Received: 18 March 2019 | Revised: 15 July 2019 | Accepted: 29 July 2019
DOI: 10.1111/gfs.12445

ORIGINAL ARTICLE

Grass and Forage Science WILEY

Grazing management for more resilient mixed livestock farming systems on native grasslands of southern South America

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Funding information
EACEA (Education, Audiovisual and Culture Executive Agency) of the ; European Commission; CSIC—UDELAR

[Correction added on 08 October after first online publication: Complete list of affiliations is reflected in this version]

Abstract

Droughts in southern South America affect grazing systems in many ways. They reduce biomass productivity; decrease livestock feed intake, weight and reproductive performance; increase farmers' costs; and reduce farm income. It was hypothesized that simple grazing management variables affect the resilience of grazing systems to droughts at the paddock and farm scales. The effects of grazing management on herbage and animal production were assessed at paddock level, and how technological and structural variables relate to the production and economic performances at farm level. Results of a grazing experiment controlling herbage allowance at paddock level showed that resistance of herbage accumulation and animal live weight to drought was significantly higher for paddocks with higher pre-drought herbage allowance than for those managed to low herbage allowance treatments. A strong positive linear relationship was found between pre-drought herbage height and resistance of herbage accumulation rate ($p < .01$). In a longitudinal study of nine farms in Uruguay, resistance of cow pregnancy rate to drought was positively correlated with cow pregnancy rate ($r = .72$, $p = .02$) and farm net income ($r = .78$, $p = .02$), and negatively correlated with sheep-to-cattle ratio ($r = -.80$, $p = .01$). These correlations suggest that farms with higher incomes and low proportions of sheep in the herd withstand drought better (in terms of pregnancy rate). Four common regional production strategies were identified that react differently when farmers face drought, and these results can aid farmers in those regions to design more resilient mixed livestock farming systems and can inform policymakers about effective strategies for mitigating drought impacts in the region.

KEYWORDS
drought, grazing management, livestock farming systems, native grasslands, resilience, Rio de la Plata grasslands

1 | INTRODUCTION

Climate change is a major challenge for food security (Douxchamps et al., 2016; Godfray et al., 2010). Historical climate records and future climate model projections show that variability in annual precipitation is increasing, both at the global and local scales (IPCC, 2013). For instance, in southern South America, weather records for the last 50 years reveal increased variability in rainfall patterns (Barros, Clarke, & Dias, 2006; Marengo et al., 2012). Projecting this trend forward in time, more frequent water deficits are expected

(Shiu, Liu, Fu, Dai, & Sun, 2012). As a result, it is increasingly important to investigate the resilience, resistance and recovery of agricultural systems at multiple hierarchical scales (Grimm & Wissel, 1997; López-Ridaura, Keulen, Ittersum, & Leffelaar, 2005a; Picasso, Casler, & Undersander, 2019). “Resilience” is a key concept in this investigation, and this term refers to the ability of a system to withstand a short-term crisis, perturbation or shock, like a drought (Grimm & Wissel, 1997; López-Ridaura, Keulen, Ittersum, & Leffelaar, 2005b; Picasso et al., 2019); it can be studied by focussing upon two complementary attributes: “resistance”, which is the extent of change due to a crisis, and “recovery”, which is the ability of a system to recover from a crisis (Oliver et al., 2015).

Grazing systems are highly dependent on rainfall, which makes them vulnerable to extreme events like droughts. Droughts are perceived by contemporary farmers as one of the most important shocks stressing their production systems (FAO, 2013). They force farmers to sell cattle at a low price, resulting in economic loss, or may cause the death of animals (Cruz et al., 2018), resulting in more serious economic loss. In response, it was proposed that a resilience-oriented approach may assist contemporary farmers to address the threats of droughts through development of a knowledge system that employs ecological models and science to improve on-farm management (Bestelmeyer & Briske, 2012).

Drought effects cascade through grazing systems: they reduce plant growth, biomass and primary productivity; decrease livestock feed intake, weight and reproductive performance; increase farm production costs; reduce income for farmers; affect rural communities; and even affect nation-scale economies (Ahmed, Azeze, Babiker, & Tsegaye, 2002; FAO, 2013; Paolino, Methol, & Quintans, 2010).

Appropriate grazing management offers an opportunity to buffer the effect of droughts on biodiverse grasslands (Cobon et al., 2009; Thurow & Taylor, 1999). The biodiverse grassland of interest in this study lies in the *Río de la Plata grasslands* region of southern South America. This is a grassland biome with 400 years of livestock rearing history that harbours more than 4,000 native species of C3 and C4 grasses (Soriano, 1992). While species composition is highly diverse and heterogeneous, the most common grass genera are *Poa*, *Bromus*, *Stipa*, *Briza*, *Piptochaetium*, *Paspalum*, *Panicum*, *Bothriochloa*, *Digitaria* and *Setaria* (Bilenca & Miñarro, 2004). In this region, cattle (mostly Britannic Rare Breeds: Hereford and Angus) and sheep (mostly Corriedale and Merino breeds) graze all year round. Overgrazing (Carvalho & Batello, 2009; Gutierrez & Modernel, 2011; Maraschin, 2001; Overbeck et al., 2007) and changing land use are the main threats to this semi-natural agroecosystem (Modernel et al., 2016).

Long-term experiments in Brazil and Uruguay have shown that herbage allowance (kilograms of herbage dry matter available per kilogram of animal live weight) (Allen et al., 2011; Sollenberger, Moore, Allen, & Pedreira, 2005) is a key variable in grazing management that can be regulated to significantly increase current productivity and income (Claramunt, Fernández-Foren, & Soca, 2017; Da Trindade et al., 2012; Do Carmo, Sollenberger, Carriquiry, & Soca, 2018; Soares et al., 2003). Higher herbage allowance corresponds with a taller sward. This, typically, will have greater species diversity (Carvalho et al., 2003; Overbeck, Müller, Pillar, & Pfadenhauer, 2006; Soca et al., 2008) and can be achieved through stocking rate management (Do Carmo, Claramunt, Carriquiry, & Soca, 2016; Sollenberger, 2015). Higher levels of aboveground biomass are related to deeper and denser rooting systems, and these improve the resilience of grasslands to droughts (Bartaburu, Duarte, Montes, Morales Grosskopf, & Pereira, 2009; Norton, Malinowski, & Volaire, 2016; Van Ruijven & Berendse, 2010). As a result, on land with higher herbage allowances, animal live weight is less affected during drought, and fewer farm inputs and fewer farm management economic expenses are needed to withstand the drought (Cobon et al., 2009; FAO, 2013). However, there is a need to translate results generated from these experiments to management recommendations at the farm level (Briske et al., 2008; Teague, Provenza, Norton, & Steffens, 2009). Integrating management variables at paddock level (e.g., herbage allowance) with technological variables at the farm level (e.g., stocking rate) and farm performance (e.g., beef productivity or farm income) is a challenge this paper aims to address.

