regions (Table 2). The average age of farmers in the survey was 54 years; one-third were younger than 50, and another third were over 60. The average family size was 2.7 persons. Over 50% of the farmers managed their farms for over 20 years; 7% operated their farms for less than five years.

Adoption of ecological intensification techniques

Techniques for ecological intensification of cow-calf systems in the native grasslands of Uruguay are not used widely by farmers. Stocking rates should be related to forage availability to match the farm's carrying capacity and ensure sufficient animal energy intake. Considering that farms roughly have a forage availability of 1 000–1 200 kg ha^{-1} (Ruggia et al., 2021; Do Carmo et al., 2019), and the mean stocking rate is 1.05 AU ha^{-1} (Table 2), the forage allowance is only 3 kg DM kg^{-1} LW. Consequently, animal energy intake is low (Da Trindade et al., 2016), enhancing overgrazing and limiting forage production (Nabinger and Carvalho, 2009).

Almost 50% of the farmers do not have a delimited mating season (Table 2), leaving the farmer clueless about the approximate time of pregnancy start. As a result, prioritising forage allocation based on animal requirements at an early enough stage is impossible. Only 36% of farmers wean calves in March or April. Weaning is predominantly done in May, June, July and August, compromising the recovery of the pregnant cows' body condition before winter.

Tactical techniques to increase pregnancy rates are not used or applied uniformly to all cows, resulting in inefficient use of resources. More than 70% of farmers do not perform a pregnancy diagnosis in autumn, which implies not knowing which cows are pregnant and which are not. Consequently, they cannot make early projections of which cows will calve and prioritise the allocation of available forage. In addition, reduction of stocking rate by selling empty cows before the decline of forage availability in winter is precluded.

Temporary weaning is applied by 35% of farmers, and 8% combined temporary weaning with flushing. An extended mating and calving season hinders the application of calf suckling control techniques.

Regarding decision-supporting techniques, only 15% of farmers have their bulls checked by a veterinarian before the mating season. Most farmers, therefore, run the risk that any bulls' fertility problems are discovered too late to prevent pregnancy failures. As the classification of cows by BCS is done on only 32% of farms, most farmers cannot make grazing management decisions based on animal requirements. Diagnosis of ovarian activity is rare. Therefore, most farmers do not know whether the cows are cycling, in superficial or deep anoestrus, or pregnant. Finally, only 30% of farmers have a pregnancy diagnosis.

Cow-calf system types

Type 1 "Systems without time and space management" – cow-calf

Table 2
Implementation of strategic, tactical, and decision-supporting techniques for ecological intensification of cow-calf systems on Uruguayan Campos grasslands in Sierras del Este and Cuesta Basáltica. Results are based on a representative survey of MGAP (2021) among 250 farmers.

Category	Technique	Survey result
Strategic	Annual stocking rate	1.05 ± 0.45 AU[1] ha^{-1}
	Determining mating season start and length	Continuous mating: 40% of farmsDouble mating season (spring/summer and autumn) : 9% of farmsMating season is restricted to spring and summer (December to February) and not more than 90 days: 51% of farms
	Determining lactation period length	Weaning in March or April: 36% of farms Weaning in May: 32% of farms Weaning in June, July and August: 19% of farms Weaning in other months: 13% of farms
	First pregnancy of heifers at two years of age	First pregnancy at two years: 60% of farms First pregnancy at three years: 40% of farms
Tactical	Applying temporary weaning: suckling restriction for two weeks during the mating season.	36% of farms
	Applying temporary weaning combined with dietary flushing	8% of farms
Decision-supporting	Testing bulls' fertility before the mating season	31% of farms, of which 50% through a vet
	Monitoring Body Condition Score (BCS)	Decisions about forage allowance based on BCS: 32% of farms
	Ovarian activity diagnosis	5% of farms
	Pregnancy diagnosis	30% of farms

[1] Animal Unit (AU) is equivalent to a cow of 380 kg live weight.

systems with low control over natural production processes and high grazing intensities resulting in low forage production and low herd energy intake. On farms of type 1, the evolution of the system's main state variables (cow BCS, forage height and biomass per paddock) is not monitored. Rather than farmer management decisions, weather determines the timing of main events in the animal production cycle. The bulls spend most of the year with the herd, and weaning happens over the course of several months. A lack of cows' BCS recovery before calving results in around 60% pregnancy rates, i.e., a cow produces one calf almost every two years.

Type 1 farms probably have a high stocking rate, around 1 AU ha^{-1} on average. Forage is not allocated according to animal requirements and animal physiological status. Typically, forage allowance is below 3–4 kg DM kg^{-1} of live weight throughout the year (Do Carmo et al., 2018; Claramunt et al., 2017; Nabinger and Carvalho, 2009). The sward height is 3–4 cm in autumn, 2–3 cm in winter, and 4–6 cm in spring-summer. The cows' BCS remains low, around 3–4.

Typically, these farms attain 60–70 kg of meat per hectare per year, associated with a weaning percentage between 55 and 65%, and calves are sold at 120–140 kg of animal live weight at eight months of age, mostly in winter. Ruggia et al. (2021) reported such values in the diagnoses or baseline of their case study livestock farms.

