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Mobilizing Ecological Processes for Herbivore Production: Farmers and Researchers Learning Together

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Grazing plays a key role in reducing the external inputs required for ruminant production and in alleviating feed-food competition. Beyond the production of meat and milk, grassland-based systems provide a wide range of ecosystem services. Agroecology and organic farming aim to reconcile natural resource management and food production, in the long term, based on the management of ecological processes. In this perspective paper, we report what we have learned from case studies with beef cattle, sheep, and dairy cattle across Uruguay and western Europe, in which we have been involved. Multicriteria methods, such as Pareto frontiers and positive deviances, were used to analyze trade-offs and identify win–wins from farm surveys. Long-term farm networks coupled with bioeconomic optimization models revealed fluctuations in farm income and allowed estimating system resilience. Extensive farmlet experiments made it possible to integrate knowledge on animal physiology and grassland ecology in the system redesign process and to test for innovative and risky management options that could lead to unacceptable learning costs in commercial farms. Finally, learning from farmers' local knowledge in teams with researchers and technical advisers can provide positive changes in grazing systems. In Uruguayan family farms, for example, the scientific knowledge gained from farmlet experiments led to advice on management options based on farm-specific diagnosis. Farmers adapted the proposals, with researchers supporting the processes by providing quantitative information on consequences and spaces for reflection. In a French cheese production area, the focus was on farmers' own experience. Games facilitated interactions as participants could challenge each other's reasoning and conclusions in a safe environment. These two case studies illustrate the diversity of co-innovation approaches, but in both cases knowledge sharing between researchers, farmers, and other stakeholders appeared more efficient to help farmers understand and adapt their own system properties than researching "best practice" solutions for large-scale transfer.

Keywords: agroecology, co-innovation, grazing, management, trade-offs

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INTRODUCTION

As a result of the increasing consumption of meat and milk, livestock farming systems face unprecedented pressure to alleviate their negative impacts on the environment. Recent IPCC (Intergovernmental Panel on Climate Change) reports (https://www.ipcc.ch/2019/), and various scientific publications (e.g., Aleksandrowicz et al., 2016; Mottet et al., 2017; Springmann et al., 2018; Dumont et al., 2019; Leroy et al., 2020), have framed the debate in terms of a tension between food security objectives, consumption ethics, and the damaging environmental and climate impacts associated with livestock production. Domestic herbivores, especially cattle, contribute to 14.5% of human-induced greenhouse gas (GHG) emissions (Gerber et al., 2013), and livestock production systems occupy 2.5 billion ha of land, which is approximately half of the global agricultural area (Mottet et al., 2017). The largest share of this area is comprised of grasslands, with almost 2 billion ha. In these grassland-based systems, herbivores transform feed resources that are not directly edible by humans into proteins, vitamins, and long-chain polyunsaturated fatty acids that help to fulfill our nutritional requirements (Mottet et al., 2017; Leroy et al., 2020).

Long-term carbon storage in soils, under permanent grazing lands, has a positive effect on the mitigation of climate change, soil fertility, and soil stability (Lal, 2004; Wiesmeier et al., 2019). In addition, grassland-based systems provide a wide range of ecosystem services (Rodríguez-Ortega et al., 2014), including unique cultural services such as landscape aesthetics, gastronomic heritage, and educational and spiritual experiences (Oteros-Rozas et al., 2014; Huber and Finger, 2020). Grassland-based agroecological (Dumont et al., 2013, 2020; Duru and Therond, 2015) and organic (Bouttes et al., 2019) farming systems are thus expected not only to reduce the external inputs required for meat and milk production, including soybeans and corn for animal feeds, mineral fertilizers, and energy, but also to provide a more balanced portfolio of ecosystem services than intensive production areas (Foley et al., 2005; Dumont et al., 2019). This, however, requires adequate management of herds and grasslands.

Managing the key ecological processes, to be optimized in grassland-based systems, is likely to lead in the direction of a strong form of ecological modernization, but it is also knowledge intensive. However, despite the vast amount of knowledge already accumulated on complex and changing systems, there is still limited emphasis on understanding how to learn and implement desirable transitions benefiting from these ecological processes (Geertsema et al., 2016; Rossing et al., in review). It implies learning about and monitoring of interactions among system components, developing new skills and field tools (Duru, 2013), and participatory methods to benefit from farmer experience (Berthet et al., 2016). Indeed, agroecology places strong value on local knowledge and places farmers as the designers of their production system (Rosset et al., 2011; Dumont et al., 2013, 2018; Prost et al., 2018). Engaging with farmers and other local stakeholders to generate "actionable knowledge," that is, "knowledge that specifically supports stakeholder decision making and consequent actions" (Geertsema et al., 2016), allows for the fostering of agroecological innovations. This implies integrating farmers' practices, perceptions, and values (Kosgey et al., 2006; Coquil et al., 2018), accounting for the singularities of the local production system to be transformed, e.g., edaphic and climatic conditions, new demands for products and markets (Oosting et al., 2014), and disseminating knowledge among local communities and regional stakeholders (Albicette et al., 2017). The "how to" question thus involves changes in the perspectives and values that underlie perceptions of how things need to be done (Tittonell et al., 2016).

In this perspective article, we report what we have learned from some case studies with beef cattle, sheep, and dairy cattle across western Europe and Uruguay, in which we have been involved (**Figure 1**). According to Eurostat 2010, grassland-based production areas accounted for 34% of the European herd (mainly ruminants) on 31% of the EU-wide utilized agricultural area (Dumont et al., 2019). Our case studies are located along a gradient from the most intensive areas with dairy cows (in the Netherlands) or sheep (Ireland), to intermediate- and low-density areas in French Massif Central uplands and Mediterranean grazing lands where ruminant systems deliver many regulating and cultural services. Campos grasslands occupy 700,000 km² in South America. The cow–calf system is the main livestock activity in this region, mainly in family farms (Modernel et al., 2016). Farmers raise animals for meat, and finishing takes place on-farm at pasture.

These case studies of grazing system transition to agroecological or organic systems reveal three complementary research approaches. First, the use of farm networks and farm system models generates generic knowledge by investigating the complexity, diversity, and long-term dynamics of grassland-based agroecosystems. Second, farmlet experiments allow production of technical and practical knowledge under long-term and well-controlled settings. Third, participative situations where farmers team up with researchers and technical advisers in identifying the main system problems and implementing options to improve them are likely to generate situational knowledge with a territorial scope. These different case studies reveal different modes of actionable knowledge production according to different modes of involvement of researchers with farmers.