Here, the relationship between resilience to droughts and grazing management practice at the paddock and farm level was studied. The effects of grazing management on herbage and animal production were assessed at paddock level, and how technological and structural variables relate to the production and economic performances at farm level. An investigation was made of the effect of grazing management on a series of resilience metrics at these two hierarchical levels where farmers make their management decisions. Hypotheses were:

1. at the paddock level, higher herbage allowance increases resilience of grazing systems to drought; that is, grazing systems resist and/or recover faster after the drought in terms of grass and animal productivity when managed at higher herbage allowance;
2. at the farm level, lower stocking rates increase the resilience of livestock reproductive and productive parameters and economic indicators to drought.

2 | MATERIALS AND METHODS

2.1 | Study region and farming systems

Uruguay is part of a large biome known as the *Rio de la Plata grasslands*, where native grasslands and cattle have coexisted for the last 400 years. There is a high diversity of farming systems in the region (Modernel et al., 2018), but two main types of farms can be distinguished: reproduction or “cow–calf” and meat production or “finishing” farms (Becoña, Astigarraga, & Picasso, 2014; Modernel et al., 2016). This study focused on cow–calf systems, which represent 53% of farming systems in the country (MGAP, 2015). The main income of cow–calf farms comes from selling calves and culled cows. As a result, pregnancy rate is a key production factor. Native grasslands typically provide 90%–100% of the diet of these animals. As complementary income, these farms also raise sheep for wool or meat production, giving rise to mixed grazing systems where sheep and cattle compete for the native grasslands as feed resource (Paparamborda, 2017; Ruggia et al., 2015). Finishing farms mainly fatten male calves that may be fed on native grasslands, leys or grains (feedlots) (Modernel, Astigarraga, & Picasso, 2013). Precipitation in the *Rio de la Plata grasslands* region is highly variable between and within years (Barros et al., 2006; Caffera, 2005) with recurrent spring–summer droughts (Cruz, Baethgen, Picasso, & Terra, 2014). One of the most severe droughts in the last 30 years in Uruguay occurred in the spring–summer of 2008–2009 (Cruz et al., 2014; Paolino et al., 2010) (Figure 1).

2.2 | Resilience metrics

The concept and theoretical framework of "resilience" have evolved since Holling (1973) first defined it (Ives & Carpenter, 2007). Many efforts have also been undertaken to operationalize resilience metrics in agricultural literature (van Apeldoorn, Sonneveld, & Kok, 2011; Cabel & Oelofse, 2012; Darnhofer, Fairweather, & Moller, 2010; Groot, Cortez-Arriola, Rossing, Massiotti, & Tittonell, 2016; López-Ridaura, van Keulen, et al., 2005b; Picasso et al., 2019; Tittonell, 2014; Van Ruijven & Berendse, 2010). Here, effects of varying grazing managements on the productivity of grazing systems responding to a perturbation (drought) were analysed. Two resilience metrics were selected for this purpose: resistance (Walker, Holling, Carpenter, & Kinzig, 2004) and recovery (Holling, 1996; Urruty, Tailliez-Lefebvre, & Huyghe, 2016). Resistance was determined as the magnitude of the effect of a perturbation on the system (e.g., how much the productivity decreased during the drought relative to a normal weather situation). This was calculated as the ratio between the state of the response variable during the drought and a previous normal season, for instance, herbage mass during the season of drought divided by herbage mass during the same season of the previous year with normal weather (Figure 2a). Recovery was determined as the speed at which the system came back to a previous stable state after the drop caused by the perturbation. It was calculated as the slope of the variable against time after the perturbation, for instance, the increase in herbage mass between the season of drought and the season after the drought divided by the period of time (Figure 2b). While resistance is unitless, recovery is expressed in the units of the variable per unit of time (i.e., season or year).

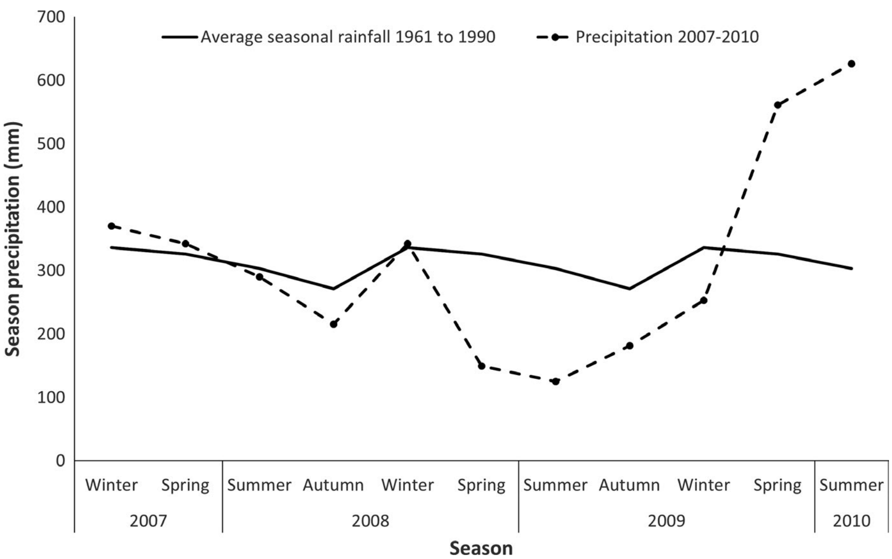

FIGURE 1 Thirty-year average seasonal rainfall (continuous line) and 2007–2010 seasonal rainfall (dotted line) in Treinta y Tres (−33°15′S, 54°28′, eastern Uruguay). Data from INUMET (2018)

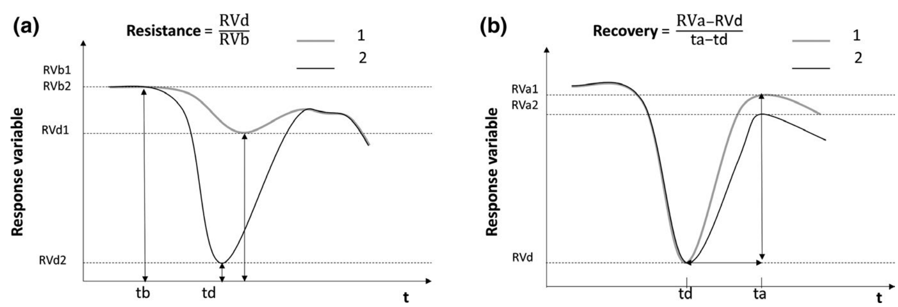

FIGURE 2 Metrics used for the assessment of resilience. The behaviour of a response variable is depicted for two different systems 1 and 2 (grey and black lines). (a) Calculation of resistance (higher for system 1 than system 2); (b) Calculation of recovery (faster for system 1 than system 2). RVb: response variable before drought; RVd: response variable during drought; RVa: response variable after drought; tb: time before drought; td: time during drought. ta: time after drought

2.3 | Case studies

The resilience analysis was performed in the *Rio de la Plata grasslands* region in Uruguay for two case studies at two different levels: paddock and farm (Figure 3).