Type 2 "Systems with temporal management" - cow-calf systems with control over the timing of the main events in the production cycle but no monitoring of the main state variables and, therefore, no grazing management in space. On farms of this type, the evolution of the system's main state variables is not monitored, but farmers use a calendar of events. Type 2 farms typically have a defined but prolonged mating season, from the end of November to the end of March or April. Depending on the weather, the calves' weight, and the final weaning takes place between mid-April and the end of May. This timing reduces the chances for the cows to recover BCS before winter, compromising the BCS at calving and the pregnancy rate for the following year.

No decision-supporting techniques are implemented, and forage allowance is not planned according to BCS and animal requirements. Farmers use particular paddocks for specific categories of animals during critical periods, e.g., where the primiparous cows give birth or where the calves are taken to pass the first winter. However, the choice of the paddocks would be based on arguments such as the convenience of access rather than on an assessment of the paddocks' current or expected forage availability as a basis for managing grazing intensity.

Type 2 farms work at a forage allowance of 3.5–5 kg DM kg^{-1} live animal weight, with a stocking rate of around 0.9–0.8 AU ha^{-1}. The height of the sward is 4 cm in autumn, 3 cm in winter, and 5–6 in spring and summer. The cow's BCS would be 3–3.5 at calving; in some cows, it could reach 4–4.5 in late autumn (March).

Low BCS at calving combined with low adoption of temporary weaning and flushing results in 30 to 35% of the cows failing to become pregnant since they are in anoestrus.

The meat production achieved by Type 2 farms would be around 80–100 kg ha^{-1}, with 70–75% pregnancy rates and calf weights of 130–140 kg in April or May at approximately six months of age.

Type 3 "Systems that apply the strategic, tactical and decision-supporting techniques". In these farms, there is a control of the timing of pregnancy, calving and lactation. Final weaning in March allows for an adequate energy balance of the herd. On Type 3 farms, the main system state variables are monitored. The allocation of animals to different paddocks is governed by forage availability on the one hand and BCS and animal physiological requirements on the other, considering the time of year and what is expected for the coming months. The monitoring involves observations of the animals or pastures but is not necessarily based on measurements.

Type 3 farms work at a forage allowance of 5–8 kg DM kg^{-1} live weight with a stocking rate around 0.9–0.8 AU ha^{-1}, which implies an average sward height of around 8 cm in autumn, 4–5 cm in winter, and 8–12 cm in spring and summer. The resulting animal intake translates into BCSs of the cows between 4.5 and 4 at calving, maintained during lactation to the final weaning in March, and increasing to 5–6 BCS at the start of winter.

Meat production is between 120 and 150 kg ha^{-1} per year, twice the current national values of 70–80 kg ha^{-1} per year. This production level results from a pregnancy rate of around 90% and a calf live weight of 160 kg or more at six months, in March or April.

Discussion

This study proposed a conceptual model of cow-calf systems in the Campos and Pampas region of southern South America. In this section, we first discuss the scope for ecological intensification strategies to increase production and ecosystem services compared to intensification strategies based on inputs and natural grassland substitution. Second, we discuss how the conceptual model can support cow-calf systems sustainability transition processes under an ecological intensification paradigm.

The scope for ecological intensification strategies to increase production and ecosystem services

Strategies suggested to improve the cow-calf systems' current productive, economic, and environmental performance in the Pampas and Campos regions differ greatly. Several authors have proposed an intensification trajectory based on increasing inputs through the replacement of native grasslands with improved pastures and the increase in the amount of off-farm produced feed (Kanter et al., 2016; Bilotto et al., 2019; López-González et al. 2020). Kanter et al. (2016) applied a participatory backcasting approach to set productivity and environmental targets for the Uruguayan beef sector and arrive at strategies to achieve these. In their study, an increase in meat production from 102 to 128 kg ha^{-1} and a reduction in greenhouse gas emissions by 25% was achieved by increasing the area of improved pastures from 15–30% to the detriment of native grasslands and by almost doubling the use of external feed from 19 kg ha^{-1} to 37 kg ha^{-1}. They also proposed using nitrification inhibitors and tree plantations to reduce greenhouse gas emissions. This intensification strategy will likely result in biodiversity loss due to the loss of native grasslands and their replacement by low-diversity sown plant communities. The strategy is also likely to increase the vulnerability of production systems since improved pastures have shown a decrease in productivity over time (Carámbula, 1991) and low recovery ability after drought events.

The external-input intensification proposal is not new to Uruguayan livestock farming. Since the 1960s, the substitution of native grasslands by "more productive" species or the idea of "improving" the native grasslands by overseeding species or fertilising has been promoted by various actors (Moraes, 2001). Applying this external-input intensification strategy to Uruguayan cow-calf farms with poor control of the grazing intensity and timing of main events in the production cycle (Type 1 and Type 2 farms) would increase the risk of financial losses. The projected positive impact on meat production by improved pastures and external feed is likely to be lessened by extant overgrazing and poor herd management, resulting in increased production costs, more financial dependency on off-farm loans, and low or no positive effects on gross income.