LEARNING ABOUT SYSTEM COMPLEXITY AND TRADE-OFFS USING FARM NETWORK DATA

The use of farm network data facilitates learning about the complexity of agroecosystems from long-term series and/or from farms covering a gradient of pedoclimatic or management conditions. Farm system models allow the exploration of farm resilience. An original approach for capturing innovations occurring in commercial farms comes from the "positive deviants" approach (Sternin and Choo, 2000), where farmers identify peers with outstanding economic and environmental performance.

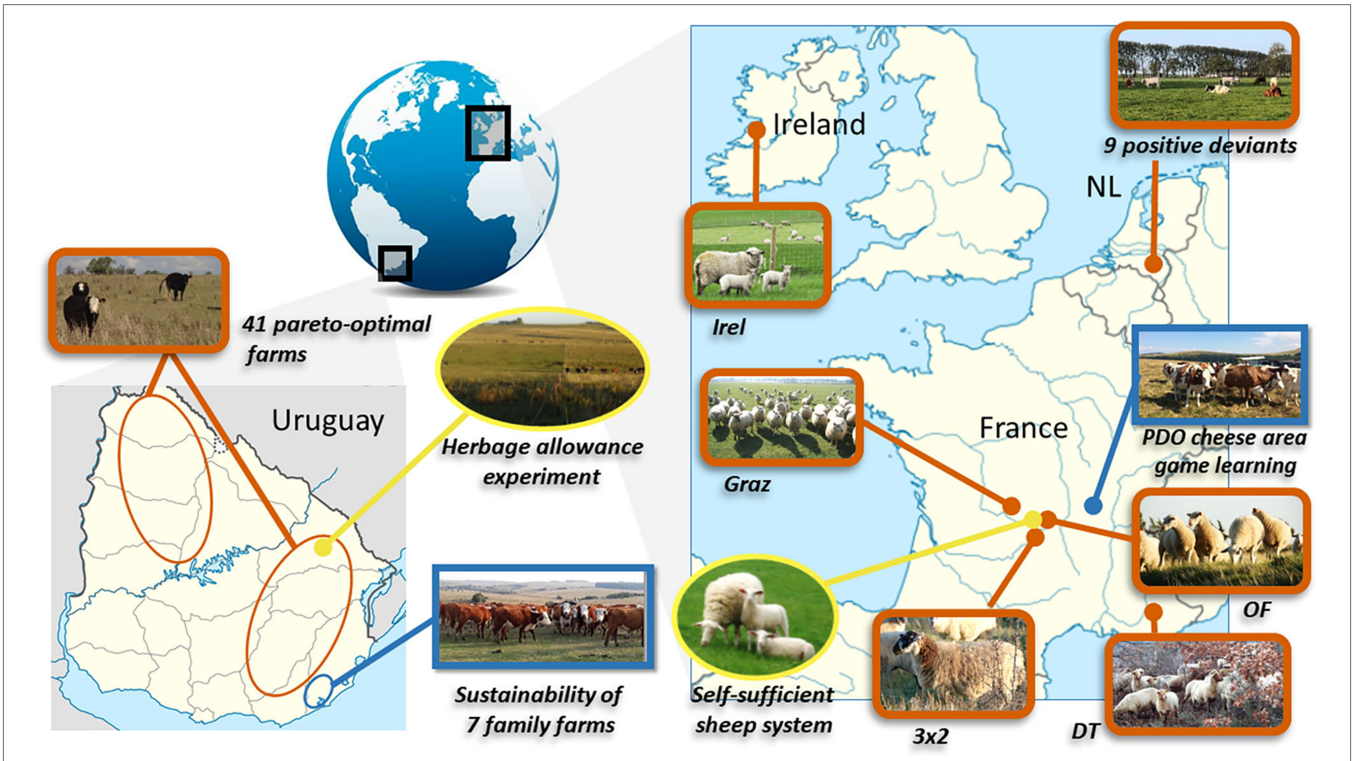

FIGURE 1 | Location of case studies. Brown rectangles are farms where trade-offs were analyzed, yellow ovals are long-term system experiments, and blue rectangles indicate a co-innovation approach.

Pareto Frontiers Identify Farms That Outperform Others in Several Dimensions

Multicriteria optimization methods such as Pareto frontiers have been successfully applied in various types of agricultural landscapes (Groot et al., 2012; Andreotti et al., 2018; Verhagen et al., 2018) to identify management options or farms that outperform others. In the Rio de la Plata grasslands, Modernel et al. (2018) identified outstanding beef farms in terms of economic and environmental performance. Performance was assessed through indicators built from field data and interviews collected from 280 farms. These farms were representative of the diversity of the farming systems of the region when contrasted with a typology based on census and large-scale farm surveys. Two methods were applied to classify the farms in both economic and environmental terms. First, through Pareto ranking, 41 farms were classified as Pareto optimal, i.e., outperforming the other farms. In a second step, four archetypes were created based on Fischer et al. (2017) production-biodiversity framework (Fischer's, 2017) and experts' threshold values. Five farms were classified as "win–win" farms, achieving beef yields of 192 kg LW.ha^{-1}.year^{-1}, earning 201 US\$.ha^{-1}.year^{-1} of farm income, with negligible fossil energy consumption, near-zero phosphorus and nitrogen balances, 13 kg CO_2-eq kg^{-1} LW of carbon footprint, and 95% of their land under native, high-biodiversity grassland. These five farms were all Pareto-optimal, which showed the complementarity of both methods in identifying multidimensionally best-performing farms. Putting this analysis in perspective, the win–win farms showed similar levels of production per hectare and carbon footprint (per kg LW) to those of the OECD countries but with significantly lower levels of fossil fuel consumption. This is explained by the low use of external feeds and inputs, making these farms of Río de la Plata grasslands an example of self-sufficiency.

Analyzing Multiperformance and Resilience in a Long-Term Farm Network

Though not formally using Pareto frontiers, Benoit et al. (2019) selected three sheep-meat farms with outstanding performance out of 118 commercial farms from central France encompassing both lowlands and uplands. These farms were surveyed for an average of 12 years and characterized based on two key variables that are good proxies for farm efficiency: concentrate feeds used per ewe and per year as these represent the main production cost for sheep farming (64% of costs in this farm network), and ewe annual productivity that is highly correlated with farm net income (Benoit and Laignel, 2011). The selected farms were *Graz,* a grazing system in the French western lowlands; *3x2,* an accelerated reproduction system with three lambings every 2 years in the upland area of Massif Central; and *OF,* an organic farm from the same area but with more shallow soils. Two other farms, *DT*, a dual transhumant system in French Mediterranean rangelands (Vigan et al., 2017), and *Irel,* a Teagasc experimental farm in Ireland (Earle et al., 2017), were selected to

TABLE 1 | Main characteristics of the five farms, including their structure, flock management strategy, and economic and environmental performance [adapted from Benoit et al. (2019)].