2.3.1 | Paddock-level analysis

An experiment to assess the effect of herbage allowance on native grassland and animal performance was carried out at the "Prof. Bernardo Rosengurtt" experimental station in Cerro Largo (Uruguay) (32°35′S, 54°15′W, 160 m) between June 2007 and February 2010. The experimental area comprised 92 ha, and the experimental design consisted of randomized blocks, with two replicates in each block, and eight paddocks in total. Blocks were selected by soil type: clayey soils (Argiudolls) and sandy soils (Hapluderts and Argiudolls). The management variable at paddock level was herbage allowance. This metric is used in grazing experiments because it can be directly related to animal performance since it describes the quantity of herbage per unit of animal weight. Two treatments were applied: low (3.5 kg dry matter [DM] kg^{-1} live weight [LW]) and high (5 kg DM kg^{-1} LW) herbage allowance (hereafter referred as LHA and HHA respectively). The LHA treatment mimicked the typical management in most of the farms of the country (overgrazing), while the HHA treatment aimed to match the herbage availability with animal nutritional demands. Herbage accumulation rate (kg DM ha day^{-1}), herbage mass (kg DM/ha), herbage height (cm), stocking rate (kg LW ha^{-1} year^{-1}), cow body condition score, cow weight (kg LW) and calf weight at weaning (kg LW) were measured at intervals ranging from 19 to 61 days between 2007 and 2010. At the beginning of each measurement period, herbage availability (kg DM ha^{-1}) was measured in order to allocate the animal live weight required to fit the herbage allowance levels previously defined. This means that the number of cows (and thus the stocking rate) changed from one measurement period to the next. Detailed experimental measurements and results were reported by Soca et al. (2008) and Do Carmo et al. (2018).

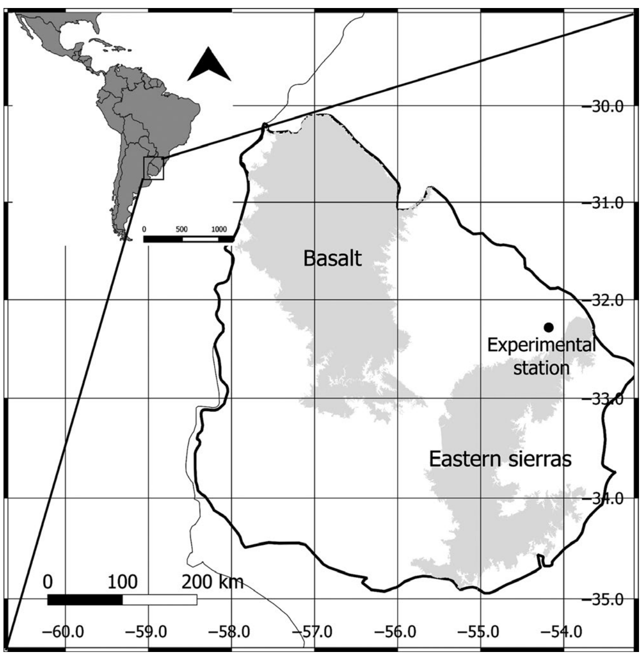

FIGURE 3 Location of the case studies in Uruguay. The resilience analysis at paddock level was done with data from the experimental station. The analysis at farm level with farm survey data from the North (Basalt) and East (Eastern Sierras) regions. (grey shadow)

Herbage mass and height were quantified using the comparative yield method (Haydock & Shaw, 1975). Ten reference quadrats were used for calibration, and 100 randomly selected quadrats were rated at each measurement date on each paddock (Table 1). Herbage height was measured in the quadrat, and standing biomass was cut to ground level to quantify herbage mass. Herbage accumulation rate was measured by means of exclusion cages with a surface area of 0.25 m^2. As described by Do Carmo et al. (2018), in each paddock two areas of 0.25 m^2 were selected with similar herbage mass. In one area, herbage height was measured, and herbage was cut to soil level and weighed after drying at 60°C until constant weight. The second area was covered by a cage to exclude grazing until the end of the exclusion period (between 23 and 111 days). At the end of the exclusion period, herbage biomass was harvested, dried and weighed in the same way as for the first area. The difference in herbage mass between the sampling dates was defined as herbage accumulation ('T Mannetje, 1978). Cows were weighed at the beginning of each exclusion period, and the weight was averaged per animal per paddock. The animal live weight gain was calculated as the difference of the animal weight of each animal between consecutive periods, divided by the number of days of the period.

Resistance to drought was calculated for herbage accumulation rate and animal live weight gain as the ratio between the average of spring–summer 2008–2009 (drought) and the average of spring–summer 2007–2008 (before drought) (Figure 2). Recovery from drought was calculated for each measured variable as the slope of the regression line between the averages of the spring of the drought year and the winter after the drought.

2.3.2 | Farm-level analysis

Longitudinal data of nine livestock farms included productivity records from at least 3 years before and after the drought of the spring–summer of 2008–2009 and were collected by the National Livestock Extension Agency in Uruguay (Instituto Plan Agropecuario). These farms were selected since they are broadly representative of the typical farm types of the region, and have reported productive and economic information for 6 years. The farms are located in two regions, one in the north (*Basalt*) and the other one in the East (*Eastern Sierras*) of Uruguay (Modernel et al., 2016) (Figure 3), and manage mixed beef cattle and sheep, grazing on native grasslands (Table 1). The two regions were selected because the land use in both regions was predominantly native grasslands (more than 80%) and because they encompassed most cattle farmers in Uruguay (65%). The variables studied on these cow–calf operations were cow pregnancy rate, equivalent meat productivity and farm net income (gross income

TABLE 1 Sampling methods, mean, coefficient of variation (CV), minimum (Min) and maximum (Max) values for the studied variables at paddock level

Variable	Samples per paddock	Method	Mean	CV (%)	Min	Max
Herbage height (cm)	10 reference quadrats for calibration; 100 randomly selected quadrats	Comparative yield method (Haydock and Shaw, 1975)	6.3	82	0.5	35.6
Herbage biomass (kg DM ha^{-1})			3,017	79	160	16,444
Herbage accumulation rate (kg DM ha day^{-1})	32 exclusion cages of 0.5 × 0.5 m	'T Mannetje (1978)	13.4	103	0	85
Animal weight (kg)	1–24 animals	Individual weight measurement	438	14	307	602

minus direct costs). The equivalent meat productivity is a metric used in Uruguay to compare different production systems with variable proportions of sheep and cows in the herd. The metric transforms the energy of beef, wool and lamb into a single unit (beef kg LW + lamb kg LW + 2.5 × kg wool) (Oficialedgui, 1985). Resistance of pregnancy rate and productivity to drought was calculated as the ratio between the drought year (2009) and the average values of the farm during the previous 1–3 years, depending on data availability of each farm. Recovery of pregnancy rate and productivity from drought was calculated as the slope of the regression between the year of the drought (2009) and the next year (2010).

2.4 | Statistical analysis

Analysis of variance (ANOVA) was used to evaluate differences in resistance and recovery between herbage allowance treatments at paddock level. Correlation matrices were calculated for all variables (at paddock and farm levels, respectively) to explore relationships between management variables and output variables. All analysis was performed using the "stats" R package (R Core Team, 2015).

