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Native Grasslands at the Core: A New Paradigm of Intensification for the *Campos* of Southern South America to Increase Economic and Environmental Sustainability

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Extensive livestock production in southern South America occupies ∼0.5 M km^2 in central-eastern Argentina, Uruguay and southern Brazil. These systems have been sustained for more than 300 years by year-long grazing of the highly biodiverse native Campos ecosystems that provides many valuable additional ecosystem services. However, their low productivity (∼70 kg liveweight/ha per year), at least relative to values recorded in experiments and by best farmers, has been driving continued land use conversion towards agriculture and forestry. Therefore, there is a pressing need for usable, cost effective technological options based on scientific knowledge that increase profitability while supporting the conservation of native grasslands. In the early 2000s, existing knowledge was synthesized in a path of six sequential steps of increasing intensification. Even though higher productivity underlined that path, it was recognized that trade-offs would occur, with increases in productivity being concomitant to reductions in diversity, resilience to droughts, and a higher exposure to financial risks. Here, we put forward a proposal to shift the current paradigm away from a linear sequence and toward a flexible dashboard of intensification options to be implemented in defined modules within a farm whose aims are (i) to maintain native grasslands as the main feed source, and (ii) ameliorate its two major productive drawbacks: marked seasonality and relatively rapid loss of low nutritive value-hence the title "native grasslands at the core." At its center, the proposal highlights a key role for optimal grazing management of native grasslands to increase productivity and resilience while maintaining low system wide costs and financial risk, but acknowledges that achieving the required spatio-temporal control of grazing intensity requires using (a portfolio of) complementary, synergistic intensification options. We sum up experimental evidence and case studies supporting the hypothesis that integrating intensification options increases both profitability and environmental sustainability of livestock production in Campos ecosystems.

Keywords: livestock, adaptative management, intensification options, South America, Pampa biome, grassland management

INTRODUCTION

Global and Regional Context of Agricultural Intensification

In the last 20 years, agricultural production has increased in most regions of the world through improving yields and through the expansion of the cultivated land area, typically at the expense of natural habitats (Burney et al., 2010). As a result, food production per capita is today 22% higher than 20 years ago (FAOSTAT, 2019). The world population and food consumption per capita have also increased in the last 20 years, by 30 and 8%, respectively (FAOSTAT, 2019). These trends are expected to continue in the foreseeable future with an increasing demand for animal protein for human consumption.

In this context, it is unlikely that extensification would suffice to cover such demands without major negative environmental effects. Land degradation is already extensive, affecting 23% of the world's terrestrial area and 1.5 billion people globally, and increases by 5–10 million ha year^{-1} (Munir et al., 2017). Conversely, there is room for moderate intensification of under-yielding agricultural systems so that increases in production are made with known and controlled environmental impact (Tilman et al., 2011). However, this path of moderate intensification requires a solid knowledge of the multiple trade-offs operating between agricultural output and other environmental services in these agroecosystems.

The South American *Campos* is an ecological region that extends over 0.5 M km^2, between 27° S and 35° S in central-eastern Argentina, Uruguay, and southern Brazil (**Figure 1**). It is dominated by spatially heterogeneous temperate and subtropical grasslands conformed by a complex mosaic of species assemblages related to soil types and grazing intensity (Berretta et al., 2000). Average annual temperature in Campos region varies from 16.6°C in southern Uruguay to 21.1°C in the northern Corrientes, while the average annual rainfall varies from 1,000 mm in southern Uruguay to 1,600 mm in the northern Campos in Brazil (https://en.climate-data.org/south-america/).

Campos ecosystems are mainly used for extensive livestock production but also provide a range of valuable ecosystem services that affect human well-being (Viglizzo and Frank, 2006; Weyland et al., 2017). Such ecosystem services include the sustenance of plant and animal biodiversity (4,864 plant species: Andrade et al., 2018; 385 bird species and 90 mammal species: Bilenca and Miñarro, 2004), control of soil erosion and storage of soil organic carbon, nutrient cycle regulation and water provision (Costanza et al., 1997; Chalar et al., 2017), climate regulation as well as providing scenic beauty, culture, and livelihood for local rural residents (Costanza et al., 1997). These high-diversity and unique grasslands may also be used as a source to improve biochemical richness of meat and milk, as well as environmental health, as it was hypothesized by Provenza et al. (2019). However, these species-rich grasslands are being threatened by changes in

FIGURE 1 | The Campos ecosystem of South America. It includes the South and North grasslands of Uruguay, Pampa biome of south Brazil, and central-eastern grasslands of Argentina.

the land use (Overbeck et al., 2007), and strategies are needed to improve livestock production in synergy with ecosystem conservation (Carvalho and Batello, 2009).

Agroecosystems based on the use of *Campos* grasslands have been managed extensively for livestock production for more than 300 years with negligible use of external inputs (Viglizzo et al., 2001), and thus often show relatively high environmental sustainability (Viglizzo and Frank, 2006; Blumetto et al., 2019). However, very few farms are capable of combining this with high productivity and profitability, and indeed most farms present large yield gaps relative to the productive potential (Modernel et al., 2018). Therefore, the area of native *Campos* ecosystems has been declining since the 1970s due to conversion to grain crops, cultivated pastures, and forestry plantations (Viglizzo and Frank, 2006; Baeza and Paruelo, 2020). Today, remnant native grasslands occupy 36% of their original extension in Rio Grande do Sul-Brazil (Trindade et al., 2018), 64% in Uruguay (Cortelezzi and Mondelli, 2014), and 26% in Entre Ríos and 72% in Corrientes in Argentina (INDEC, 2018).

Thus, in these non-subsidized economies that do not pay for the ecosystem services and have very few specific instruments to regulate the conservation of native grasslands, low comparative profitability of extensive livestock production is driving a sustained process of land-use change based on the replacement of native *Campos* grasslands. Lack of profitability leads to above-optimal stocking rates, particularly in small farms, which gives place to a vicious cycle of degradation and consequent low productivity and even lower profitability (Tiscornia et al., 2019). The challenge is to devise strategies of intensification that increase profitability while maintaining the native *Campos* grasslands as a main feed source for livestock, so that higher productivity can be reconciled with the maintenance or improvement of all other services provided by these agroecosystems as proposed by Dumont et al. (2018).