Ecological intensification has been proposed to improve the cow-calf system's productive, economic and environmental performance as an alternative to external-input intensification (Do Carmo et al., 2016; Soca et al., 2007). This proposal is based on improving the on-farm production, use, and conversion of forage from the native grasslands into animal products. On-farm testing of this proposal in Uruguay (Ruggia et al., 2021) showed that all farms improved their productive, economic and environmental performance over a period of 3 years compared to the baseline. Improvements were observed in the economic indicators gross margin (+55%), return to labour (+71%), and family income (+53%). These changes were explained by the uptake of coherent sets of ecological intensification practices causing changes in forage height, forage allowance, pregnancy rate, and weight of weaning calf per mating cow, increasing meat production per hectare by 22%, achieving 122 kg ha^{-1}.

Several studies (Soca et al., 2007; Do Carmo et al., 2019; Ruggia et al., 2021) show that it is possible to increase meat production per ha from the current 80 to 120 kg ha^{-1} by applying an ecological intensification strategy without increasing inputs or replacing the native grassland. However, the productivity ceiling associated with the ecological intensification of cow-calf systems on native grasslands remains unclear. In long-term experiments on a regional research station, meat production levels of 180 kg ha^{-1} were achieved on native grassland with increased herbage allowance (Do Carmo et al., 2018, Claramunt et al., 2017). Other experiments in the region showed that forage production of native grassland could be as high as 8 Mg DM ha^{-1} per year with a grazing intensity that maintained a forage height between 6 and 12 cm (Rodríguez Palma and Rodríguez, 2017). These results were achieved on soils of medium depth and medium capacity to accumulate water, similar to those found on an important proportion of cow-calf farms in Uruguay (Molfino and Califra, 2001). These forage production levels of 8 Mg DM ha^{-1} per year would improve the systems' carrying capacity.

Besides increasing forage production and allowance, improving animal biotypes to increase energy efficiency is another promising strategy. Using animals with higher energy efficiency due to lower energy requirements for maintenance is a goal that could be achieved by crossbreeding between breeds or biotypes within the most commonly used breeds, Hereford and Angus (Trujillo et al., 2013). Criollo cattle's role in achieving higher energy efficiency should be further investigated (Armstrong et al., 2022). In addition to selecting for lower maintenance requirements, animal grazing preferences may differ. Animals that accept a greater dietary diversity in heterogeneous environments will satisfy their intake needs more easily than specialists (Do Carmo et al., 2021; Pauler et al., 2020), resulting in greater forage utilisation efficiency.

The weight of calves at weaning at the farms that apply ecological intensification techniques is about 180 kg, while the current average is 140 kg (Ruggia et al., 2021). Knowledge of the grazing behaviour of the cow-calf pair in response to changes in grazing intensity is central to increasing the calves' weight at weaning (Claramunt et al., 2020). Other factors determining weaning weight are concentrating births in August and September and improving the cows' milk production during the first three months (Iewdiukow et al., 2020) by facilitating an adequate body condition at calving and providing high forage allowance (Do Carmo et al., 2021). In addition, providing preferential feeding to calves (creep grazing) is a promising strategy. Creep grazing modules (Corriher et al., 2007) either resulting from sward improvement of native grasslands (5–6 cm with a high proportion of green leaves) or native grasslands with *Lotus* spp. overseeding in a small area could be used to improve the energy intake of calves. Such management would allow achieving a weaning weight of calves of around 220 kg at six months (Corriher et al., 2007).

Automated sensors and information technologies designed to aid the real-time monitoring of the main system's state variables (forage height per paddock and animals' BCS) and processes (forage growth rate, intake, and animal behaviour) are other promising avenues to facilitate ecological intensification (Horn and Isselstein, 2022). For example, cameras monitoring the BCS of individual cows could reduce labour demand. Using satellite images to estimate current forage mass and to make predictions based on radiation and soil moisture is another decision-supporting avenue. Accelerometers, GPS, and other equipment can be invoked to monitor the grazing activity of the cows and estimate the daily intake of forage (Horn and Isselstein, 2022). These technologies require further research and local evaluation by farmers. They should be part of a research agenda to foster and facilitate the ecological intensification of cow-calf systems on native grasslands.

The ecological intensification process in cow-calf systems should be based on adopting and properly integrating the strategic, technical, and decision-supporting techniques described in this paper. This challenge requires learning by farmers and other actors (Dumont et al., 2020). Also, learning is pivotal to advancing productive outcomes and ecosystem services provision of Type 3 farms.

The role of the conceptual model in supporting cow-calf systems' ecological intensification transition processes

Cow-calf systems in native grasslands are complex adaptive systems (**CAS**) characterised by many interacting components (Lynam and Stafford Smith, 2004). Within CAS, farm sustainability can only be achieved through adaptability and change (Darnhofer et al., 2010). In these systems, human processes are as important as ecological ones (Stuth and Maraschin, 2001). Lynam and Stafford Smith (2004) describe the critical importance of mental models in complex adaptive grassland systems. A mental model is a person's understanding of how the world works, which they use to make sense of the world and interpret and evaluate their actions. From this perspective, any action that seeks to help farmers change the functioning of their production system must contribute to evolve farmers' mental models, which is achieved by seeking to bring about learning (Briske et al., 2011).