3 | RESULTS AND DISCUSSION

3.1 | Paddock level

3.1.1 | Herbage accumulation and animal weight

The herbage accumulation rate was the lowest in winter and highest in spring and summer respectively (Figure 4a). The effect of drought is more evident from the lower values in the spring–summer of 2008–2009 than in the prior and posterior spring–summer seasons. Animal live weight changed in a similar way to the herbage accumulation rate (Figure 4b). Animals lost weight during winter and gained weight in spring–summer before and after the drought. During the spring–summer of 2008–2009, animals lost weight due to the drought-induced reduction of the herbage accumulation rate, the herbage mass and, consequently, the herbage feed intake of the animals.

High (HHA) and low herbage allowance (LHA) treatments generated different responses to drought. Animal weight was higher for HHA than LHA ($p < .05$) in all the measurement periods after spring 2008 and over the entire experimental period (Table 2). Similarly, herbage height and accumulation rate were significantly higher for HHA than LHA over the 3-year experimental period (Table 2) (Do Carmo et al., 2018).

3.1.2 | Drought resistance and recovery

Resistance of herbage accumulation and animal live weight to drought was significantly higher for HHA than LHA ($p < .01$) (Table 4). Herbage accumulation rate during the drought was on average 66% and 46% of the rates in normal spring–summer seasons for HHA and LHA respectively. While this reduction is an immediate problem during the drought period, it also has longer lasting effects on herbage availability, since spring–summer is the season when most of the herbage accumulation occurs (Berretta, Risso, Montossi, & Pigurina, 2000; Risso, Ayala, Bermúdez, & Berretta, 2005; Soriano, 1992). Animal live weight during the drought was 98% and 94% of the weights in normal spring–summer seasons for HHA and LHA respectively.

Recovery of herbage accumulation rate was on average 3.37 kg DM/ha day^{-1} season^{-1}, representing an accumulation of 306 kg DM in one season, not different between herbage allowance treatments ($p < .05$, Table 4). Recovery of annual live weight was on average 19.4 kg

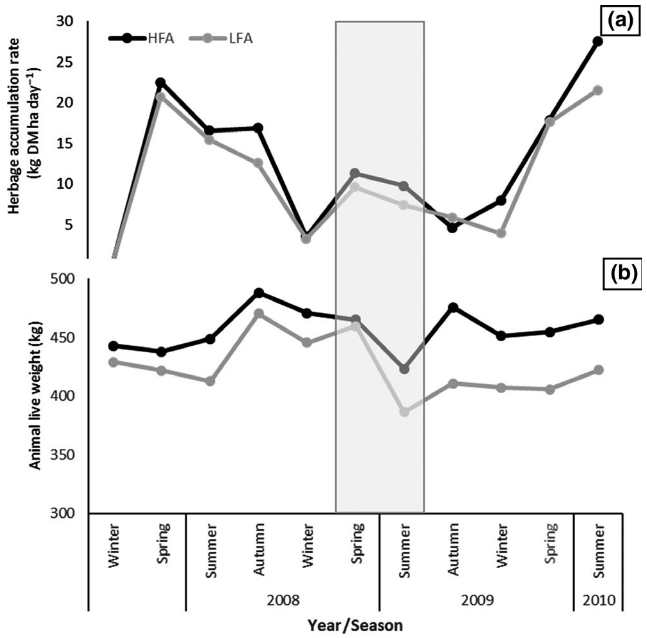

FIGURE 4 Herbage accumulation rate (a) and animal live weight (b) for high (HHA) and low (LHA) herbage allowance treatments. Points indicate average values per season. The black line corresponds to high herbage allowance; the grey line indicates low herbage allowance. The grey shadow area indicates the drought period. Adapted from Do Carmo et al. (2018)

TABLE 2 Mean, coefficient of variation (CV), minimum (Min) and maximum (Max) for selected variables of the studied farms

Variable	Mean	CV (%)	Min	Max
Soil productivity index[a]	103	64	58	270
Grazing area (ha)	621	55	157	1100
Area improved pastures (%)	10	77	0	23
Cattle stocking rate (LU/ha)	0.53	29	0.31	0.77
Sheep stocking rate (LU/ha)	0.26	78	0.02	0.57
Total stocking rate (LU/ha)	0.81	21	0.62	1.17
Sheep-to-cattle ratio[b]	2.9	88	0.1	7.6
Cow pregnancy rate (%)[c]	74	11	64	84
Meat productivity (kg/ha)[d]	87	21	65	121
Net income farm (US$/ha)[e]	19	88	−65	98
Input-to-output ratio[f]	0.79	73	0.29	3.4

Abbreviations: LU, livestock unit (a cow of 380 kg).
[a]'CONEAT' index, used in Uruguay as a proxy for soil quality (MGAP, 2018). The average index for the country is 100.
[b]In livestock units.
[c](Weaned calves/served cows) × 100.
[d]In equivalent meat productivity (beef kg LW + lamb kg LW + 2.5 × kg wool).
[e]Gross income − direct costs.
[f]Ratio between costs (input) and income (product).

LW season^{-1}, representing gains of 0.21 kg LW/day after the drought, not different between herbage allowance treatments (Table 4). This suggests that regardless of the grazing management methods, grazing systems in native grasslands can recover quickly when rainfall resumes after drought. While this experimental result suggests the good resilience of Uruguay's grasslands, we caution that this condition might change under conditions of long-term overgrazing (under LHA). Conditions that might affect resilience include the appearance of areas of bare soil, induced soil erosion (Roesch Wurdig et al., 2009) and invasion of non-productive non-native species (such as *Eragrostis plana* Nees) (Bresciano, Rodrigues, Lezama, & Altesor, 2014; Focht & Borges de Medeiros, 2012). These were not, however, observed during our experiment.

A strong positive linear relationship was found between pre-drought herbage height and resistance of herbage accumulation rate ($p < .01$, Figure 5). Resistance, or the ratio between herbage accumulation rate during and before the drought, was greater in paddocks where high herbage heights were maintained (HHA), exhibiting productivity values that ranged between 60% and 70% of the average productivity in the seasons before the drought. In contrast, in paddocks managed with LHA, herbage accumulation rate during drought ranged between 35% and 55% of average productivity before the drought. Pre-drought herbage height is therefore a good predictor of grassland resistance to drought (Figure 5), and LHA paddocks clearly suffered greater reductions than HHA paddocks.

Vogel, Scherer-Lorenzen, and Weigelt (2012) found similar results in an experiment designed to measure the effect of management on resistance to drought. They artificially simulated a prolonged summer drought in plots with different: numbers of grass species (1–60) and management intensity (four levels of mowing frequency and fertilizer doses). Their main conclusion was that moderate grazing intensity with higher herbage height improves the resistance of the grassland when faced with a drought.