PORTFOLIO OF LIVESTOCK INTENSIFICATION IN *CAMPOS* ECOSYSTEM

Livestock production systems based in *Campos* ecosystems are characterized by year-round grazing at relatively constant stocking rates (Royo Pallares et al., 2005). Native grasslands mean primary production range from 2900 to 6300 kg DM ha^{-1} year^{-1} (Berretta et al., 2000; Bendersky et al., 2017) and mean secondary production 60–70 kg liveweight ha^{-1} year^{-1} (Carvalho et al., 2006). The primary productivity and nutritional value of these grasslands show large seasonal variations, with minimal values in the winter period due to the decrease in temperature and solar radiation and the predominance of C4 grasses. Indeed, a large proportion of the annual production of native grasslands is concentrated over a few spring and summer months (Berretta et al., 2000). Imposed over this seasonality, inter-annual variation is mainly related to rainfall variability (Cruz et al., 2014; Guido et al., 2014). Under these conditions, grasslands become recurrently overgrazed in periods of low forage production, a situation that becomes particularly aggravated during the severe droughts that occur every 10 years or so. In order to overcome these constraints, several intensification options are available and have been assessed in these systems.

Process-Based Technologies

Stocking Rate Management

The control of grazing intensity through the management of stocking rates is a key tool to adjust the forage offered to animals in livestock systems. A few long-term set stocking experiments were implemented in the *Campos* ecosystem in order to determine stocking rates that maximize individual and per area productivity, so that general recommendations can be given to farmers (Royo Pallares et al., 1986). However, due to high soil and climatic variability, the results of these experiments were useful only to set general guidelines to set stocking rates. A long-term experiment aimed at describing the quadratic relationship between forage on offer and animal liveweight gain using short-term stocking rate adjustment (Mott, 1960) indicated that productivity was optimized at 8% of forage on offer (Maraschin et al., 1997).

Forage on offer affects standing forage mass and therefore forage growth (Soares et al., 2005), forage intake (Da Trindade et al., 2016), and energy partitioning (Do Carmo et al., 2016). In order to implement this practice, monitoring forage production and animal liveweight is a prerequisite for regulating plant-animal relationship. Monitoring frequency depends mainly on pasture growth rates and management and business decisions. In cow-calf experiments, Claramunt et al. (2018) and Do Carmo et al. (2018) evidenced that monthly adjustments of the stocking rates to achieve target forage offer levels are key to increased animal productivity. Several case studies also demonstrated that stocking rate management at farm scale increased livestock production *via* higher calf weaning weights, pregnancy rates, and increased profitability (Albicette et al., 2017; Do Carmo et al., 2019; Claramunt and Meikle, 2020).

Sward Structure Control

Sward structure is defined as the arrangement of species, plant biomass, and different plant components (leaves, stems, and senescent tissues) in the horizontal and vertical planes (Marriott and Carrère, 1998). Typically, in *Campos* grasslands, several structures coexist, characterized by differences in height, species, and green:dead and lamina:stem ratios. Herbivores interact with such spatiotemporal heterogeneity producing uneven grazing distribution (Parsons and Dumont, 2003), which further creates and maintains heterogeneity and results in variable grazing efficiencies (Ganskopp and Bohnert, 2009), with consequent effects on grassland productivity and biodiversity (Bailey and Provenza, 2008).

Sward structure can impair the production of grazing animals more than forage quality (Azambuja et al., 2020), so grazing intensity should be used also to create optimal sward structures to make the foraging process more efficient (Carvalho, 2013). Thus, sward structure manipulations, such as mechanical mowing or tactical grazing at high stocking rates, are tools that could be used to increase effectively grazed area (Neves et al., 2009) or volumetric density of green leaves in a range of height that it is not limiting for forage intake (Gonçalves et al., 2009). The effect of the manipulation of sward structure was evidenced in calf-rearing experiments in the south of Brazil, which showed that an increase of spring grazing intensity increased livestock productivity in the following seasons (Soares et al., 2005) and in Uruguay which evidenced that maintaining sward height between 6 and 12 cm lead to sustained high levels of livestock productivity over 10 years (Rodríguez Palma and Rodríguez, 2017a).

Forage Stockpiling

Stockpiling forage, defined as forage allowed to accumulate for grazing at a later time (Allen et al., 2011), is a strategy to make "*in situ*" forage banks for use it later in periods of low seasonal pasture growth (Derner and Augustine, 2016) or to mitigate drought effects (Scasta et al., 2016). In most springs and in rainy summers, native grasslands produce a greater amount of forage than grazing animal demand, while during most winters and dry summers, the opposite situation occurs, because primary productivity is highly dependent of precipitations during the end of spring and summer (Berretta et al., 2000). Often, this asynchrony between supply and demand of nutrients occur in all paddocks of a farm, since different paddocks usually grow in sync with weather conditions, and with few adjustments of stocking, resulting in an inefficient use of the forage. The accumulation of forage in small areas, as opposed to dispersed over the whole farm, could avoid energy losses in the grazing process and allow the application of differential nutritional management practices at each paddock.

Stockpiling of forage is a low-cost and easy-to-use intensification option to improve the space-time management of forage in livestock farm systems. However, there is a trade-off between the quantity and quality of stockpiled forage that can be managed by adjusting the duration of the resting period so that stockpiled forage can meet demands of specific animal categories (Mufarrege et al., 1977). Specifically, the area to be stockpiled depends on how the livestock number is in relation to carrying capacity, on the potential growth of the forage in the grazing exclusion period (Fedrigo, 2011), and on the required forage quality and on how much the forage deficit would be in the later shortage period.

Nutritional Management of Livestock

In extensive livestock systems, there are mainly three low-cost nutritional management tools that can be used to improve profitability and reduce the economic risk: (i) matching the breeding period and hence beef cattle and sheep energy requirements with the seasonal pattern of pasture production (Do Carmo et al., 2016), to optimize feeding resources; (ii) prioritizing the feeding of primiparous cows and ewes using high-quality forage resources in order to ensure the functions of growth and reproduction (Spitzer et al., 1995); and (iii) applying short-term (10–14 days) calf suckling restrictions with nose plates (otherwise known as temporary weaning) to reduce energy demand and in consequence increasing the reproductive performance in cows calving in a lower body condition score (Quintans et al., 2009).

These management tools could help us to ensure adequate levels of body condition score at calving, and therefore higher annual pregnancy rates (Quintans et al., 2010, Soca et al., 2013; Do Carmo et al., 2018), and to increase calf weight when suckling restriction is combined with a high forage offer (Claramunt and Meikle, 2020). Most of these tools were developed from the conceptual model proposed by Soca and Orcasberro (1992) that combine indicators of pasture structure and the energy balance of grazing cows to guide the management decisions in *Campos* ecosystems. Aside from that, the preferential allocation of the most demanding categories in better pastures (higher green leaves mass) is another strategy that may help to improve animal performance. Lastly, cattle crossbreds can increase animal production, Do Carmo et al. (2018) evidenced that the control of grazing intensity by manipulating herbage allowances combined with the use of F1 crosses (Hereford × Angus) increased livestock production and the efficiency of energy use.