	Irel	Graz	3x2	OF	DT
Total area (ha)	36.8	81.9	53.9	91.9	4463
Stocking rate (ewe/ha)	11.4	6.6	8.7	4.4	0.5
FLOCK MANAGEMENT					
Ewe annual productivity %	154	133	166	132	82
Concentrates (kg/ewe)	36.5	42.2	134.6	77.1	0.0
Concentrates/kg carcass	1.22	1.55	5.24	3.41	0.00
Feed self-sufficiency (%)	94.9	94.3	78.2	88.1	100
ECONOMIC PERFORMANCE					
Gross margin (€/ewe)	89	132	121	115	74
Production costs (€/LU)	555	533	642	794	483
Added value (€/worker)	21,400	31,700	19,800	22,500	31,900
ENVIRONMENTAL PERFORMANCE					
Gross GHG (CO_2-eq/kg carcass)	21.7	18.3	22.5	24.8	28.6
Net GHG (CO_2-eq/kg carcass)	19.2	13.7	16.6	8.5	−130
NR Energy (MJ/kg carc.)	50.6	31.4	50.9	47.6	22.7
HEP conv. efficiency (%)	158	125	33	51	∞

Irel is for the Irish system, Graz is for grazing, 3x2 is for accelerated reproduction system, OF is for organic farming, and DT is for dual transhumant system. NR Energy is for non renewable energy. HEP conv. efficiency is for human edible protein conversion efficiency (Ertl et al., 2015).

extend biogeographical conditions and the stocking density range (**Table 1**).

The two farms relying the most on grasslands and rangelands (*Graz* and *DT*) showed the best economic and environmental performance (Benoit et al., 2019). Farm profitability was assessed from added value per total worker as it does not account for subsidies or wages and social costs and thus reveals the ability of the system to produce sheep meat with the maximum utilization of on-farm resources. These two farm added values were the highest thanks to a strong reduction (*Graz*) or complete avoidance (*DT*) of concentrate feeds, reducing production costs (**Table 1**). In addition, limited equipment (due to the absence of fodder stocks) and buildings led to the lowest production costs for *DT*. *Graz* and *DT* had the same added value but with contrasted production objectives, ewe productivity being 38% lower and gross margin per ewe 44% lower in *DT* than in *Graz*. Gross GHG emissions per kg carcass were the lowest in *Graz* at 18.3 kg CO_2-eq kg^{-1} carcass thanks to its high ewe productivity and limitation of inputs. When accounting for carbon sequestration in grasslands and rangelands, net GHG was among the lowest for *OF* (8.5 kg CO_2-eq kg^{-1} carcass) and even became negative for *DT*, which had a positive carbon balance. The Irish system also followed a forage autonomy strategy but with poorer environmental and economic performance due to mineral fertilization, higher prices of land, and lower meat prices (Benoit et al., 2019). Concentrate feed consumption was the highest in the highly stocked and accelerated reproduction *3x2* system, where 10.1% of the total proteins consumed by ewes were human edible, which demonstrated significant feed-food competition. Conversely, calculating the human edible protein conversion efficiency (Ertl et al., 2015) showed that the three farms that followed a forage autonomy strategy (*DT, Irel*, and *Graz*) yielded more human-edible proteins in meat than they utilized for producing it (**Table 1**). The high seasonality of lambing associated with these systems revealed a new type of trade-off between farm multiperformance and the meat industry demand for a regular meat supply throughout the year (Benoit et al., 2019) and would require adjustments in consumer demand (Singh-Knights et al., 2005).

By using a bioeconomic optimization model, Benoit et al. (2020) explored the resilience of these five farms. Simulated hazards were related to technical (ewe fertility and prolificacy, lamb mortality) and economic variables (price of lambs, concentrate and energy use). Farm performance was assessed over 3000 iterations based on simultaneous random draws with hazards related to these variables. Farm resilience was estimated from the (i) coefficient of variation of net income and (ii) frequency of two or three successive years with a drop in income. Variations in technical variables had the largest effects on income variability. The most resilience farms were those where ewes were fed little concentrates, and two or more lambing periods were planned every year, i.e., *DT*, *OF*, and *Graz*. Multiperiod lambing indeed buffered the variability of technical variables and offered adaptive management options to cope with them, i.e., moving empty ewes to a new batch for re-mating in order to maximize ewe annual fertility.

Identifying Farmer Excellence Criteria From a Positive Deviance Approach

In a case study on organic dairy farming in the Netherlands (de Adelhart Toorop and Gosselink, 2013; Rossing et al., 2019), the concept of "positive deviants" (Sternin and Choo, 2000) was used to identify farmers who, according to their peers, were exemplary. A selection of these farmers was then approached, and their farms were characterized in terms of economic and environmental performance. The aim of the study was 2-fold, firstly to identify criteria that farmers considered relevant for evaluating farm performance, and secondly to assess to what extent peer-nominated exemplary farms stood out when using science-based analytical approaches. Through a web-based questionnaire, farmers were asked to rate the importance of 12 predefined and any self-proposed additional criteria when considering good farm management. The predefined criteria were derived from the literature, experts and experience. In the next step, respondents were asked to identify the top 5 criteria and nominate farmers that they considered exemplary according to these criteria. The results showed good soil management, low use of antibiotics, income, pasture time, and climate-friendly factors to represent the top 5 indicators for positive deviance according to the dairy farmers. Respondents nominated 34 peer farmers as exemplary, some multiple times. Out of the list of these nominated farmers, three experts selected nine farms that were approached for a semi-structured interview in which more details were collected on the farmer criteria and for multi-criteria evaluation using the FarmDESIGN bioeconomic model

(Groot et al., 2012). Analysis of the nine selected farms revealed consistently long grazing seasons, low use of maize silage, positive soil organic matter balances, relatively low replacement rates of 22%, and medium-level milk production in comparison to organic or conventional averages (Rossing et al., 2019). An interesting conclusion is that farms identified by peer farmers as exemplary farms managed to balance the various performance indicators rather than excel in specific ones, except for the low or no use of antibiotics (Rossing et al., 2019). The peer-nominated exemplary farmers achieved their status by drawing on internal farm resources related to grazing and soil organic matter supply, with limited use of maize silage. The "art" of doing so with less inputs was thus reflected in peer appreciation and revealed a convergence between farmer and researcher excellence criteria.