Our field observations confirm that weather forecasts and early warning systems provide farmers with relevant information needed to face an upcoming drought and to make mediating decisions (Ahmed et al., 2002; Bestelmeyer & Briske, 2012; Cruz et al., 2018), and our experiment suggests that the pre-drought status of the herbage mass/height should be taken into account. According to our results, an increase of one cm in herbage height reduces the impact of drought on herbage accumulation rate by 20% (Figure 5). Managing grazing systems to HHA seems to give farmers and farms the capacity to better maintain herbage productivity and to better withstand the drought.

Differences in resistance between HHA and LHA were found for animal live weight (Table 3). These indicate that animals were able to withstand the drought and lose less weight under HHA. This could be a result of either the higher pre-drought herbage mass (represented by height) of the HHA treatment or the higher accumulation rate observed during the drought in the HHA. Both allow for greater herbage intake in HHA during the drought. This observation confirms other studies, whose overall results show that higher HHA increases animal productivity as a whole (Claramunt et al., 2017; Do Carmo et al., 2018).

3.2 | Farm level

3.2.1 | Meat productivity, cow pregnancy rate and farm income

The average behaviour of the farms showed that cow pregnancy rate and meat productivity decreased from 2007 to 2009 by 15% and 11%, respectively, and recovered from 2009 to 2010 (Figure 6). Farm net income decreased from 2007 to 2008 and increased from 2008 to 2010.

TABLE 3 Average values, standard errors and P-values (ANOVA) of herbage height, herbage accumulation, stocking rate and animal live weight for contrasting herbage allowance treatments in a 3 years experiment in eastern Uruguay reported by Do Carmo et al. (2018)

Variable	HHA	LHA	Standard Error	*p*-Value
Herbage height (cm)	5.5	3.5	0.2	<.05
Herbage accumulation (kg DM ha^{-1} day^{-1})	15.0	12.5	1.1	<.05
Stocking rate (kg LW ha^{-1} year^{-1})	382	398	7.0	NS
Animal live weight (kg)	453	425	3.9	<.05

Abbreviations: HHA, high herbage allowance (5.0 kg dry matter [DM] kg^{-1} live weight [LW]); LHA, low herbage allowance (3.5 kg dry matter [DM] kg^{-1} live weight [LW]).

TABLE 4 Average values and *p*-values (ANOVA) of resistance and recovery of herbage accumulation rate and animal live weight for contrasting herbage allowance treatments in a 3 years experiment in eastern Uruguay reported by Do Carmo et al. (2018)

	Herbage accumulation rate			Animal live weight		
	HHA	LHA	*p*	HHA	LHA	*p*
Resistance[a]	0.66	0.46	.03	0.98	0.94	<.01
Recovery[b]	3.08	3.65	NS	20.8	18.1	NS

Abbreviations: HHA, high herbage allowance; LHA, low herbage allowance.
[a]Resistance is a ratio of values during drought and before drought with same units, therefore unitless.
[b]Recovery is calculated as difference between after drought and during drought response variable over time (season). Units: kg DM ha day^{-1} season^{-1}; and kg animal live weight season^{-1}.

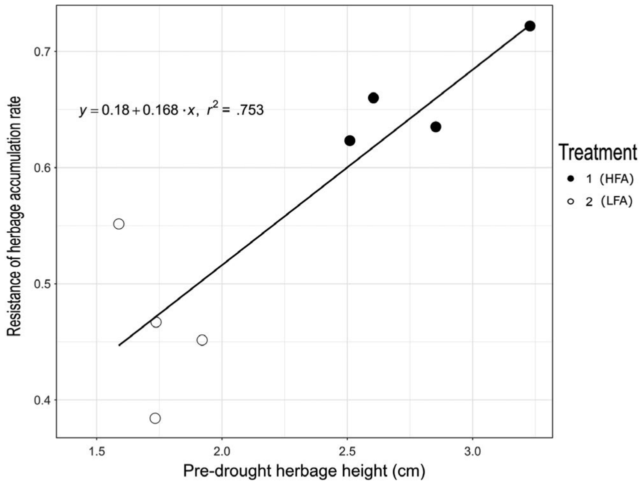

FIGURE 5 Resistance of herbage accumulation rate to drought versus herbage height one month before the drought. Closed circles indicate paddocks managed at high herbage allowance (HHA), and open circles indicate paddocks managed at low herbage allowance (LHA). The regression is significant at $p < .01$

Interestingly, the year when pregnancy rate and productivity reached a minimum (2009) was different from the year when farm income was minimum (2008). This finding may be understood, at least in part, as a data-reporting artefact, because the farm-economy variables are reported in fiscal years (from July 1st to June 30th). The drought period lasted from October 2008 to February 2009, corresponding to the fiscal year 2008. The pregnancy rate after the drought was measured in the calving season (September–November) 2009 and therefore reported in the fiscal year 2009. The meat productivity affected was therefore the one from 2009. However, the higher expenses (costs) to withstand drought occurred during the fiscal year 2008.

Cow pregnancy rate was affected by the drought because lower herbage growth and supply caused weight loss of the animals. The drought particularly affected cow–calf systems since it occurred during the mating season (December–February), when the nutritional status of the cows strongly determines the pregnancy rate (Do Carmo et al., 2016; Soca & Orcasberro, 1992). Farm meat productivity is a direct function of pregnancy rate, since the most important product of these farms are calves, and lower pregnancy rates mean fewer calves, less livestock to market and lower meat productivity (Paparamborda, 2017).

3.2.2 | Drought resistance and recovery

While farm income is one of the most relevant variables required to understand the sustainability of farming systems, it was not considered in the present investigation of resistance and recovery because many confounding variables can affect the report of farm income. As a result, the resistance and recovery analysis were conceptualized using indices of cow pregnancy rate and meat productivity. These variables may be understood as both an independent (at the beginning of the drought period) and dependent variables (at the end of the drought) in our conceptualization of this process.

Resistance of cow pregnancy rate was positively correlated with pregnancy rate ($r = .72$, $p = .02$) and farm net income ($r = .78$, $p = .02$) (Table S1) and negatively correlated with sheep-to-cattle ratio ($r = -.81$, $p = .01$) (Figure 7). These correlations suggest that farms with average high incomes and a low proportion of sheep in the herd withstand the drought better in terms of pregnancy rate.

In order to study the “highest” level in our analytic hierarchy, the farm, the nine farms were classified into four groups according to two criteria: region (North Basalt vs. Eastern Sierras, Figure 3) and resistance of pregnancy rate and productivity to drought (low vs. high). The structural variables of the farms were then analysed to identify different strategies that might explain the differences.

Group 1 comprises farms located in the north, with a low proportion of sheep in the herd, high resistance of pregnancy rate and meat productivity to drought, and high average pregnancy rates (farms *North 1* and *North 2*). *Group 2* comprises farms from the north (*North 3*, *North 4* and *North 5*) with low resistance of pregnancy rate to drought and high proportion of sheep in the herd. *Group 3* comprises farms from the Eastern Sierras, with high resistance of pregnancy rate to drought, but not of meat productivity and high levels of improved pastures (*East 1* and *East 2*). Finally, *Group 4* comprises farms (*East 3* and *East 4*) which present high levels of resistance of pregnancy rate and meat productivity to drought. These farms present moderate levels of improved pastures and low sheep-to-cattle ratios.