Input-Based Technologies

Fertilization of Native Grasslands

Forage yield and quality of *Campos* native grasslands is strongly and frequently limited by soil fertility. Fertilizing with N increases primary production, and, at the same time, improves the forage nutritional value (Boggiano, 2000; Jaurena et al., 2014). Two-fold increases in forage production are often found (Boggiano, 2000; Jaurena et al., 2014). A synergistic response between nitrogen and phosphorus addition is reported in Jaurena et al. (2014). These technologies have a particular use to short-term improvements of both forage productivity and quality and could improve animal production from 60 to 200% compared with unfertilized grasslands (Rodríguez Palma and Rodríguez, 2017b). Santos et al. (2008) reported that 200 kg N ha^{-1} year^{-1} increased liveweight gain to 700 kg liveweight ha^{-1} year^{-1}, but soil correction with lower lime and NPK fertilizer (500 kg ha^{-1} 5-20-20) was superior in financial returns. However, fertilization should be used with caution, since it has been found that it could lead to a decrease in species richness (Bobbink et al., 2010) and favors the invasions by exotic species (Shen et al., 2011).

Oveerseeding of C3 Species Into Native Grassland

Another option to overcome the limitations of native grasslands is overseeding legumes, mainly *Lotus* sp. and *Trifolium* sp., combined with P fertilization (Del Pino et al., 2016; Jaurena et al., 2016), or overseeding annual grasses, mainly *Lolium multiflorum*, combined with N fertilization (Ferreira et al., 2011a; Brambilla et al., 2012), or a mix of legumes and grasses and N and P fertilizers (Oliveira et al., 2015). These technologies are effective strategies to establish productive, high-quality C3 forage species into native grasslands that could be used to reduce seasonality and increase animal performance and stocking rates. However, this technology should be managed with care since it could lead to reductions in plant species richness and facilitate the invasions by exotic species (Jaurena et al., 2016).

Replacement of Native Grasslands by Annual or Perennial Pastures

Sown pastures are made by replacing the native vegetation by annuals or perennials exotic species coupled with high levels of fertilizers. The use of sown pastures is greater in more intensive livestock systems. Sown pastures typically include annual or perennial exotic grasses and legumes coupled with high levels of fertilizers. Most of the annual pastures are winter season (mainly *Avena* and *Lolium*), while perennial pastures are mixtures of grasses (mainly *Festuca* sp. and *Dactylis* sp.) and legumes (mainly *Lotus* sp. and *Trifolium* sp.). Perennial pastures are used to prioritize the feeding of the most demanding livestock categories due to their higher productivity and nutritive value, which could allow for at least a 3-fold increase in animal production (Berretta et al., 2000). However, this superiority is limited by their short persistence, and sown pastures require higher maintenance expenses compared with native grasslands. Notwithstanding the evidence of the short-term increase in productivity, the transformation of native grasslands to crop land changes the original pools and fluxes of carbon (C), nitrogen (N), and phosphorus (P) of that ecosystems (McLauchlan, 2006) in addition to the above-mentioned increased production variability and economic risks.

Pasture Irrigation

Campos grasslands are exposed to high variability in rainfall causing large fluctuations in forage production and nutritional value, which is expected to increase in most future climate change scenarios (Giménez et al., 2009). In this context, supplemental irrigation of native grasslands (Jaurena et al., 2014) or sown pastures may be a strategic tool to ensure a feed basis for the animals. Although the development of this technology in *Campos* grasslands is limited by high initial investments and high running costs, it could be applied in a small area of the farm.

Supplementation

The energy and crude protein contents of native *Campos* grasslands are not enough to meet the potential requirements for growth of young animals during several months of the year (Ramos et al., 2019). Exceptions can be observed in spring or in good soils without water restriction and good management of forage on offer as related by Ferreira et al. (2011b). Therefore, several alternatives of supplementary food have been used to overcome these restrictions using mineral-, protein-, or energy-concentrated supplements, balanced rations, or preserved forage. The supplements could be strategically used to: (i) avoid weight loss during winter, which also has a positive effect on the rest of the productive life of the animals; (ii) maintain forage offer and stocking rate despite low pasture production; (iii) recover primiparous cows or mature cows with low body condition score; and (iv) anticipate slaughter age of fattening animals. However, if supplementation is used to increase the stocking rate at low forage offers, it could lead to overgrazing.

System Technologies

Stocking Methods

For the purposes of this paper, grazing systems are understood as the integrated strategies to manage soil, plant, and animals with the aim to achieve specific social, environmental, and economic results (Allen et al., 2011). Stocking method could be either continuous or rotational. Fenced multipaddock grazing systems allow direct control of the resting period (Allen et al., 2011; Di Virgilio et al., 2019), while in continuous stocking, the control is indirect, *via* stocking rate adjustment. Where paddocks are continuously occupied, grazing animals have more freedom to choose their diet than in the rotational stocking. In smaller paddocks, rotational stocking is used to ensure a higher harvesting efficiency of the forage. Studies carried out in the region have not found evidence of advantages of any stocking method, given the appropriate forage on offer is maintained (Berretta et al., 2000; Jochims et al., 2013). It is worth noting that none of the studies was carried out at the long term or at the farm level.

In *Campos* grasslands, continuous stocking is the most widespread stocking method. Often, this is associated with poor basic infrastructure resulting in farms with a few large paddocks and many small ones (typically nearby the house) and few watering and shade points. Such designs, not based on the pattern of plant communities, animal species, categories, and stocking rates, severely limits the implementation of processes technologies that aim to offer to the animals an optimal sward structure (Carvalho, 2013) that favors the foraging process independently of the stocking method (Carvalho et al., 2019). To put it into practice, it is needed to monitor the forage mass, forage growth, and animal weights and/or monitor forage structure (e.g., pasture height, tussock frequency, etc.). The frequency of monitoring needs to be tailored to the speed at which decisions are taken at farm level.