Co-innovation is an appropriate way to promote learning processes between farmers, technicians and researchers and a well-tested framework for making knowledge actionable (Rossing et al., 2021). From the co-innovation perspective, the farm is a CAS in which analysis and design become a cycle of joint scientific and farmer knowledge development (Dogliotti et al., 2014). This cycle of analysis, design and evaluation of production systems fosters the learning of the actors involved in the process (Dumont et al., 2020; Rossing et al., 2021). Co-innovation has been implemented to support farmers during processes of technical change, enabling them to improve their farming systems' productive, economic and environmental performance (Dogliotti et al., 2014; Ruggia et al., 2021).

The conceptual model formulated in this paper can be used in a co-innovation approach as a boundary object (Klerkx et al., 2012) to support learning. The conceptual model can be helpful as a guide to cow-calf systems' diagnosis and redesign. It can help diagnose the farms' functioning by focusing on key variables and their relations that explain the results. It allows a dialogue between the farmer practices in the technical sub-system and ecophysiological responses that are part of the biophysical sub-system, which improves the diagnosis of the problems of the farms and their causal relationships. Simultaneously, it allows visualising consequences of redesign options' effects on the state variables (e.g. height and mass of forage and BCS). Therefore, the model can be a tool to support the interactive redesign process between the farmers and technical advisers and facilitate negotiation about system changes in co-innovation processes. Accumulating experiences from such processes will enrich the conceptual model through new scientific knowledge and practical experiences arising from mutual learning between technicians, farmers and researchers.

Conclusions

There is a wide gap between the current and attainable productive and environmental performances of most cow-calf farms in the Campos grasslands. Ecological intensification could reduce this sustainability gap as an alternative to the dominant strategy of external-input intensification. The sustainability gap is a knowledge gap, as demonstrated by farmers' low application of strategic, tactical and decision-support techniques, which results in poor control of the main processes behind forage production and utilisation of energy by animals.

The conceptual model developed in this paper identifies and classifies the main levers farmers have to control forage production and animal energy utilisation and their relation to the farms' productive performance. Applying the model, we proposed three types of farms according to their degree of control of these levers and productive performance. These types represent different challenges for ecological intensification. The conceptual model is a tool that may contribute to the ecological intensification of farms of all types by aiding the interaction between farmers and extension agents during the diagnosis and redesign of farms in the framework of participatory transition processes.

Ethics approval

Not applicable.

Data and model availability statement

None of the data was deposited in an official repository. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence-assisted technologies in the writing process.

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IP: conception, analysis and interpretation of data, writing the first draft, revising and editing the manuscript. **SD, PS** and **WR:** conception, drafting and critically revising the manuscript.

Declaration of interest

None.

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References

Allen, V.G., Batello, C., Berretta, E.J., Hodgson, J., Kothmann, M., Li, X., McIvor, J., Milne, J., Morris, C., Peeters, A., Sanderson, M., 2011. An international terminology for grazing lands and grazing animals. Grass and Forage Science 66, 2–28. https://doi.org/10.1111/j.1365-2494.2010.00780.x.

Armstrong, E., Rodriguez Almeida, F.A., McIntosh, M.M., Poli, M., Cibils, A.F., Martínez-Quintana, J.A., Félix-Portillo, M., Estell, R.E., 2022. Genetic and productive background of Criollo cattle in Argentina, Mexico, Uruguay and the United States. Journal of Arid Environments 200,. https://doi.org/10.1016/j.jaridenv.2022.104722 104722.

Astessiano, A.L., Pérez-Clariget, R., Quintans, G., Soca, P., Carriquiry, M., 2012. Effects of a short-term increase in the nutritional plane before the mating period on metabolic and endocrine parameters, hepatic gene expression and reproduction in primiparous beef cows on grazing conditions. Journal of Animal Physiology and Animal Nutrition 96, 535–544. https://doi.org/10.1111/j.1439-0396.2011.01178.x.

Baeza, S., Paruelo, J.M., 2020. Land use/land cover change (2000–2014) in the rio de la plata grasslands: An analysis based on MODIS NDVI time series. Remote Sensing 12, 1–22. https://doi.org/10.3390/rs12030381.

Beal, W.E., Perry, R.C., Corah, L.R., 1992. The use of ultrasound in monitoring reproductive physiology of beef cattle. Journal of Animal Science 70, 924–929. https://doi.org/10.2527/1992.703924x.

Bilotto, F., Recavarren, P., Vibart, R., Machado, C.F., 2019. Backgrounding strategy effects on farm productivity, profitability and greenhouse gas emissions of cow-calf systems in the Flooding Pampas of Argentina. Agricultural Systems 176,. https://doi.org/10.1016/j.agsy.2019.102688 102688.

Briske, D.D., Heitschmidt, R.K., 1991. An ecological perspective. In: Heitschmidt, R. K., Stuth, J.W. (Eds.), Grazing management an ecological perspective. Timber Press, Portland, OR, USA, pp. 11–26.