Group 1 Extensive cattle farmers from the north. (North 1 and North 2)

These farms show relatively high resistance of cow pregnancy and meat productivity to drought. They share the same geographic location, similar low stocking rates, high meat productivity, a moderate sheep-to-cattle ratio and moderate recovery of meat productivity from drought. Both farms are among those with the highest incomes and the lowest input-to-output ratios. This group demonstrates that it is possible to achieve high productivity levels, resistance, recovery and income simultaneously. Its pregnancy rate was 81% on average,

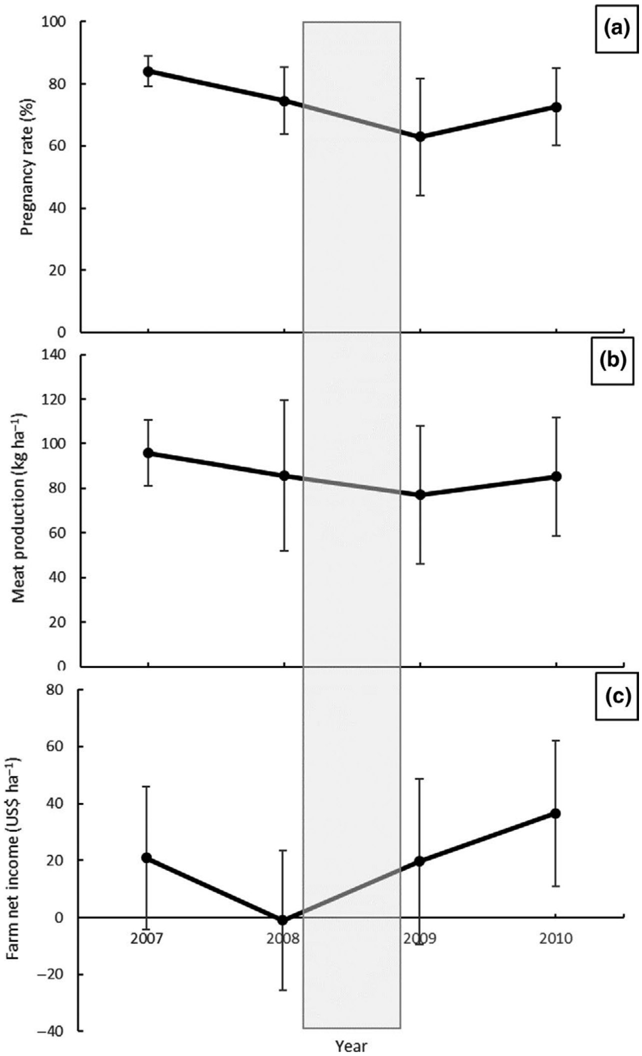

FIGURE 6 Pregnancy rate (a), meat productivity (b) and farm net income (c) for the nine livestock grazing farms during 4 years in Uruguay. Vertical lines indicate standard deviations. The grey shadow area indicates the drought period

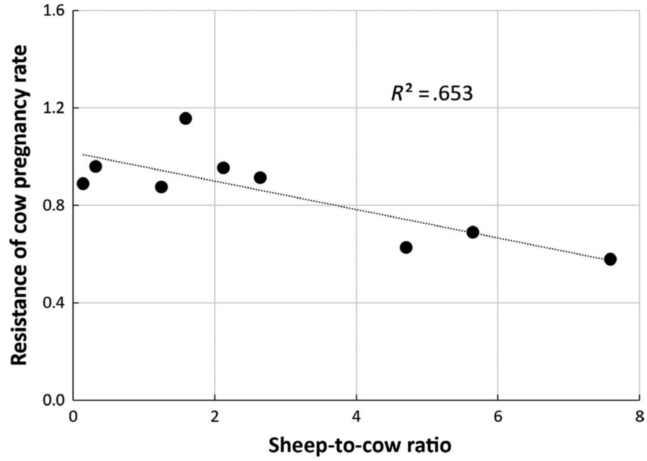

FIGURE 7 Sheep-to-cow ratio and cow pregnancy rate for nine farms in the Basalt and Eastern Sierras regions of Uruguay. The straight line and equation indicate the linear regression between variables. The regression is significant at $p < .01$

and Figure 8a,b shows the behaviour of *North 1* over time. The figure shows that meat productivity decreased in 2008 but increased sharply in 2009 (Figure 8b). While farm net income was low during 2008 and 2010, the group's low input-to-output ratio (Table 4) maintains farm income at reasonable levels compared to the entire population of farms.

Group 2 Sheep-oriented farmers from the north

These farms (*North 3*, *North 4* and *North 5*) show the lowest resistance (through cow pregnancy rates) and variable resistance of meat productivity. This group of farms represents traditional cow–calf farms, coupled with a high proportion of sheep in the herd, and a low percentage of improved pastures (Table 4). Farms belonging to this group have high stocking rates (hence low herbage allowances), low cow pregnancy rates, the lowest incomes, the lowest resistance of pregnancy rate and variable resistance of meat productivity. This type of farm configuration is very common on shallow basaltic soils of the north of the country and usually shows low levels of productivity and income (Paparamborda, 2017). This farm type was more common in the 1990s, but most of the farms converted from sheep to cattle production after the global drop in wool prices (Waquil, 2013). A common strategy among thee farms, during droughts, is to accumulate sheep, because they harvest forage at lower herbage heights and are less affected by drought than cattle (Nunes Gonçalves, 2007). These farms display high input-to-output ratios, even though they usually have relatively low production costs. The low output in terms of productivity reduces farm net income (Table 5). Farm *North* 3, for example, displays pregnancy rates that decrease, down from levels around 80% to 50% in 2009 (Figure 8c). Those low rates did not recover after the drought. Productivity levels decrease towards 2009 but recover afterwards (Figure 8c). The trend in farm net income is similar to that of meat productivity, with lower values in 2008 than in 2007 and recovery afterwards (Figure 8d). The input-to-output ratio increases from 2007 to 2008. While meat productivity levels were relatively high (110–130 kg LW/ha), these did not translate into higher income. This may be explained by the fact that 50% of the productivity of the farm consisted of sheep meat (30%) and wool (20%), which have considerably lower market prices than beef.