Silvopastoral Systems

Silvopastoral systems combine trees, grasslands, and livestock under a comprehensive management system. It has been proposed as an alternative model for increasing the sustainability of livestock farms. Trees are not exactly abundant in *Campos* ecosystems, except for the riverbanks and small woodlots of cultivated trees that provide shade and shelter for livestock (Cubbage et al., 2012). Silvopastoral systems play a fundamental role in animal welfare by reducing the caloric stress (Lopes et al., 2016) and also helps to diversify farmers' income. Interestingly, some field plot experiments have demonstrated synergies between pasture, animals, and trees (Fedrigo et al., 2018). However, silvopastoral systems explicitly designed to exploit the synergies between grasslands and forests have not been developed yet in the *Campos* mainly due to the high initial costs for installing trees.

Integrated Crop-Livestock Systems

The rotation of annual crops (2–3 years) alternated with sown grass-legume pastures (3–4 years) is a technology already developed in the Campos ecosystem (Lunardi et al., 2008; Ernst et al., 2018; Alves et al., 2019). These integrated crop-livestock systems (ICLS) were highlighted by Lemaire et al. (2014) as a way to: (i) facilitate the installation of sown pastures and improve the quality of grasslands through regular renovations; (ii) reverse soil degradation and decrease environmental impacts by including multiyear pastures in pure annual crop rotations; (iii) allow a higher diversification of the landscape that facilitate habitat diversity; and (iv) promote a higher flexibility of the whole system to cope with climate and economic hazards. This

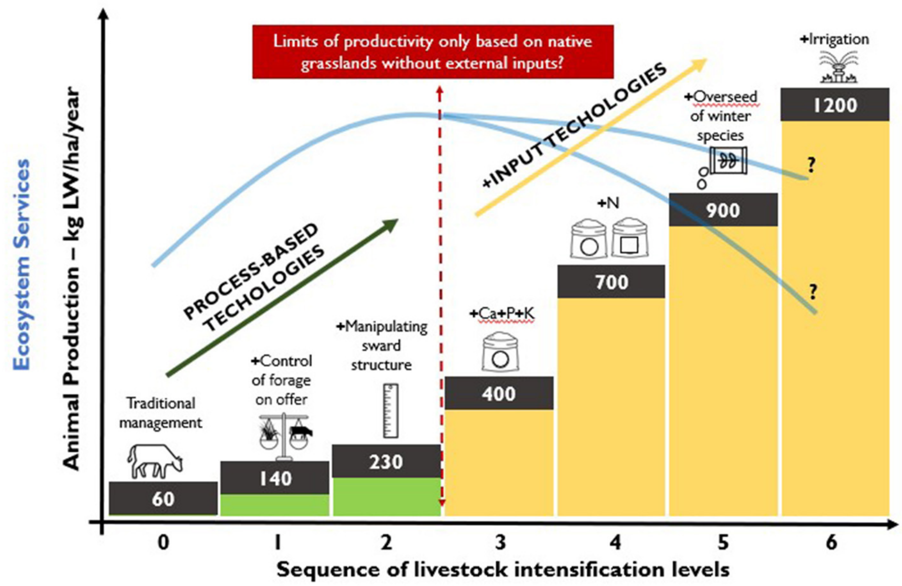

FIGURE 2 | Sequence of livestock intensification across process-based and input technology pathways. The model assumes the increasing levels of potential productivity of a rearing to finishing steers system based on native grasslands of the Pampa biome (Brazilian part of *Campos*) and consequences to the provision of ecosystem services. Adapted from Carvalho et al. (2011) and Nabinger and Jacques (2019), with means from the study area. Nowadays, ecosystem services response curves to livestock intensification are not well-studied, so the decline of the curve may be more or less pronounced depending on the predominance of trade-offs or synergies at the system level.

is a technology partially adopted in livestock farms, especially in those close to agricultural areas. If planned at the territorial level, ICLS can help to improve the profitability of livestock systems and indeed the conservation of *Campos* ecosystems by indirectly valuing the calves, which are highly demanded in regions where ICLS are implemented (De Moraes et al., 2019). In addition, ICLS can buffer native grassland seasonality, so it seems reasonable to recouple crop- and livestock-specialized farms to exploit synergies at landscape level (Garrett et al., 2020).

Evolution of Intensification Approaches in *Campos* Ecosystem

National Programs for Technical Change

In *Campos* ecosystems, the first proposals for technical change in livestock systems based on native grasslands were raised in the 1960s and 1970s. The "New Zealand package" in Uruguay (Alonso and Pérez Arrarte, 1980); "Plan Balcarce" in Argentina (De Obschatko and De Janvry, 1972), and "PRONAP" (Pasture National Program), "PRONEP" (Beef Cattle National Program), and CONDEPE (National Council for Livestock Development) in Brazil (Pinazza and Alimandro, 2000; Bini, 2009) were institutionally subsidized programs that stimulated the replacement of native grasslands by intensively fertilized sown pastures (grasses and legumes) to increase forage production and quality.

These plans were widely incorporated in the most intensive crop and dairy farms. However, they did not have the expected results in extensive systems mainly due to an increase in uncertainty related to the lack of persistence of perennial pastures under local conditions (Alonso and Pérez Arrarte, 1980). Perennial pastures have short longevity in the *Campos* ecosystem (currently 3–5 years), which implied both higher production variability and economic risks (Alonso and Pérez Arrarte, 1980). The question that arises is why sown pastures became successful in dairy farms and why not in extensive livestock systems. One possible explanation is that the dairy industry provides credits to dairy farmers to make cultivated pastures that have a short-term economic return and are profitable, while in livestock extensive systems, this integration does not exist, and cultivated pastures are generally not profitable.

Intensification Levels

In the early 2000s, the existing experimental knowledge concerning the potential of livestock production on native grassland was categorized into six levels of increasing intensification (**Figure 2**). Level 0 corresponds to "typical" or "average" of rearing and finishing systems of beef cattle in the region (Carvalho et al., 2006; Nabinger, 2006). On this basis, controlled grazing intensity (level 1) is a fundamental tool for improving livestock production due to improvements in forage budgets (offer vs. demand) (Maraschin et al., 1997; Do Carmo et al., 2019) which can be improved in a further step (level 2) by the manipulation of sward structure to maintain forage quality and optimize grazing time and maximize forage intake (Soares et al., 2005; Da Trindade et al., 2016). Management using moderate grazing intensity in levels 1 and 2 is pivotal to