Briske, D.D., Sayre, N.F., Huntsinger, L., Fernandez-Gimenez, M., Budd, B., Derner, J. D., 2011. Origin, persistence, and resolution of the rotational grazing debate: Integrating human dimensions into rangeland research. Rangeland Ecology and Management 64, 325–334. https://doi.org/10.2111/REM-D-10-00084.1.

Carámbula, M., 1991. Aspectos relevantes para la producción forrajera: Serie técnica 19. INIA, Montevideo, Uruguay.

Carámbula, M., Ayala, W., Carriquiry, E., Bermúdez, R., 1994. Siembra de mejoramientos en cobertura. Boletín de divulgación n° 46 (ISBN:9974-38-015-4). INIA, Montevide, Uruguay.

Carvalho, P.C.D.F., Fisher, V., dos Santos, D.T., Ribeiro, A.M.L., De Quadros, F.L.F., Castilhos, Z.M.S., Poli, C.H.E.C., Monteiro, A.L.G., Nabinger, C., Genro, T.C.M., Jacques, A.V.A., 2006. Produção Animal no Bioma Campos Sulinos. Brazilian Journal of Animal Science 35, 156–202.

Claramunt, M., Fernandez-Foren, A., Soca, P., 2017. Effect of herbage allowance on productive and reproductive responses of primiparous beef cows grazing on Campos grassland. Animal Production Science 58, 1615–1624. https://doi.org/10.1071/AN16601.

Claramunt, M., Meikle, A., Soca, P., 2020. Metabolic hormones, grazing behaviour, offspring physical distance and productive response of beef cow grazing at two herbage allowances. Animal 14, 1520–1528. https://doi.org/10.1017/S1751731119003021.

Cochran, W., 1977. Sampling techniques. Wiley Series, New York, NY, USA.

Corriher, V.A., Hill, G.M., Andrae, J.G., Froetschel, M.A., Mullinix, B.G., 2007. Cow and calf performance on Coastal or Tifton 85 Bermudagrass pastures with aeschynomene creep-grazing paddocks. Journal of Animal Science 85, 2762–2771. https://doi.org/10.2527/jas.2007-0015.

da Silva, S., Sbrissia, A., Pereira, L., 2015. Ecophysiology of C4 forage grasses—Understanding plant growth for optimising their use and management. Agriculture 5, 598–625. https://doi.org/10.3390/agriculture5030598.

Da Trindade, J.K.D., Neves, F.P., Pinto, C.E., Bremm, C., Mezzalira, J.C., Nadin, L.B., Genro, T.C.M., Gonda, H.L., Carvalho, P.C.F., 2016. Daily forage intake by cattle on natural grassland: Response to forage allowance and sward structure. Rangeland Ecology and Management 69, 59–67. https://doi.org/10.1016/j.rama.2015.10.002.

Darnhofer, I., Fairweather, J., Moller, H., 2010. Assessing a farm's sustainability: Insights from resilience thinking. International Journal of Agricultural Sustainability 8, 186–198. https://doi.org/10.3763/ijas.2010.0480.

Do Carmo, M., Claramunt, M., Carriquiry, M., Soca, P., 2016. Animal energetics in extensive grazing systems: Rationality and results of research models to