Group 3 Intensive cattle farmers on improved pastures

These farms have high resistance of cow pregnancy but low resistance of meat productivity to drought. For instance, *East 1* had the highest resistance of pregnancy rate (1.16), which means that, in contrast with the other farms, pregnancy rate increased during the drought (Table 4). While pregnancy rate was not affected during the drought year, possibly because the farm sold cows with low body condition, or supplemented grazing with external feeds (Figure 8e), meat productivity was the lowest. This type of farm represents the highest input-to-output ratio within our sample, which means that, on average over the 3 years,

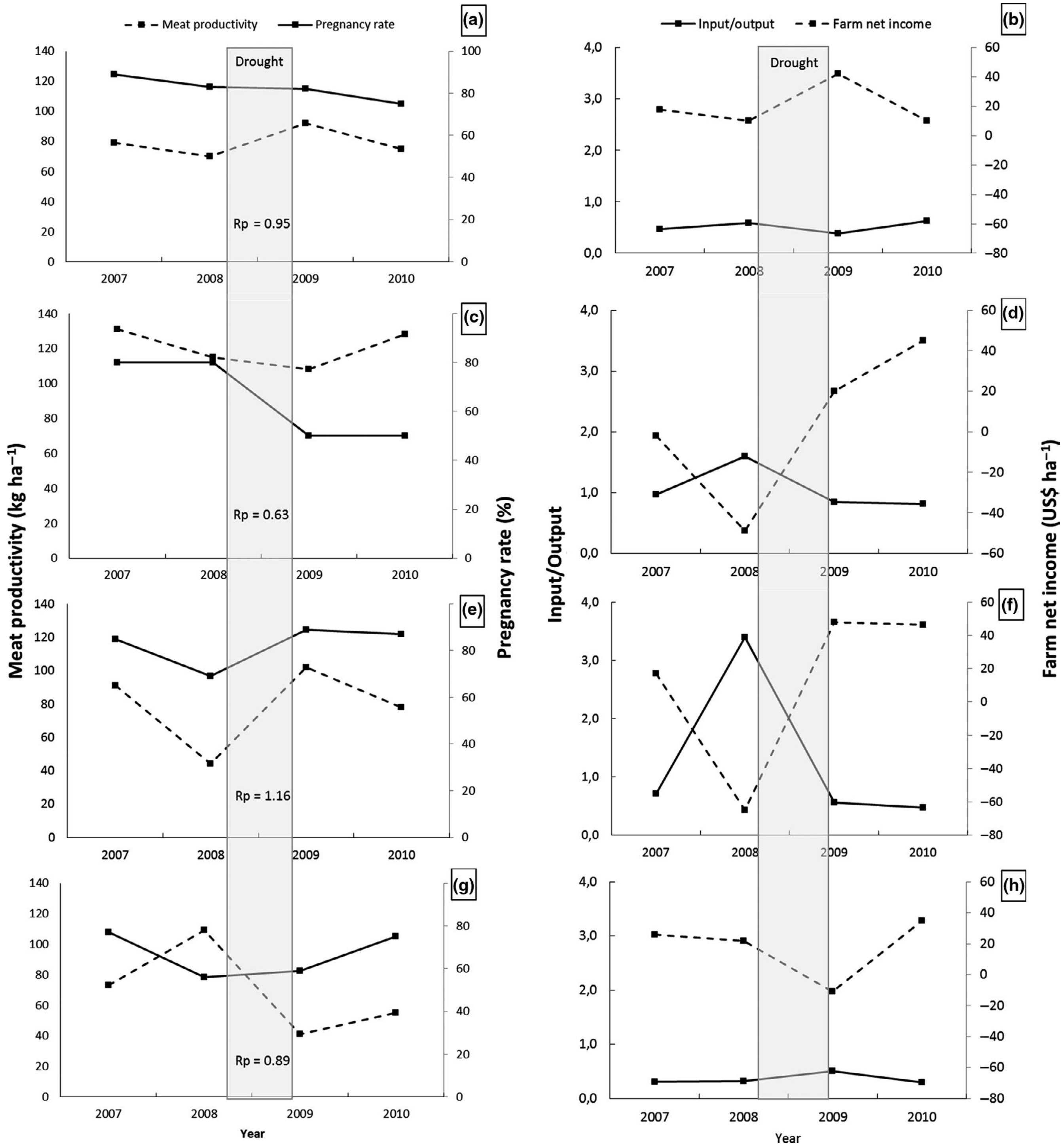

FIGURE 8 Trajectories of cow pregnancy rate (%), meat productivity (kg LW/ha), input/output ratio and farm net income (kg US$ ha^{-1}) for farms North 1 (a and b), North 3 (c and d), East 1 (e and f) and East 3 (g and h) during the period 2007–2010. Panels on the left indicate meat productivity (full lines) and pregnancy rate (dashed lines). Panels on the right indicate economic input–output ratio (full lines) and farm net income (dashed lines). Resistance indicators are identified for each farm as Rp (resistance pregnancy rate) and Rm (resistance meat productivity)

this type spent 29% more of its gross farm income than the other farm types (Table 4). While farm income is, on average, positive, the large fluctuations between years suggest high vulnerability to external shocks. Deeper investigation showed that this type of farm followed a conventional intensification pathway proposed for the region, that is to increase productivity and farm income through higher inputs (expressed by the fact that 23% of the grazing area is under sown pasture as opposed to native grassland). The high investment needed for improving the herbage quantity and quality in the long term increases the financial risk of the farm, and the exotic grass and legume species

TABLE 5 Structural and management variables, resistance and recovery for each farm of the study. Structural and management variables calculated as averages for the period 2007–2010

	North 1	North 2	North 3	North 4	North 5	East 1	East 2	East 3	East 4
Group	1	1	2	2	2	3	3	4	4
Soil productivity index[a]	63	109	101	64	120	88	270	58	58
Grazing area (ha)	1100	696	157	990	398	354	247	904	743
Area improved pastures (%)	0.0	8.0	4.0	6.0	5.4	23	22	12	12
Stocking rate (LU/ha)	0.6	0.6	1.2	0.7	0.9	0.7	0.9	0.8	0.8
Sheep-to-cattle ratio[b]	2.1	1.3	4.7	5.7	7.6	1.6	2.7	0.1	0.3
Cow pregnancy rate (%)[b]	81	81	65	69	64	81	84	69	69
Meat productivity (kg/ha)	84	89	121	73	90	82	109	71	65
Farm net income (US$/ha)	35	17	4.0	8.0	-8.0	19	31	22	16
Input-to-output ratio[b]	0.44	0.61	1.06	0.81	0.93	1.29	0.72	0.36	0.72
Resistance of pregnancy rate	0.95	0.88	0.63	0.69	0.58	1.16	0.91	0.89	0.96
Resistance of meat productivity	0.93	0.90	0.88	0.86	1.26	0.48	0.81	1.60	0.99
Recovery of pregnancy rate	-7.0	22	0.0	15	28	-2	-11	16	26
Recovery of meat productivity	7.0	2.0	20	9.0	-7.0	-24	21	14	31

Abbreviation: LU, livestock unit.

[a]'CONEAT' index, used in Uruguay as a proxy for soil quality (MGAP, 2018). The average index for the country is 100.

[b]Ratio between costs (input) and income (product).

sown may be less adapted to recurrent drought and less resistant to these events, risking productivity. While this intensification pathway has been promoted as "sustainable intensification" from an economic and environmental perspective (Dick, Abreu da Silva, & Dewes, 2015; de Oliveira Silva et al., 2016; Pashaei et al., 2016), recent studies show that higher productivity does not necessarily translate in higher income, and can even worsen environmental performance as measured by biodiversity, fossil fuel energy consumption and nutrient balances (Modernel et al., 2018).