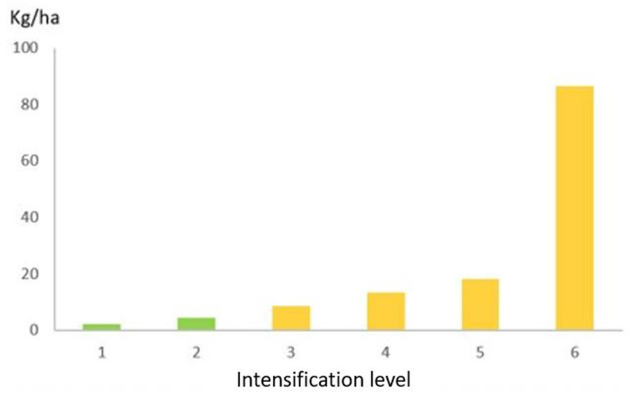

FIGURE 3 | Minimum increase in livestock productivity of a rearing to finishing steer system needed to cover the increased annual costs when 10% of the farm is intensified with each intensification level.

improve primary and secondary productivity (Carvalho et al., 2011). These two low-cost tools for managing native grasslands can provide the "win-win benefits." On the one hand, they increase livestock productivity and reduce system vulnerability. On the other hand, they improve environmental services by maintaining biodiversity and, decreasing beef cattle methane yield and intensity (Cezimbra, 2015) and nitrous oxide emission factor from urine (Chirinda et al., 2019).

Subsequent steps to further increase productivity are based on the addition of external inputs, such as calcium (Ca), phosphorus (P), and potassium (K) (level 3) and N (level 4) to overcome the nutritional limitations of native forage species (Boggiano, 2000). Additional intensification levels can be achieved by combining the addition of fertilizers with overseeded exotic legumes and/or grasses (level 5) (Santos et al., 2008; Brambilla et al., 2012). Lastly, at the highest level of intensification (level 6), native grasslands that are fertilized, overseeded, and irrigated can potentially embody all the previous improvements.

As we move from levels 3 to 6 of intensification, some trade-off may exist between increasing livestock productivity and loss of diversity (Carvalho et al., 2011), reducing the extent of ecosystem services. The minimum level of productivity needed to cover the costs of each level of intensification is low with process technologies, but it increases substantially with each subsequent level of intensification based on the use of inputs (**Figure 3**). This is because each additional step of intensification with inputs increases the financial costs (Santos et al., 2008) and thus the economic vulnerability of the systems. At the same time, these high-productive systems often become more vulnerable to climate variability.

A New Paradigm for Sustainable Intensification at the Farm System Level

The levels of intensification were the first agroecological path that integrates the ecological dimension with farmers' livelihoods in *Campos* ecosystems. The conceptual relationships shown in **Figure 2** indicate the trade-off responses between intensification and ecosystem services. In the first instance, both productivity and ecosystem services could be enhanced by the use of grassland management technologies leading to a win-win situation. However, this form of intensification has a limit imposed by rainfall and the soil nutrient content that determines the amount of forage growth and nutritional value.

To overcome these limitations, input technologies could be used to continue increasing livestock production, but at the cost of reducing many of the ecosystem services, leading to a conflicting situation. Nevertheless, farm system management is challenging, because of the multiple synergies and tradeoffs involved in farmer decisions and by the dynamic non-linear responses of the vegetation. In order to address these complexities, a new paradigm is needed to comprehensively focus on the intensification process at the farm system level. This leads us to propose a new approach shifting from steady-state management tools to integrated strategies that may reduce system vulnerability while ensuring ecosystem service provision.

DISCUSSION

Intensification to Cope With Vulnerability Challenges

In the *Campos* ecosystem, the animals graze outdoors in species-rich grasslands all year round, making the livestock systems highly dependent on the climate and on the prices of products. In consequence, in meat-exporting countries, like Argentina, Brazil, and Uruguay, where subsidies are minimal or inexistent and the prices of the products constantly change, technological development should be oriented toward minimizing the economic risk and the reduction of climate vulnerability. With these conditions, the approach of short-term maximization of livestock production through the massive use of inputs can decouple this finely tuned agroecosystem. The failure of the "New Zealand," "Balcarce," "PRONAP" and "PRONEP," and "CONDEPE" plans in *Campos* ecosystem due to its lack of adaptation to the local extensive livestock systems is a clear evidence of this decoupling process.

As evidenced in **Figure 4**, the substitution of native by sown pastures further increases the already high variability in forage production, increasing the uncertainty of sown pasture production from the third year, as well as both productive and financial risk. For these reasons, we consider that the use of sown pastures, stocking methods, fertilization, and feed supplementation in addition to other intensification technologies can be used strategically to aid and complement native grassland management in the *Campos* ecosystem but not as an ends in themselves. New models for livestock sustainable intensification should optimize the use of a diversity of alternative strategies to increase the quantity of low-cost products while minimizing all possible negative effects on ecosystem services.

Win-Win Intensification Solutions

The challenge of sustainable intensification of livestock production in *Campos* ecosystems is to increase the production

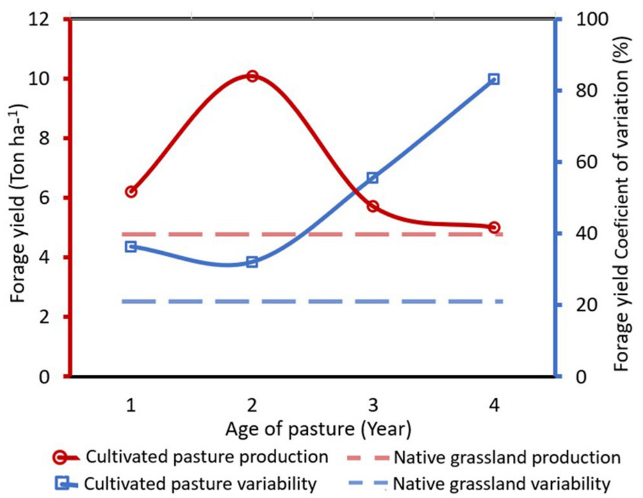

FIGURE 4 | Temporal dynamics of forage yield of sown pastures (solid red line) and its interannual coefficient of variation (solid blue line) compared with native grasslands (dashed lines). Average of mean annual and its coefficient of variation of: (i) the first 3 years of *Festuca arundinacea*, *Trifolium repens*, and *Lotus corniculatus* monospecific pastures from 27 years (1993–2019) of INASE-INIA cultivar evaluations in the southwest of Uruguay and the fourth year from Carámbula (1991); and (ii) native grassland data series of forage production > 10 years in north of Uruguay (Berretta et al., 2001; Rodríguez Palma and Rodríguez, 2017b), east of Uruguay (Bermúdez and Ayala, 2005), and central-eastern Argentina (Bendersky et al., 2017).

and utilization of forage, and its efficiency of conversion to animal products with economic, social, and environmental benefits. Within a context of accelerated intensification, there is a need to adapt to rapid changes and decrease overall vulnerability promoting synergies and reducing trade-offs at the farm system level. For its purpose, the use of techniques to ground the spatial and temporal management of forage and the exploitation of the complementarities among livestock nutrition, nutrient-diverse forage species, and grassland management are key to promoting livestock production under a range of scenarios.