improve energy efficiency of beef cow-calf grazing campos systems. Journal of Animal Science 94, 84–92. https://doi.org/10.2527/jas.2016-0596.
Do Carmo, M., Sollenberger, L.E., Carriquiry, M., Soca, P., 2018. Controlling herbage allowance and selection of cow genotype improve cow-calf productivity in Campos grasslands. The Professional Animal Scientist 34, 32–41. https://doi.org/10.15232/pas.2016-01600.
Do Carmo, M., Cardozo, G., Jaurena, M., Soca, P., 2019. Demonstrating control of forage allowance for beef cattle grazing Campos grassland in Uruguay to improve system productivity. Grasslands-Forrajes Tropicales 7, 35–47. https://doi.org/10.17138/tgft(7)35-47.
Do Carmo, M., Cardozo, G., Mecatti, F., Soca, P., Hirata, M., 2020. Number of samples for accurate visual estimation of mean herbage mass in Campos grassland. Agronomy Journal 112, 2734–2740. https://doi.org/10.1002/agj2.20237.
Do Carmo, M., Genro, T.C.M., Cibils, A.F., Soca, P.M., 2021. Herbage mass and allowance and animal genotype affect daily herbage intake, productivity, and efficiency of beef cows grazing native subtropical grassland. Journal of Animal Science 99, 1–9. https://doi.org/10.1093/jas/skab279.
Dogliotti, S., García, M.C., Peluffo, S., Dieste, J.P., Pedemonte, A.J., Bacigalupe, G.F., Scarlato, M., Alliaume, F., Alvarez, J., Chiappe, M., Rossing, W.A.H., 2014. Coinnovation of family farm systems: a systems approach to sustainable agriculture. Agricultural Systems 126, 76–86. https://doi.org/10.1016/j.agsy.2013.02.009.
Doré, T., Makowski, D., Malézieux, E., Munier-Jolain, N., Tchamitchian, M., Tittonell, P., 2011. Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowledge. European Journal of Agronomy 34, 197–210. https://doi.org/10.1016/j.eja.2011.02.006.
Dumont, B., Modernel, P., Benoit, M., Ruggia, A., Soca, P., Dernat, S., Tournadre, H., Dogliotti, S., Rossing, W.A.H., 2020. Mobilising ecological processes for herbivore production: Farmers and researchers learning together. Frontiers in Sustainable Food Systems 4,. https://doi.org/10.3389/fsufs.2020.544828 544828.
Duru, M., Hubert, B., 2003. Management of grazing systems: From decision and biophysical models to principles for action. Agronomie 23, 689–703. https://doi.org/10.1007/978-90-481-2666-8.
Fernández Rosso, C., Bilotto, F., Lauric, A., De Leo, G.A., Torres Carbonell, C., Arroqui, M.A., Sørensen, C.G., Machado, C.F., 2020. An innovation path in Argentinean cow–calf operations: Insights from participatory farm system modelling. Systems Research and Behavioral Science 38, 488–502. https://doi.org/10.1002/sres.2679.
Funston, R.N., Grings, E.E., Roberts, A.J., Tibbitts, B.T., 2016. Invited review: Choosing a calving date. Professional Animal Scientist 32, 145–153. https://doi.org/10.15232/pas.2015-01463.
Gutiérrez, V., Espasandin, A.C., Astessiano, A.L., Casal, A., López-Mazz, C., Carriquiry, M., 2013. Calf foetal and early life nutrition on grazing conditions: Metabolic and endocrine profiles and body composition during the growing phase. Journal of Animal Physiology and Animal Nutrition 97, 720–731. https://doi.org/10.1111/j.1439-0396.2012.01314.x.
Hodgson, J., 1990. Grazing Management: Science into Practice. Longman Scientific and Technical, Harlow, Essex, United kingdom.
Horn, J., Isselstein, J., 2022. How do we feed grazing livestock in the future? A case for knowledge-driven grazing systems. Grass and Forage Science 77, 153–166. https://doi.org/10.1111/gfs.12577.
Iewdiukow, M., Lema, O.M., Velazco, J.I., Quintans, G., 2020. Is it possible to accurately estimate lactation curve parameters in extensive beef production systems? Applied Animal Science 36, 509–514. https://doi.org/10.15232/aas.2019-01965.
Jaurena, M., Lezama, F., Salvo, L., Cardozo, G., Ayala, W., Terra, J., Nabinger, C., 2016. The dilemma of improving native grasslands by overseeding legumes: Production intensification or diversity conservation. Rangeland Ecology and Management 69, 35–42. https://doi.org/10.1016/j.rama.2015.10.006.
Kanter, D.R., Schwoob, M.H., Baethgen, W.E., Bervejillo, J.E., Carriquiry, M., Dobermann, A., Ferraro, B., Lanfranco, B., Mondelli, M., Penengo, C., Saldias, R., Silva, M.E., Soares de Lima, J.M., 2016. Translating the sustainable development goals into action: A participatory backcasting approach for developing national agricultural transformation pathways. Global Food Security 10, 71–79. https://doi.org/10.1016/j.gfs.2016.08.002.
Klerkx, L., van Bommel, S., Bos, B., Holster, H., Zwartkruis, J.V., Aarts, N., 2012. Design process outputs as boundary objects in agricultural innovation projects: Functions and limitations. Agricultural Systems 113, 39–49. https://doi.org/10.1016/j.agsy.2012.07.006.
Landais, E., Deffontaines, J.-P., Benoît, M., 1988. Les pratiques des agriculteurs. Point de vue sur un courant nouveau de la recherche agronomique. Études Rurales 109, 125–158. https://doi.org/10.3406/rural.1988.3226.
Lezama, F., Pereira, M., Altesor, A., Paruelo, J.M., 2019. Grasslands of Uruguay: Classification based on vegetation plots. Phytocoenologia 49, 211–229. https://doi.org/10.1127/phyto/2019/0215.
López-González, F.A., Allende, R., de Lima, J.M.S., Canozzi, M.E.A., Sessim, A.G., Barcellos, J.O.J., 2020. How does the system respond biologically to energy inputs in a long-term horizon? Livestock Science 237,. https://doi.org/10.1016/j.livsci.2020.104058 104058.
Lynam, T.J.P., Stafford Smith, M., 2004. Monitoring in a complex world – Seeking slow variables, a scaled focus, and speedier learning. African Journal of Range and Forage Science 21, 69–78. https://doi.org/10.2989/10220110409485837.
Meikle, A., Carriquiry, M., Soca, P., Sosa, C., Adrien, L., Chilibroste, P., Abecia, J.A., 2018. Influences of nutrition and metabolism on reproduction of the female ruminant. Animal Reproduction 15, 899–911. https://doi.org/10.21451/1984-3143-AR2018-0017.