LEARNING BY DOING IN WELL-CONTROLLED SETTINGS

Long-term farmlet experiments allow "learning by doing" in well-controlled settings. A first case study in French Massif central uplands consisted of four successive cycles of farmlet experiments that were conducted between 1988 and 2009 to design a self-sufficient and sustainable system for upland sheep production. Analytical trials were associated with the main experiment for exploring some of the biotechnical limiting issues, such as how to implement the ram effect to maximize ewe fertility for spring mating (Tournadre et al., 2002). Outputs from the system experiment were compared with technical and economic references from a network of commercial farms in the same study area (Benoit and Laignel, 2011). A second case study from the Campos grasslands illustrates how knowledge of animal physiology and plant–herbivore interactions was used to propose a conceptual model of herd and grassland management (Soca and Orcasberro, 1992) that was then tested on two experimental farms.

Farm Extensification and Transition to Organic Farming in Upland Sheep Systems

At the end of the eighties, European regulation policies were introduced into the livestock sector, including subsidies to support farming in marginal areas. These areas of low agronomic potential were gradually abandoned, which led the European Commission to set up an incentive measure to decrease stocking density by enlarging the farm area. A new research program was set up at Redon experimental farm (https://doi.org/10.15454/1.5572318050509348E12) to design a sustainable sheep system in this context of farm "extensification." We opted for a systemic approach to ensure system consistency. The first phase (1988–1992) of the experiment (**Figure 2**) aimed to adjust available forage resources to animal requirements when the available area per ewe was increased by 40%. Two farmlets (F1 and F2) were compared with the same flock size (130 Limousin ewes), one lambing per ewe and per year (2/3 in spring, 1/3 in autumn to match resource availability and optimize ewe annual productivity), and two stocking rates: 1.20 LU ha^{-1} for F1 and 0.85 LU ha^{-1} for F2. The same treatments were applied for 5 years to allow medium-term ecological processes such as shifts in plant community structure and animal adaptations. Extensification did not reduce ewe productivity and increased lamb carcass weight by 6%, despite a 26% decrease in concentrate feeds per ewe and per year. Gross margin per ewe was on average 27% higher in F2 than in F1. Three-quarters of the gross margin gain in F2 could be directly related to this 50% reduction in input costs (including mineral fertilization) that compensated for the structural costs of renting additional land. However, technical, and economic results were variable and required anticipation of management decisions and a greater technicity, especially for fodder resources (Thériez et al., 1997). Despite European incentives, only a few farmers opted for this extensification strategy. One farm from the reference network (Benoit and Laignel, 2011) did so in 1994 by increasing farm area by 20%. This farmer's net income increased by 10% per hectare between 1988–1989 and 1994–2002 thanks to a better control of production costs, which was higher than the 5% average increase reported for the 28 other sheep farms from the same area.

A second phase of the research (1993–1998) aimed at assessing the feasibility of further reducing the stocking rate. Two new systems were created with grazing at a very low stocking rate of 0.6 LU ha^{-1}. In F3, management aimed at optimizing the use of grasslands and meat production by keeping the same reproduction rhythm as in F2. As the pasture utilization rate (i.e., the ratio of grazing pressure to maximum standing biomass) was only 37% at 0.6 LU ha^{-1}, an additional goal of limiting scrub encroachment was added in F4. Grassland management led to (i) reducing farm-scale N inputs by 70% with no mineral fertilization in plots where grassland management was assumed to favor white clover; (ii) grazing early, ewes returning to pastures every 3 weeks during spring so that they browse young shoots of broom; (iii) controlling grass growth by early cuts for stocks in spring; (iv) grazing far-away plots in late spring and summer to limit shrub encroachment; and (v) grazing during winter to exploit residual herbage and preserve sward quality (Brelurut et al., 1998; Louault et al., 1998). Shrub encroachment was twice as slow in F4 as compared with F3, while system technical and economic performances were excellent for upland areas, with a 153% increase in ewe annual productivity (Dedieu et al., 2002) and only 59 kg of concentrate per ewe and per year (Brelurut et al., 1998). Lambs and lactating ewes that are more susceptible to strongyle infection were excluded from pastures grazed during the previous winter. Stock management secured the system and produced high-quality hay for lactating ewes and spring lambs that were fattened at pasture.

At the end of the nineties, organic farming was seen as an opportunity to (i) respond to an emerging societal demand and (ii) simulate innovations that would make sense in a context of exploding input costs. A third phase of the research (2000–2004) thus aimed at comparing two organic systems with a stocking rate of 0.8 LU ha^{-1} but differing in ewe reproduction rhythm. The first system was based on one lambing per ewe per year (F5), lambing being equally distributed in two periods, March and November. The second system tested an accelerated reproduction strategy with three lambings every 2 years (F6) to