To carry it out, we need to redesign the systems, if necessary, and generate a decision support system to aid farmers' management activities in a complex environment. Therefore, before adding inputs into the system, you must optimize the management so that the fertilizers, species supplement, or system technologies could create win-win situations. Particularly, there is a set of specific low-cost validated techniques that could have a great impact on the productivity and stability of livestock systems in the *Campos* ecosystem. Here, we highlight seven suggested alternative strategies, based on experimental evidence and case studies that incorporate flexibility to deal with uncertainty and help manage system complexity, ultimately boosting resilience:

(i) During spring, when pasture growth is regularly high, the generation of modules of *in situ* stockpiling (deferred paddocks) can be used to: (a) optimize forage structure and therefore high-quality forage harvest in the non-deferred paddocks by adjusting the stocking rate to the period of luxurious forage growth; (b) *in situ* forage stockpiling to face climate uncertainty and to compensate for the increased variability in pasture production generated in areas intensified by input technologies; and (c) favor seedling recruitment and seed production of the most palatable species and enhancing the recovery of the most overgrazed areas. To adopt this alternative management, farmers need to exclude at least one paddock, something easily achieved by those already using alternate or rotational stocking in their grazing management systems.

(ii) During summer, when pasture growth shows high variability, the use of: (a) calf suckling restrictions with nose plates (temporary weaning), or early weaning for cows with a body condition score below the target, are fundamental to achieving a high reproductive efficiency through a better management of the nutritional supply/demand ratio; (b) stockpiled forage and/or feed supplements in cows and sheep could maintain the forage on offer, if necessary; and (c) creep-grazing to the calves while restricting cow access in small specially designed areas of sown pastures or fertilized native grasslands could provide high-quality forage.

(iii) During autumn, when pasture growth begins to decline, the: (a) annual stocking rate adjustment, through selling cull cows and less productive animals and/or by the early weaning of calves, is central to recover the body condition score of the groups of target cows and to avoid overgrazing in native grasslands; and (b) the generation of modules of paddocks for stockpile legume overseeded or nitrogen fertilized grasslands to offer this forage to the most demanding livestock categories in the following winter.

(iv) During winter, when pasture growth is the lowest, the use of: (a) low-quality forage accumulated in the stockpiled modules could be offered to the less demanding animal categories through restricted time access combined with protein supplements to sustain the forage on offer on the native grasslands, and therefore decreasing overall overgrazing; (b) high-quality forage produced in farm modules of sown pastures specially designed to overcome native grassland seasonality and to be offered to the most demanding livestock categories (e.g., legume overseeded, sown or fertilized pastures preferably assigned to calves, heifers, or primiparous cows), could have a positive impact on the rest of the productive life of the animals.

(v) During below-average rainfall seasons, the use of: (a) stockpiled forage and/or supplemental feed could be used to sustain forage on offer despite low pasture growth, reducing overgrazing in native grasslands; (b) efficient irrigation to pastures with high potential growth rate could be used in small areas to overcome the forage deficit.

(vi) The implementation of modules of specialized rotational stocking by splitting paddocks with uniform plant communities, and at the same time with available water and shade could be used to improve pasture management. In these conditions, the resting time of paddocks can be directly controlled according to the thermal sum required for leaf expansion of desired species or functional types, and specific management targets, as well as post-grazing forage height. Again, what is important is to offer to the animals an optimal sward structure (Carvalho, 2013) to optimize the utilization and growth of both native and sown pastures, which is facilitated by using multiple-fenced paddocks.

(vii) Diversify farm system income using silvopastoral or crop-livestock systems, and at the same time, exploit its advantages to improve animal welfare and perennial pasture renovation, respectively.

Native Grasslands at the Core: A New Paradigm for *Campos* Grassland Intensification

Based on the results of the previous models suggested for livestock intensification in Campos ecosystem, we propose to further develop the existing paradigm including resilience-based concepts underlined by Bestelmeyer and Briske (2012) and scaling it from paddocks to farming systems. Sustainable intensification aims to increase grassland productivity while increasing sustainability (Garnett et al., 2013). To overcome this challenge, the abovementioned management, input, and design intensification strategies will help to increase the ability of livestock farming systems to cope with external shocks (climate uncertainty and/or prices volatility). Thus, the question that arises is how to use these strategies to solve problems in different farming systems and dynamic conditions.

At the farming system level, native grassland is central to assuring the main source of ecosystem services, so process-based and input-based technologies orbit native grasslands to build a farming system which is predominantly based on native grasslands. Livestock intensification options are spatiotemporally designed to cope with native grassland vulnerabilities. Which levels of livestock intensification and how and when they will be arranged depend on a co-designing process with local stakeholders. To overcome these challenges, we propose a new model for livestock sustainable intensification that highlights the role of the optimal management of native grasslands as a cornerstone to increase productivity and preserve sustainability. This proposal is focused on small and medium livestock farmers that have access to public extension programs and will be called "native grasslands at the core" (**Figure 5**).

Given that the best environmental functioning is achieved through well-managed native grasslands (Nabinger et al., 2011; Modernel et al., 2018), we proposed that livestock intensification strategies should focus on optimizing the management of the native grasslands base (the core). One way to achieve the optimal management of native grasslands is to create specialized modules within livestock farms to fulfill a specific function that may help to improve the overall farm productivity and resilience. Examples of these modules are shown in **Table 1**.

In this context, adaptive management, a structured approach that uses monitoring to make simple decisions in complex systems that are exposed to changing conditions (Briske et al., 2017), could be used to guide can aid farmers' decision-making process. Adaptive grazing management strategies are a set of envisaged alternatives to be selected with the assistance of specialists in order to attenuate the main vulnerabilities of an agroecosystem, and to react to specific events that may affect them. In this paper, we propose an intensification framework for extensive livestock production systems that focuses on the role of the optimal management of native *Campos* grasslands. In this framework, short- and medium-term stocking rate adjustment and sward structure control are key to increase productivity and resilience.