Group 4 Extensive cattle farmers of the east

These farms (*East 3* and *East 4*) have high resistance of cow pregnancy and meat productivity to drought. Both farms show similarities with the farmers of the north given the highest levels of resistance of pregnancy rate and productivity and high levels of farm income. On the other hand, they differ in structural variables. This type of farms has lower sheep-to-cattle ratios, higher stocking rate and higher area of improved pastures than *Group 1* farms. Interestingly, the pregnancy rates and productivity levels are among the lowest of the entire population of farms. Farm *East 3* illustrates this. The pregnancy rate decreased from 2007 to 2008 and continued at low levels in 2009. Meat productivity was strongly affected by the drought (63% decrease) but recovered, although at lower levels than before the drought (Figure 8).

3.3 | Integration of paddock and farm level

Two main findings arise from this study. First, managing herbage allowance at the paddock level increases resistance of herbage accumulation and animal weight to drought. Second, at the farm level, managing (and minimizing) the sheep-to-cow ratio is highly related to increasing resistance of cow pregnancy rate to drought.

The correlations are valid for the nine farms that represent four "idealized" farm types in Uruguay. They suggest interesting systemic relations. We would suggest caution in the acceptance of the findings; the more interesting findings must be further investigated and cannot be generalized without further evidence.

Nevertheless, this analysis at the farm level constitutes, as far as the authors know, the first drought-related resilience assessment of native grassland-based farming systems. Four farm production strategies were identified that result in different responses to drought. These include: implementing low stocking rates (*Group 1*), maintaining high proportions of sheep in the herd (*Group 2*), increasing the amount of herbage biomass through improved pastures (*Group 3*) and keeping only cattle (*Group 4*).

Group 1 and *Group 4* farms were the most resistant in terms of cow pregnancy rate and meat productivity. Maintaining a low sheep-to-cattle ratio promotes higher cow pregnancy rates and translates into higher productivity. Future research might investigate if/how higher herbage biomass levels result from lower stocking rates and from less competition between sheep and cows for grazing.

Group 2 and *Group 3* farms seem systemically unbalanced. *Group 2* by dominance of sheep in the herd (a livestock species that can better resist droughts than cattle but has a low current economic return). *Group 3* by investing in highly "productive" pastures that, in the short term, can lead to increased forage productivity and increased animal productivity. But the non-native species employed to improve pastures are not well adapted to drought, increase the

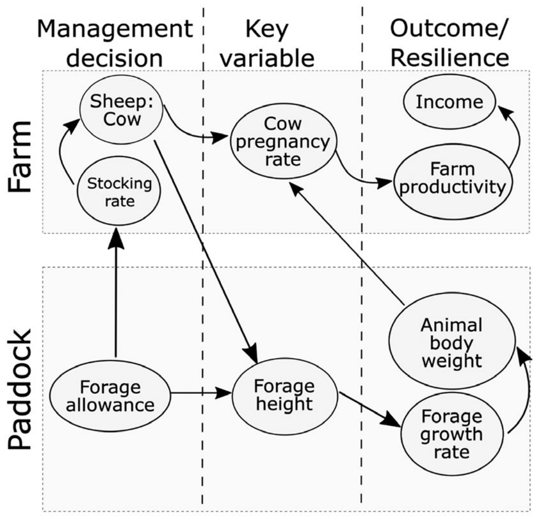

FIGURE 9 Management decisions at paddock and farm level, the key variables they are directly impacting and the outcomes for the farm performance and resilience

vulnerability of the local grazing system to drought and incur greater economic cost and risk. Future research in these areas might investigate the relative returns to investment in cattle and sheep in drought areas, as well as the relative returns to pasture improvement under drought conditions in grassland Uruguay.

The results of this study may aid in the redesign of sustainable and more resilient mixed livestock farming systems of the grassland regions of Uruguay. Figure 9 represents the relation between the study levels. It synthesizes our main findings at farm and paddock level, hypothesizing that farms that perform better in cow pregnancy rate and farm income are a result of higher forage height at paddock level.

Further research should link these two levels, either through farm surveys or on-station experiments. By integrating these two levels, it should be underlined that sheep alone are not "the problem", but rather that low forage allowance and high sheep-to-cow ratios seem directly related to low levels of farm productivity under drought conditions. This is expressed by forage allowance at paddock level and not by stocking rate, as was previously found by Do Carmo et al. (2018), Do Carmo et al. (2016) and discussed by Sollenberger et al. (2005). While stocking rate is a relevant metric for explaining farm performance, forage allowance (kg grass dry matter per kg animal body weight) is the key variable for grassland management. This means that stocking rate ought to be a function of forage allowance rather than an independent variable. The results on this topic found in this study support previous findings by Ruggia et al. (2015) and Scarlato et al. (2015). Those authors showed that the most important factor in the redesign of mixed livestock farming systems, resulting in improved pregnancy rates and farm incomes, is a decreasing sheep-to-cattle ratio. This strategy reduces competition among sheep and cattle for grazing, favours the energy balance of cattle, improves cow pregnancy rates and, thereby, increases farm incomes.

Even though the role of sheep seems detrimental in productivity levels and farm income, it does not undermine the economic and ecological value of sheep as a species. This includes increasing the diversification of products (lamb and wool) and the ability to consume non-desired grass species by cattle.

4 | CONCLUSIONS

Grazing management strategies have an important impact on ability of grazing systems to resist to droughts. Higher pre-drought herbage height increases resistance of herbage accumulation and animal weight, while lower sheep-to-cow ratios increase the resistance of cow pregnancy rate (a key variable for the income of cow–calf farmers in the region). Unexpectedly, no differences between grazing regimes were found for recovery of herbage accumulation rate or animal weight on the native grasslands. This suggests that regardless of the grazing management, grazing systems on native grasslands can recover quickly when rainfall resumes after drought. This result must be taken with caution since overgrazing situations might be more severe than those created by the low herbage allowance treatment of the experiment. The results of this study can inform farmers and policymakers to formulate strategies to mitigate the frequently occurring droughts in the region. These strategies should be based on grazing management which demand low-cost technologies and can prevent extremely negative impacts on production systems.

ACKNOWLEDGMENTS

This work has been conducted as part of a PhD thesis project of P. Modernel supported by the Agricultural Transformation by Innovation (AGTRAIN) Erasmus Mundus Joint Doctorate Program, funded by the EACEA (Education, Audiovisual and Culture Executive Agency) of the European Commission. Partial funding was received from CSIC—UDELAR grant to V. Picasso (Sustentabilidad de los sistemas de producción agropecuarios). We thank Sarah Bullock and Todd Zdorkowski for helpful suggestions to the final version of the manuscript.

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How to cite this article: Modernel P, Picasso V, Do Carmo M, et al. Grazing management for more resilient mixed livestock farming systems on native grasslands of southern South America. *Grass Forage Sci.* 2019;74:636–649. https://doi.org/10.1111/gfs.12445