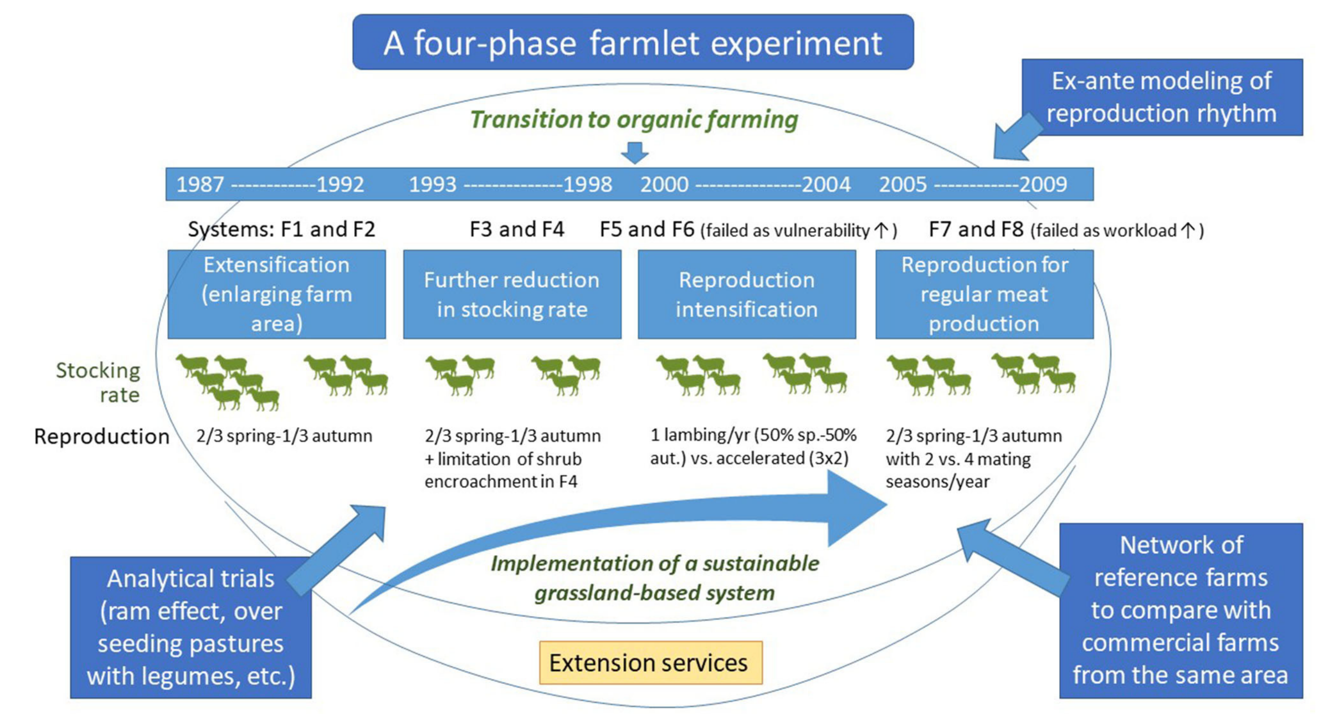

FIGURE 2 | The four successive cycles of farmlet experiments that were conducted in French Massif Central to design a self-sufficient and sustainable system for upland sheep production.

maximize ewe productivity, as observed in conventional farms from this area (i.e., *3x2* in Benoit et al., 2019; **Table 1**). In F6, ewe annual productivity was higher (161 vs. 151%) but also more variable than in F5. Ewes faced more health issues (digestive strongyles and coccidia) in F6, and lamb mortality was higher (Benoit et al., 2009). Lamb carcass weight was on average 3% less in F6 than in F5. The total concentrate per ewe was 29% higher, so the gross margin per ewe was lower in F6 than in F5 at 59 vs. 65 €, respectively. Benoit et al. (2009) concluded that reproduction intensification in an organic sheep farm did not improve economic performance and even increased system vulnerability. The less intensive reproduction system F5 had a high technical efficiency and was highly self-sufficient. The technical and economic performance of this system was better than that of commercial organic farms from the same area and similar to that of conventional farms.

The fourth phase (2005–2009) aimed to refine the reproduction rhythm to ensure regular meat production in this self-sufficient organic system. A bioeconomic optimization model (Benoit et al., 2014) suggested dividing flock mating over four (F8) rather than two periods per year (F7: 2/3 in spring, 1/3 in autumn for both systems). Putting this idea in practice led to a good utilization of forages but failed due to increased workload and difficulties in optimizing grass use with very small batches of sheep grazing large plots. Overall, this long-term farmlet experiment made it possible to incrementally develop a sustainable system for upland sheep production. Some risky options were successful, while others proved to increase system vulnerability or workload and were therefore rejected. The organic system with one lambing per ewe per year was implemented on the same land at 0.8 LU ha^{-1} by a commercial farmer at the end of this experimentation (*OF* in Benoit et al., 2019) and maximizes grass utilization with 60% lambing in spring and 40% in autumn.

Managing Herbage Allowance and Cow Body Condition in Campos Grasslands

In Uruguay, family beef cattle farmers in Campos grasslands suffer from unsustainable economic performance and degradation of these natural grasslands. The sustainability of the cow–calf system is related to the management of the cow body condition score (BCS), which influences the weaning rate. Reduced energy intake causes lower BCS at calving and lengthens postpartum anoestrus (PPA); it also decreases pregnancy rate, meat production per hectare, and farm profitability (Soca et al., 2007). Herbage production variability within and among years, together with the relatively high stocking rate traditionally used in the cow–calf system, explains why cows usually do not achieve optimum BCS at calving. Herbage allowance (HA) in kg of herbage DM per kg of animal liveweight (LW; Sollenberger et al., 2005) appears to be a relevant variable for system management. Decreasing the stocking rate leads to a higher herbage allowance from calving in spring to calf weaning in autumn (Soca and Orcasberro, 1992; **Figure 3**), which is likely to rapidly increase BCS after calving and thus shorten cow PPA and improve the pregnancy rate. This is also assumed to benefit calf weight at