MGAP, 2016. Resultados de la encuesta Ganadera Nacional 2016. MGAP, Montevideo, Uruguay.
MGAP, 2021. Publicación final Proyecto Ganaderos Familiares y Cambio Climático. Retrieved on 10 Februray 2023 from https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/sites/ministerio-ganaderia-agricultura-pesca/files/2020-10/Publicación final GFCC para web_1.pdf.
Modernel, P., Rossing, W.A.H., Corbeels, M., Dogliotti, S., Picasso, V., Tittonell, P., 2016. Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America. Environmental Research Letters 11,. https://doi.org/10.1088/1748-9326/11/11/113002 113002.
Modernel, P., Dogliotti, S., Alvarez, S., Corbeels, M., Picasso, V., Tittonell, P., Rossing, W.A.H., 2018. Identification of beef production farms in the Pampas and Campos area that stand out in economic and environmental performance. Ecological Indicators 89, 755–770. https://doi.org/10.1016/j.ecolind.2018.01.038.
Molfino, J.H., Califra, A., 2001. Agua disponible de las tierras del Uruguay: segunda aproximación. División Suelos y Aguas Dirección General de Recursos Naturales Renovables Ministerio de Ganadería, Agricultura y Pesca, Montevideo, Uruguay.
Moraes, M.I., 2001. Las determinantes tecnológicas e insitucionales del desempeño ganadero en el largo plazo MSc Thesis. Universidad de la República, Montevideo, Uruguay, pp. 1870–1970.
Nabinger, C., 1997. Eficiência do uso de pastagens: disponibilidade e perdas de forragem. In: Peixoto, A.M., Moura, J.C., Faria, V.P. (Eds.), Fundamentos do pastoreio rotacionado. FEALQ, Piracicaba, Brazil, pp. 213–251.
Nabinger, C., Carvalho, P.C., 2009. Ecofisiología de Sistemas Pastoriles: Aplicaciones para su Sustentabilidad. Agrociencia Uruguay 13, 18–27.
National Research Council (NRC), 2000. Nutrient Requirements of Beef Cattle. National Academy Press, Washington, DC, USA.
Nozières, M.O., Moulin, C.H., Dedieu, B., 2011. The herd, a source of flexibility for livestock farming systems faced with uncertainties? Animal 5, 1442–1457. https://doi.org/10.1017/S1751731111000486.
Paruelo, J.M., Oesterheld, M., Altesor, A., Piñeiro, G., Rodríguez, C., Baldassini, P., Irisarri, G., López-Mársico, L., Pillar, V.D., 2022. Grazers and fires: Their role in shaping the structure and functioning of the Río de la Plata Grasslands. Ecología Austral 32, 784–805. https://doi.org/10.25260/ea.22.32.2.1.1880.
Pauler, C.M., Isselstein, J., Suter, M., Berard, J., Braunbeck, T., Schneider, M.K., 2020. Choosy grazers: Influence of plant traits on forage selection by three cattle breeds. Functional Ecology 34, 980–992. https://doi.org/10.1111/1365-2435.13542.
Perry, G.A., Pas, Cushman, R.A., 2016. Use of ultrasonography to make reproductive management decisions. The Professional Animal Scientist 32, 154–161. https://doi.org/10.15232/pas.2015-01446.
Quintans, G., Barreto, S., Negrín, D., Ayala, W., 2008. Biotipos Carniceros En Pastoreo. APPA–ALPA Conference, 22–25 October 2007, Cusco, Perú, pp. 1–4.
Quintans, G., Viñoles, C., Sinclair, K.D., 2004. Follicular growth and ovulation in postpartum beef cows following calf removal and GnRH treatment. Animal Reproduction Science 80, 5–14. https://doi.org/10.1016/S0378-4320(03)00154-4.
Quintans, G., Banchero, G., Carriquiry, M., Lpez-Mazz, C., Baldi, F., 2010. Effect of body condition and suckling restriction with and without presence of the calf on cow and calf performance. Animal Production Science 50, 931–938. https://doi.org/10.1071/AN10021.
Quintans, G., 2016. Diagnóstico de actividad ovárica: una herramienta que debemos conocer. Revista INIA No 47, 13–14, Montevideo, Uruguay. Retrieved on 10 January 2023 from http://www.ainfo.inia.uy/digital /bitstream/item/6393/1/revista-INIA-47-P-12-13-QUINTANS.pdf.
Rapidel, B., Defèche, C., Traoré, B., Lançon, J., Wery, J., 2006. In-field development of a conceptual crop functioning and management model: A case study on cotton in southern Mali. European Journal of Agronomy 24, 304–315. https://doi.org/10.1016/j.eja.2005.10.012.
Rodríguez Palma, R., Rodríguez, T., 2017. "Campo natural de Basalto: ?'cuánto responde en producción de forraje?," in XXIV Reunión del Grupo Técnico en Forrajeras del Cono Sur-Grupo Campos (Tacuarembó), 57–59. Retrieved on 20 January 2023 from: http://www.ainfo.inia.uy/digital/bitstream/item/7112/1/Grupo-Campo-2017.pdf.
Rossing, W.A.H., Albicette, M.M., Aguerre, V., Leoni, C., Ruggia, A., Dogliotti, S., 2021. Crafting actionable knowledge on ecological intensification: Lessons from co-innovation approaches in Uruguay and Europe. Agricultural Systems 190,. https://doi.org/10.1016/j.agsy.2021.103103 103103.
Royo Pallarés, O., Berretta, E.J., Maraschin, G.E., 2005. The South American Campos ecosystem. In: Suttie, J.M. (Ed.), Grasslands of the World. FAO, Rome, Italy, pp. 171–219.
Ruggia, A., Dogliotti, S., Aguerre, V., Albicette, M.M., Albin, A., Blumetto, O., 2021. The application of ecologically intensive principles to the systemic redesign of livestock farms on native grasslands: A case of co-innovation in Rocha. Uruguay. Agricultural Systems 191,. https://doi.org/10.1016/j.agsy.2021.103148 103148.
Short, R.E., Bellows, R.A., Staigmiller, R.B., Berardinelli, J.G., Custer, E.E., 1990. Physiological mechanisms controlling anestrus and infertility in postpartum beef cattle. Journal of Animal Science 68, 799–816.
Soca, P., Orcasberro, R., 1992. Propuesta de Manejo del Rodeo de Cría en base a estado corporal, altura del pasto y aplicación del destete temporario. In: Evaluación física y económica de alternativas tecnológicas en predios ganaderos (ed. sine nomine). Facultad de Agronomía, Universidad de la República, Paysandú, Uruguay, pp. 54–56.