We envisage a co-innovation approach as described by Albicette et al. (2017) with the participation of researchers and extension agents to aid farmers in selecting, monitoring, and evaluating the intensification options. This methodology could be strengthened by the development of state-and-transition models as systematic strategies for improving native grassland management by a structured decision-support process. These models could be implemented in an approach similar to that proposed by Bestelmeyer et al. (2017) but with an increased emphasis on the integration of multiple options to intensify management while protecting the native grassland core. For these to be achievable in commercial farms, a portfolio of complementary tools is available, such as forage stockpiling, livestock supplementation, sown pastures, conserved forage, legume-, or grass-overseeded native grasslands, and nitrogen and phosphorus fertilization: To avoid extensive native grasslands replacement or degradation, these options should be restricted to specially designed modules.

Finally, the design of the agroecosystem should be readapted as needed through: (i) using grazing management strategies adjusted to the available plant communities and local infrastructure; (ii) creating new intensified modules to improve the functions that most limit the sustainability of the system; and (iii) include other synergic agricultural activities like silvopastoral or crop-livestock systems. In **Figure 6**, a schematic of an adaptive management plan depicts the use of options to actively prepare for a drought, and then to react to it.

The economic results and the risk of implementing the proposed system of intensification should be assessed at the system level and compared with other intensification options. To this purpose, some economic indicators like profitability, gross margin per hectare, financial dependence, time lags between investment and benefits, and feed autonomy should be calculated. Additionally, risk perception is a key factor in the adoption of a new technology in agriculture (Marra et al., 2003). Because whole-system risk reflects the cumulative effects of the climate, price, political, and human factors influencing the farm profit, it needs to be assessed dynamically in each specific context to aid the decision of alternative intensification options.

So far, we have considered that the synergies of land use change within an intensified based system should at least offset environmental costs. However, in order to achieve sustainable intensification at the landscape or regional level, it is also important to consider the society's priorities. At this scale, it is necessary to calculate the public costs of the loss of native grasslands ecosystem services, such as soil preservation, water provision, and landscape scenic beauty. Therefore, a proposal of sustainable intensification should also consider the public costs of native grassland ecosystem land use change, e.g., by the increased costs for the provision of drinking water to the

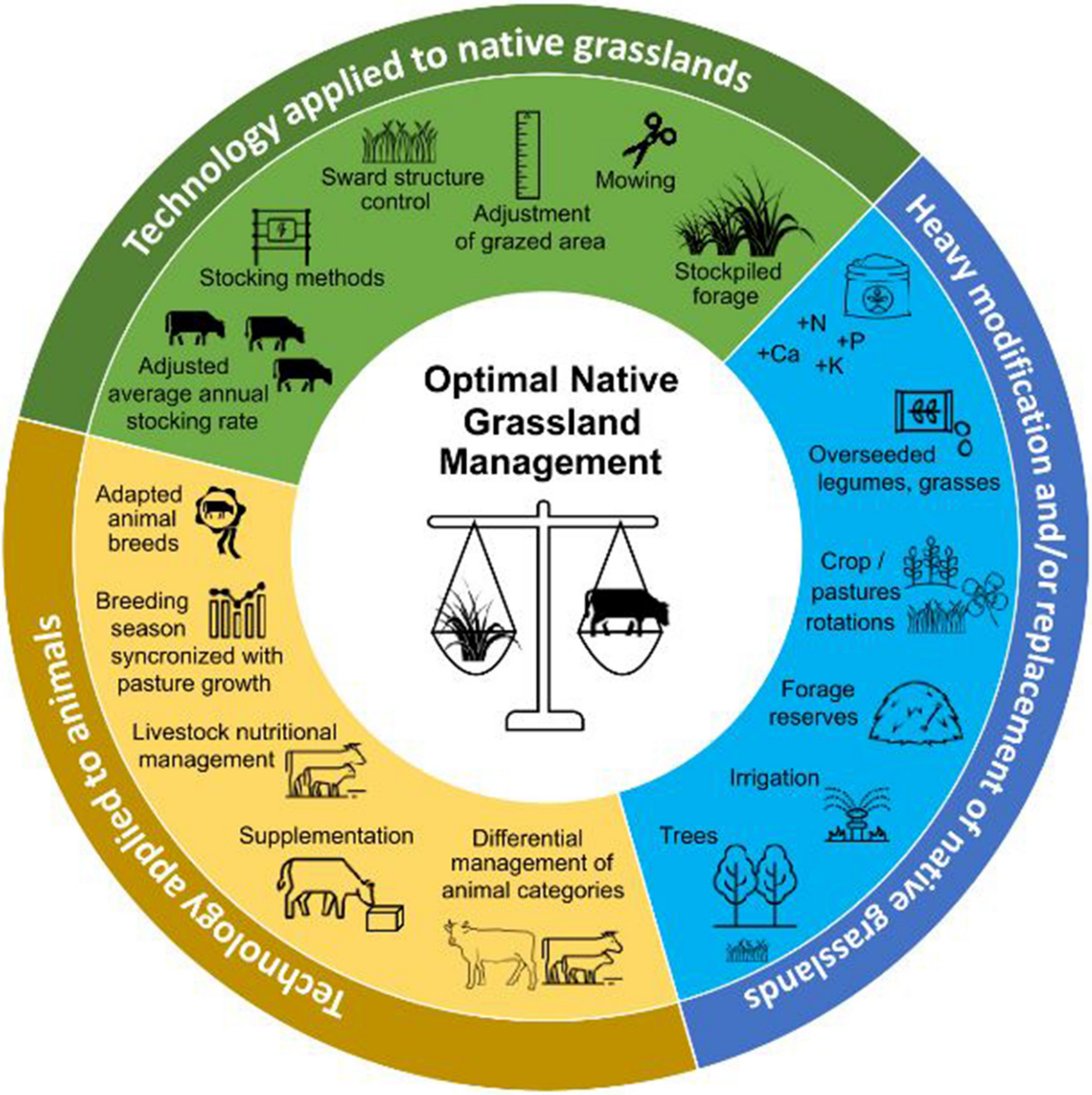

FIGURE 5 | A new model for livestock sustainable intensification that describes the role of technology applied to livestock management (orange), to modified or replaced native grasslands (blue), and to native grasslands (green) to achieve optimal native grassland management.

population after land use change. At national levels, institutions and government policies could promote the proposed model of intensification by defining regulations and incentives that facilitate the capacities of managers to make decisions regarding the productive conservation of their socioecosystems.