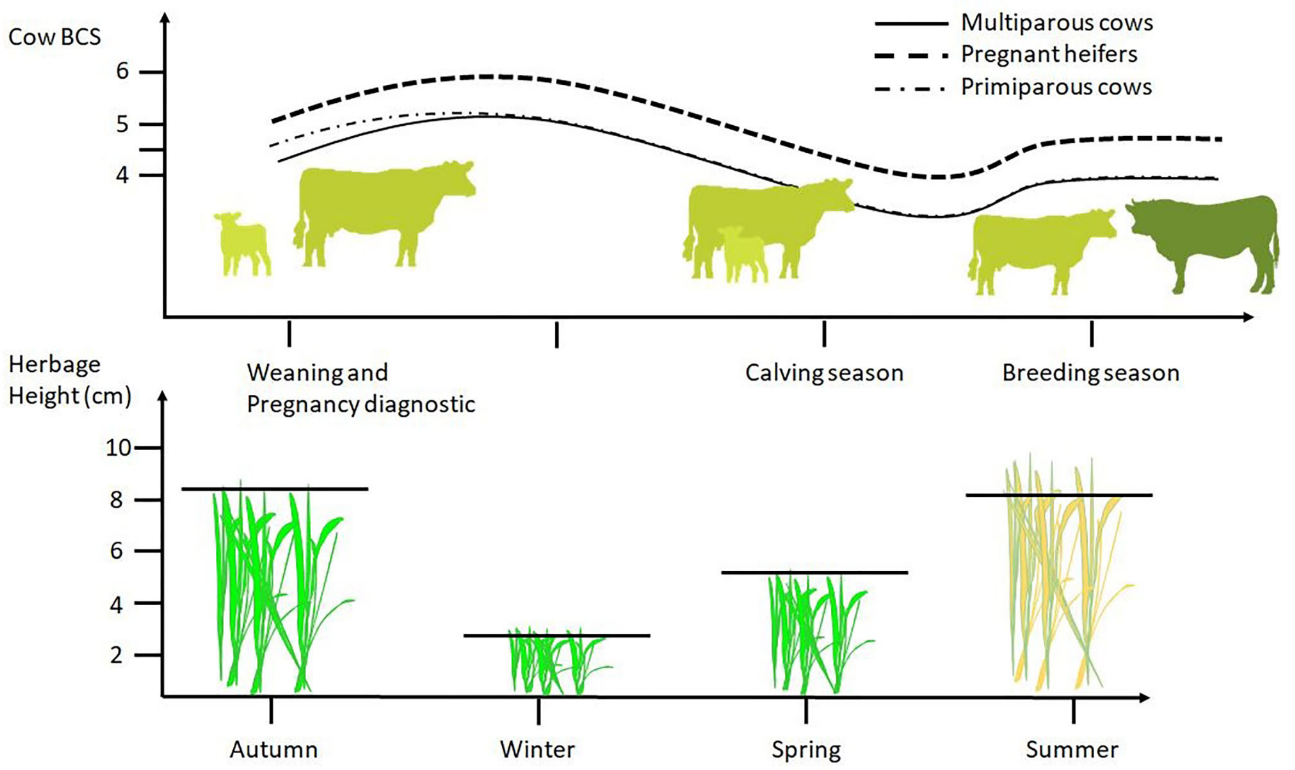

FIGURE 3 | Proposed model for the management of cow body condition (BCS) and herbage height in Campos grasslands (adapted from Soca and Orcasberro, 1992). Horizontal bars in the lower part of the figure indicate target sward heights.

weaning, meat production per ha, farm economic outputs, and ecosystem services due to a better soil cover and higher sward structural heterogeneity (Do Carmo et al., 2016).

The first phase in this research consisted of designing a grazing experiment with factorial treatments to evaluate the effects of (i) changing herbage allowance during the grazing season and (ii) using suckling restriction by fitting nose plate devices 11 days before the start of the mating period on the cow pregnancy rate and calf weight at weaning. It was confirmed that suckling restriction could shorten PPA and improve the pregnancy rate for cows with low BCS at calving (Soca et al., 2007). The second phase of this research aimed to understand the underlying metabolic mechanisms and to define when and how suckling restriction should occur. Knowledge in animal physiology suggests that (i) suckling restriction is assumed to reduce PPA by reducing cow milk production and energy requirements and by increasing circulating insulin and (ii) suckling restriction should be applied after cow energy balance nadir (55 days postpartum) when nutrient partitioning changes toward anabolic processes (Soca et al., 2007). This led researchers to investigate the consequences of suckling restriction for 12 days, from 60 to 72 days postpartum, associated with short-term (22 days) energy supplementation ("flushing" with 2 kg DM of rice middling per cow and per day) after the energy balance nadir, as a management strategy to redirect energy toward reproductive functions. Such interaction between suckling restriction and flushing appeared to be a cheap (4–10 US$ cow^{-1}) way of improving pregnancy in "thin" primiparous cows. Suckling restriction reduced milk production, which was associated with an immediate 2-fold increase in plasma IGF-I (insulin-like growth factor-I) concentrations (Soca et al., 2013b). Cow BCS at calving modulated plasma insulin and IGF-I concentrations. The metabolic response to flushing differed between cows in moderate vs. low BCS, cows with BCS lower than 4 showing poorer pregnancy rates than those in slightly better conditions (Soca et al., 2013a). Outputs from this research defined the optimal BCS targets that make manipulations of herbage allowance successful for improving cow reproductive performance (**Figure 3**).

Once these metabolic adaptations were understood, the third phase of the research consisted of testing for the effects of two levels of HA (high: HHA vs. low: LHA, which annually averaged 4 vs. 2.5 kg DM kg^{-1} LW) on cow productivity in two farms to widen environmental conditions. In one farm, multiparous cows aged 4–8 years were used, and F1 reciprocal Hereford and Angus crosses were compared with Hereford and Angus cows (Do Carmo et al., 2018). Purebred primiparous Hereford and Angus cows were used on the other farm with shallower soils (Claramunt et al., 2017). In line with the grazing management strategy summarized in **Figure 3**, herbage allowance varied seasonally. High HA increased calf weight at weaning, pregnancy success, and beef production per ha on both farms. Crossbred Angus and Hereford cattle increased kg of calf weaned per cow and cow BCS (Do Carmo et al., 2018), which confirms previous results (Morris et al., 1987). The farm stocking rate was unaffected by pasture management on this farm (Do Carmo et al., 2018) but had to be reduced by 25% in HHA compared with LHA when primiparous cows grazed on shallow soils (Claramunt et al., 2017). In this second farm, precipitation during spring–summer had a huge effect on herbage yield. The stocking rate in HHA was lower, but the cow pregnancy rate (88 vs. 59%), calf weaning weight (194 vs. 175 kg; Claramunt et al., 2017), production per unit area, and production efficiency (g calf/MJ energy consumed per cow and per year) were higher in HHA than in LHA (Do Carmo et al., 2016). High HA led to moderate improvements in cow BCS (0.5 units) and energy intake (11%) during autumn. BCS and IGF-I concentrations were greater during winter, which led to more cows ovulating early in the next breeding season and successfully increased the herd reproductive response (Claramunt et al., 2020). This set of experiments has shown how the energy flow can be efficiently used in producing beef by maximizing energy consumption by cows and improving the energy partitioning in the animals (Do Carmo et al., 2016).

LEARNING FROM FARMERS' KNOWLEDGE IN A CO-INNOVATION PROCESS

Reconfiguring farming systems to reduce reliance on external resources and enhance the availability and utilization of farm-internal resources requires rethinking both technological and organizational aspects of the farm. How to make scientific and farmer knowledge actionable for such changes is a key question (Geertsema et al., 2016; Rossing et al., in review). Knowledge sharing logic (Compagnone et al., 2018) aims to reach out to people who are traditionally excluded from scientific knowledge. Taylor and de Loë (2012) showed that scientists' "epistemological anxiety" about local knowledge was a significant barrier to its effective use in decision-making. Moreover, farmers who own local knowledge do not always feel concerned, legitimized, or even competent to contribute to their sector governance (Sterling et al., 2017). Meanwhile, the ecologization of herbivore production requires the consideration of the local context and stakeholder values, such as their relationship to nature (Coquil et al., 2018; Dumont et al., 2018). These particularities call into question the relevance of forms of intervention based on generic knowledge that do not aim for hybridization with local knowledge sources (Landini et al., 2017). We assume that such hybridization of knowledge in new learning modes between stakeholders (Caron et al., 2014; Hazard et al., 2018) would make it possible for them to share experiences and express feedback on practices and observations (Oliver et al., 2012).