Soca, P., Ayala, W., Bermudez, R., 2002. The effect of herbage allowance of Lotus pedunculatus cv. Grasslands Maku on winter and spring beef heifer performance. Proceedings of the New Zealand Grassland Association 64, 81–84. https://doi.org/10.33584/jnzg.2002.64.2478.
Soca, P., Claramunt, M., Do Carmo, M., 2007. Sistemas de cría vacuna en ganadería pastoril sobre campo nativo sin subsidios: Propuesta tecnológica para estabilizar la producción de terneros con intervenciones de bajo costo y de fácil implementación. Revista Ciencia Animal, Facultad de Ciencias Agronómicas Universidad de Chile 12, 3–26.
Soca, P., Carriquiry, M., Keisler, D.H., Claramunt, M., Do Carmo, M., Olivera-Muzante, J., Rodríguez, M., Meikle, A., 2013. Reproductive and productive response to suckling restriction and dietary flushing in primiparous grazing beef cows. Animal Production Science 53, 283–291. https://doi.org/10.1071/AN12168.
Stuth, J., Maraschin, G.E., 2001. Chapter 17: Sustainable Management of Pasture and Rangelands. In: Lemaire, G., Hodgson, J., de Moraes, A., Nabinger, C., Carvalho, P. C. de F. (Eds.), Grassland Ecophysiology and Grazing Ecology. CAB International, New York, NY, USA, pp. 339–354.
Tittonell, P., 2014. Ecological intensification of agriculture-sustainable by nature. Current Opinion in Environmental Sustainability 8, 53–61. https://doi.org/10.1016/j.cosust.2014.08.006.
Torell, L.A., Murugan, S., Ramirez, O.A., 2010. Economics of flexible versus conservative stocking strategies to manage climate variability risk. Rangeland Ecology and Management 63, 415–425.
Trujillo, A.I., Casal, A., Peñagaricano, F., Carriquiry, M., Chilibroste, P., 2013. Association of SNP of neuropeptide Y, leptin, and IGF-1 genes with residual feed intake in confinement and under grazing condition in Angus cattle. Journal of Animal Science 91, 4235–4244. https://doi.org/10.2527/jas.2013-6254.
Trujillo, A.I., Orcasberro, R., Beretta, V., Franco, J., Burgueño, J., 1996. Performance of Hereford cows under conditions of varied forage availability during late gestation. In Development of feed supplementation strategies for improving ruminant productivity on small-holder farms in Latin America through the use of immunoassay techniques. Proceedings of the Research Co-ordination Meeting of a Co-ordinate Research Programme organised by the Joint FAO/AIEA Division of Nuclear Techniques in Food and Agriculture, IAEA-TECDOC-877 (ed. sine nomine). IAEA, Vienna, Austria, pp. 69–80.
Ungar, E.D., 2019. Perspectives on the concept of rangeland carrying capacity, and their exploration by means of Noy-Meir's two-function model. Agricultural Systems 173, 403–413. https://doi.org/10.1016/j.agsy.2019.03.023.
Viñoles, C., Gamarra, V., Rodriguez, A., Rocanova, M., 2009. Evaluación de la aptitud reproductiva de los toros previo al entore. In: Una práctica necesaria para mejorar el porcentaje de procreo. Cartilla No 7. INIA, Uruguay. Retrieved on 20 January 2023 from: http://www.ainfo.inia.uy/digi tal/bitstream/item/1132/1/18429200312123057.pdf.
Vizcarra, J.A., Ibañez, W., Orcasberro, R., 1986. Repeatibility and reproducibility of two scales to estimate body condition score in Hereford cows. Investigación Agraria: Sistemas y Recursos Forestales 7, 45–47.