Summarizing, in the proposed framework, we consider that the dilemma is no longer whether or not to use input technologies and becomes how to combine the use of input technologies to boost the core. For example, sown pastures could play a key role to reduce forage production variability over the year, to improve the forage growth, quality, and animals' intake of native grassland forage, or to improve the nutrition of the most demandant animal categories among others. To this end, we propose to construct multidimensional adaptive strategies that would intensify the capacity of livestock systems to cope with ecosystem, climate, and market changes, rather than simply reacting to current conditions. The intensification proposed in this paper is proportional to the management intensity and not to the amount of external inputs applied. However, increasing management intensity requires: (i) more knowledge of how grassland vegetation responds to management practices such as grassland intensity, deferment, or fertilization; and (ii) more time dedicated to monitoring the condition of the pastures and animals and for decision making over time. Our expectations are that this new integrated management scheme is an adaptive approach that can be used to make better decisions to cope with future challenges and to make livestock production systems in *Campos* ecosystems

TABLE 1 | Specialized modules within livestock farms to carry out a function that helps improve productivity and resilience of the whole system.

System objectives	Management strategies	Synergies	Trade-offs
Improve forage quality to comply with most demanding categories	Modules of sown pastures	Complement native grasslands production and avoid overgrazing	Reduced diversity
Improve gorage utilization efficiency by controlling resting period and post-grazing pasture height	Modules of rotational stocking	Optimize forage structure, growth, and use	Increased costs and knowledge to manage
Improve intake and diet quality by controlling grazing intensity and forage structure	Modules of continuous stocking	Optimize forage structure, growth, and use	Increased knowledge to manage
Forage stocks as a climate insurance	Modules of "stockpiled forage."	Reduce vulnerability and restore overgrazed areas	Reduced forage quality
Reduce climatic effects on livestock and diversify production	Modules of silvopasture or small woodlots	Improve animal welfare and diversify the income	Reduced forage productivity
Reduce climatic effects on livestock and diversify production	Modules of crop-pasture rotations	Complement native grasslands production and diversify the income	Reduced diversity

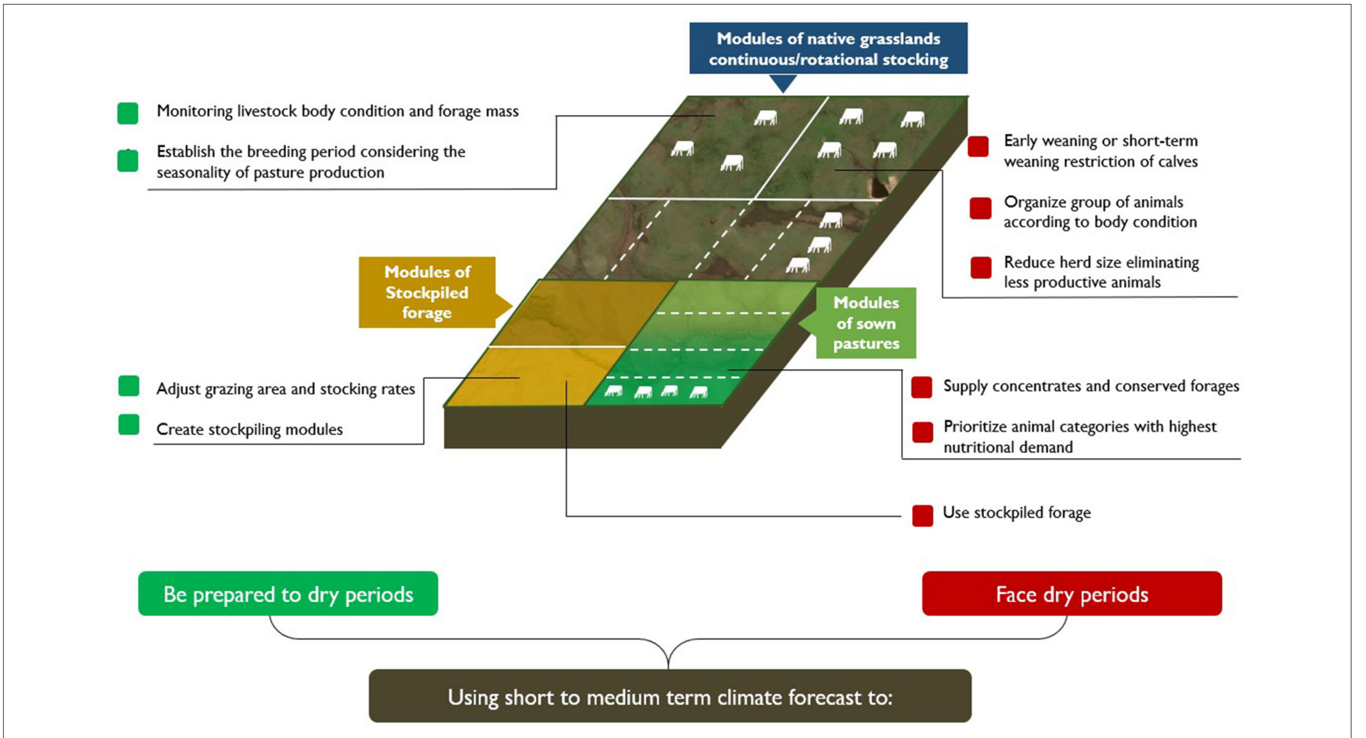

FIGURE 6 | An example of an adaptive management plan with proactive (drought anticipation) and reactive (drought response) adaptation practices suggested to cope with drought in *Campos* livestock farm systems.

more sustainable, despite the need for intensification and greater profitability.

FUTURE ISSUES

Particularly, whole-farm design models are needed to quantitatively analyze the impacts of a specific combination of tools and strategies at the farm system level. This will allow to select the best alternative models of intensification to generate new knowledge and to enhance innovation processes at farm system scale. For that purpose, farmlet experiments are a valuable tool for testing ecosystem service response to alternative farm system models of livestock intensification. The generated knowledge could be used to meet future market demand for food safety, animal well-being, and product quality, as well as to certify the state of relevant environmental variables such as carbon and water balances. Lastly, more research is needed on how to proceed with the transition between traditional and sustainable intensified livestock systems in the *Campos* ecosystem.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available for because data is private. Requests to access the datasets should be directed to Martín Jaurena, mjaurena@inia.org.uy.

AUTHOR CONTRIBUTIONS

FL and MJ conceived the topic and the initial approach. MJ analyzed and interpreted the information and wrote the first draft of the manuscript. MD, TD, JS, DB, FM, MP, PS, PC, FQ, RP, CN, and FL contributed with local information and critically discussed the new paradigm. FM designed the figures. MJ, TD, CN, MD, FL, and PC rewrote it. All authors contributed to the article and approved the submitted version.

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