Improving Sustainability of Uruguayan Family Farms Through Co-innovation

As previously discussed, research on experimental farms showed that a range of options for grassland and herd management exist that contribute to improving the sustainability of the cow–calf system. Though these advances are potentially powerful levers (Do Carmo et al., 2016; Modernel et al., 2018), uptake of the findings has been slow if not absent. It was hypothesized that a key element for the low adoption was that the scientific findings were not presented in an integrative, farm system perspective and were difficult to make locally salient for the farmers (Albicette et al., 2017). This analysis prompted a project in which a multidisciplinary team of researchers, advisors, and cow–calf family farmers worked closely together over a period of 3 years (Ruggia et al., in review). The participatory action research methodology (Moschitz et al., 2015) was used as a novel way of addressing complex agricultural problems while contributing to building capacities inside the team. Farm visits, at least monthly, supported the data gathering and mutual trust building needed to characterize, diagnose, and ultimately redesign the farms of seven participating farmer families. Beyond the farm level, half-yearly meetings were organized with selected actors from regional and national governance organizations, referred to as the inter-institutional network. The meetings served to inform these actors of the on-farm developments, thus connecting to much wider networks to enhance the spread of the results and to build the necessary institutional changes that would support farmers beyond the project's lifetime. The seven farmers had finished primary school and were on average 50-year-old (range: 37–59). At the level of the 17-person research team, meetings were held monthly to evaluate past activities in terms of both quantitative changes and changes in the attitude and skills of participants. The project thus combined a system approach with monitoring for learning while creating a setting that supported learning about new technologies and social arrangements, together denoted as a co-innovation approach.

Proposals for redesign of the seven farms were based on changes in management practices without adding external inputs and without increasing costs. The main strategy elaborated with and implemented by farmers was to increase standing biomass and forage production of the grasslands by managing the grassland–herd interaction, increasing herbage allowance (HA) and adjusting allocation of animal categories to different paddocks according to standing biomass. Associated with suckling restriction and flushing, HA management modified energy partitioning between production and reproduction, which increased the efficiency of cow energy use (Soca et al., 2013a,b; Do Carmo et al., 2016; Claramunt et al., 2017, 2020). Management of HA required variation of stocking rate and/or sheep-to-cattle ratio at the paddock or system scale and monitoring of standing biomass. Farmers contributed a lot to the redesign process by providing knowledge about land, soils, animals, and production objectives. At the beginning of the project, they used 39% of the proposed technologies. One year after starting the project, they shifted from "not planning" to starting "mid-term planning". After 2 years of implementation of the redesign proposals, farmers used 97% of the technologies (Ruggia et al., in review). Most farmers were prone to include these technologies, the more difficult ones being adjustments in stocking rate and sheep to cattle ratio (Ruggia et al., in review). On average, farmers decreased the total stocking rate by 8% and the sheep-to-cattle ratio by 42% (**Table 2**). Improvement of the grassland–herd interaction resulted in an increase in standing biomass.

TABLE 2 | Average of the main productive variables of the seven pilot farms at the start (summer 2013) and end (2015) of the co-innovation process [adapted from Ruggia et al. (in review)].

	Start	End	Diff
Total stocking rate (LU/ha)	0.92 ± 0.02	0.85 ± 0.02	−8%
Sheep to cattle ratio	2.6 ± 0.3	1.5 ± 0.5	−42%
Herbage yield (kg DM/ha)	1274 ± 390	2334 ± 344	+ 83%
Herbage allowance (kg DM/kg LW)	3.3 ± 0.2	5.6 ± 1.7	+ 70%
Pregnancy (%)	75.8 ± 3.2	91.5 ± 4.9	+ 21%
Equivalent meat, i.e., meat + wool (kg)	99.5 ± 5.9	121.5 ± 2.6	+ 22%
kg of weaning calf per breeding cow	106.4 ± 13.7	139.9 ± 11.9	+ 31%

Herbage height at the beginning of the project (summer 2012–2013 average) was half the amount required for lactating cows that should get pregnant again (i.e., 6 vs. 12 cm, respectively; Soca and Orcasberro, 1992). Over the next two summers, the average forage height and herbage allowance increased to the recommended values, which increased the herd reproductive response, production per unit area, and production efficiency (**Table 2**). Comparing the average of the 3 years before the beginning of the implementation of the redesign plans with the average of the three subsequent years, the net income nearly doubled from 31.3 ± 18.9 US\$ ha^{-1} to 59.5 ± 15.8 US\$ ha^{-1}, while production costs were slightly reduced by an average of 3% (from 109.0 ± 14.8 US\$ ha^{-1} to 105.3 ± 4.2 US\$ ha^{-1}). High standing biomass is also likely to reduce erosion risk and climate vulnerability while increasing soil carbon content. The Ecosystem Integrity Index (Blumetto et al., 2019) evaluates the state of a specific ecosystem under agricultural use in comparison to an optimal state that is established for the ecoregion. It remained stable at 3.7, which represents an acceptable to good environmental status. Finally, labor input decreased by 24% over the course of the project, which, together with the increase in productivity, resulted in an increase in labor productivity (quantity of meat produced per worker) of 97%.

The main lessons learned from the co-innovation experiences in Uruguay are as follows: (i) it is possible to significantly improve the sustainability of family farms within the limitations imposed by their current resource endowment and socioeconomic context by agroecological processes; (ii) to be successful, any change strategy should be adapted to the particular situation of each farm. Such adaptation can be achieved by a systemic process of characterization, diagnosis, redesign, implementation, and evaluation planned as a learning process with the farmers and technical advisers as main participants; (iii) researchers contribute to this process by providing scientific tools and methods to foster the learning cycle (Giller et al., 2008; Groot and Rossing, 2011); and (iv) transition to agroecological systems is a long-term process and requires developing trust between farmers, extension agents, and researchers that only a longstanding relationship can provide.

Using Games in a Local Knowledge Sharing Perspective

In France, knowledge sharing was experienced in a small Protected Designation of Origin (PDO) cheese production area (la Fourme de Montbrison) of Massif Central to build a common vision among multiple local stakeholders. The whole process consisted of six successive steps (Dernat et al., in review). First, the methodology was clearly stated with stakeholders of the PDO area, nearly 60% of all farmers, and the four processors participating in two meetings in February and March 2018. The second step consisted of 2-h interviews aiming at understanding the current concerns and perspectives of 30 PDO farmers and processors. Simultaneously, more than 300 consumers were surveyed online or on local markets for their consumption, cooking habits, and expectations on Fourme quality. The third step consisted of a collaborative day of exchanges in October 2018 with 89 stakeholders (40 farmers: 45-year-old on average [range: 22–68], 25% among the youngest with a technician certificate from agricultural college, all four processors, local officials, vets, agriculture advisors, etc.) on the PDO sector diagnosis and proposals for future actions. Two games were used as collaborative tools. The first one aimed to build a common and spatialized vision of the PDO area (Angeon and Lardon, 2008) and led to the proposal of 53 actions related to animal feeding, use of summer pastures, on-farm processing, cheese sanitary quality (e.g., safety of raw milk), conservation and valorization (e.g., opening a cheese bar), cultural heritage, and governance by a professional organization, the Fourme Union. The second one (called "the barn" because of its pentagonal appearance; **Figure 4**) provided an operational but non-spatialized representation of the PDO production area as a socio-ecological system (Ryschawy et al., 2019). It focused on how local dairy farms interact with their physical, economic, and social environment and allows the identification of synergies and trade-offs between these dimensions. Two scenarios were built, a 2030 business as usual demand and a 2030 demand with better Fourme added value. The two games were thus complementary in the knowledge they provided and allowed the expression of contrasted and sometimes antagonist viewpoints among stakeholders (Dernat et al., in review). Participants shared their empirical knowledge and collectively exercised their analytical skills by learning to position their own vision relative to that of others. In doing so, they learned to propose criteria for evaluating relevant variables and to negotiate with other participants for building a shared vision of the area. Actions proposed during the collaborative day were then submitted to an online vote of the PDO farmers and processors (step 4). The aim was to prioritize actions that were then discussed at two meetings of the Board of Directors of the Fourme Union (step 5), with researchers acting as facilitators. A 10-year strategy was then proposed based on the outputs of the whole process and presented at a meeting devoted to the farmers and processors of the PDO Union (step 6). This meeting allowed individual points of view to be expressed while strengthening the common vision. The strategy was then approved during a general assembly of the Fourme Union in March 2019.

Four major guidelines in the 10-year strategy were as follows: (i) communication focusing on the diversity of the product, reflecting the diversity of production methods and meeting consumer expectations; (ii) improvement of product sanitary quality, in particular the safety of raw milk and the conservation of cheese for a better distribution. This guideline met the expectation of both processors and farmers seeking

FIGURE 4 | Stakeholders from a French PDO cheese production area (Fourme de Montbrison) playing a game adapted from Ryschawy et al. (2019) socio-ecological framework. It allowed the expression of contrasted and sometimes antagonist viewpoints among stakeholders (Dernat et al., in review). Picture by François Johany.

empowerment and wishing to set up on-farm production; (iii) rethinking internal organization of the PDO and its functioning; and (iv) orientation of dairy production toward an agro-ecological and cultural heritage approach. This last point was also the most discussed, as it would imply a transformative approach of the current production system. It is based on an incentive (but not mandatory) to switch to a full-hay diet in at least 60% of PDO farms within 10 years. Production would thus rely on species-rich permanent pastures, which would put the ecological and cultural value of local grasslands, and the link between cattle diet and the sensory and nutritional quality of dairy products, at the heart of the production strategy. The whole collaborative process thus led to the identification and formalization of a common prospective vision for this PDO area within 1 year while accounting for contrasted priorities and values of local stakeholders.

DISCUSSION

Case studies across western Europe and Uruguay allowed us to identify win–win management options for grazing systems in terms of economic and environmental performance. Multicriteria methods, such as Pareto frontiers and positive deviances, were used to identify such win–wins from farm surveys (Modernel et al., 2018; Rossing et al., 2019), positive deviance approaches allowing a perspective from within farming communities. Long-term farmlet experiments allowed us not only to integrate scientific knowledge on animal physiology and plant–herbivore interactions in the redesign process but also to test for innovative and risky management options that would have led to unacceptable learning costs if tested on commercial farms. Some of these indeed failed, such as the *3x2* accelerated reproduction system with three lambings every 2 years under organic management (Benoit et al., 2009), and the splitting of mating into four seasons that increased workload (Benoit et al., 2014).

A key output from this case-study analysis is that while searching for multiperformance in grassland-based systems, it is essential to account for local and seasonal conditions so that the ecological and physiological processes to be optimized can provide the expected benefits (Bland and Bell, 2007; Ravetto Enri et al., 2017). A first illustration came from the herbage allowance manipulation experiments in Uruguayan Campos. In one of the farms, manipulation of herbage allowance could be made at a constant stocking rate (Do Carmo et al., 2018). On the other farm, primiparous cows grazed on shallow soils with limited water reserves, and it was mandatory to reduce the stocking rate so that improved aboveground sward productivity could increase cow energy intake during winter and BCS at calving (Claramunt et al., 2017). A second illustration came from the 3x2 accelerated reproduction system with three lambings every 2 years. While this practice is common and successful in conventional farms (see *3x2* in Benoit et al., 2019), high levels of concentrate consumption per ewe and higher lamb mortality strongly penalized this accelerated reproduction strategy under organic management (Benoit et al., 2009). Third, although an increase in self-sufficiency generally maximizes farmer profit, it could either result from (i) a drop in production costs that largely compensate for a slight or moderate decrease in milk or meat yield (Duru and Therond, 2015; *DT* system in Benoit et al., 2019) or (ii) technical gains enhancing production per animal and per hectare (Ruggia et al., in review). Different from a turn-key solution that would apply in all situations, searching for win–wins through the use of ecological processes in grazing systems thus calls for adjusting decisions to the local context and to production objectives. Such fine-tuning of grazing management is knowledge-intensive.

In analyzing these case studies, our goal was to question how researchers create actionable knowledge with farmers. We confirm the large scientific literature reviewed by Catalogna et al. (2018), who concluded that it would be more efficient to help farmers find their own solutions than searching for the best practices for large-scale transfer. For this, using social learning and collaboration approaches (Warner, 2006; Armitage et al., 2008) has a large potential to promote interactions between farmers and researchers. In Uruguay, scientific knowledge on cow reproduction physiology, plant growth, plant–herbivore interactions, and labor organization were used in a systemic way leading to a proposal of management options in the cow–calf system based on farm-specific diagnosis (Albicette et al., 2017; Ruggia et al., in review). Farmers adapted the proposals in action, with researchers supporting the processes by providing quantitative information on consequences and spaces for reflection. These reflection spaces involved regular exchanges between famers and project extension agents, as well as farmer group meetings to discuss changes in strategy. Further confidence building emerged from the involvement and enthusiasm of stakeholders operating at regional and national levels. These settings challenged some of the profound basic beliefs of farmers, including the benefits of high sheep-to-cattle ratios and attention dedicated to pasture management. Government and policy makers knowing about the project strategy and results considered it an inspiring approach for the implementation of policies. The current policy of extension services, however, does not support

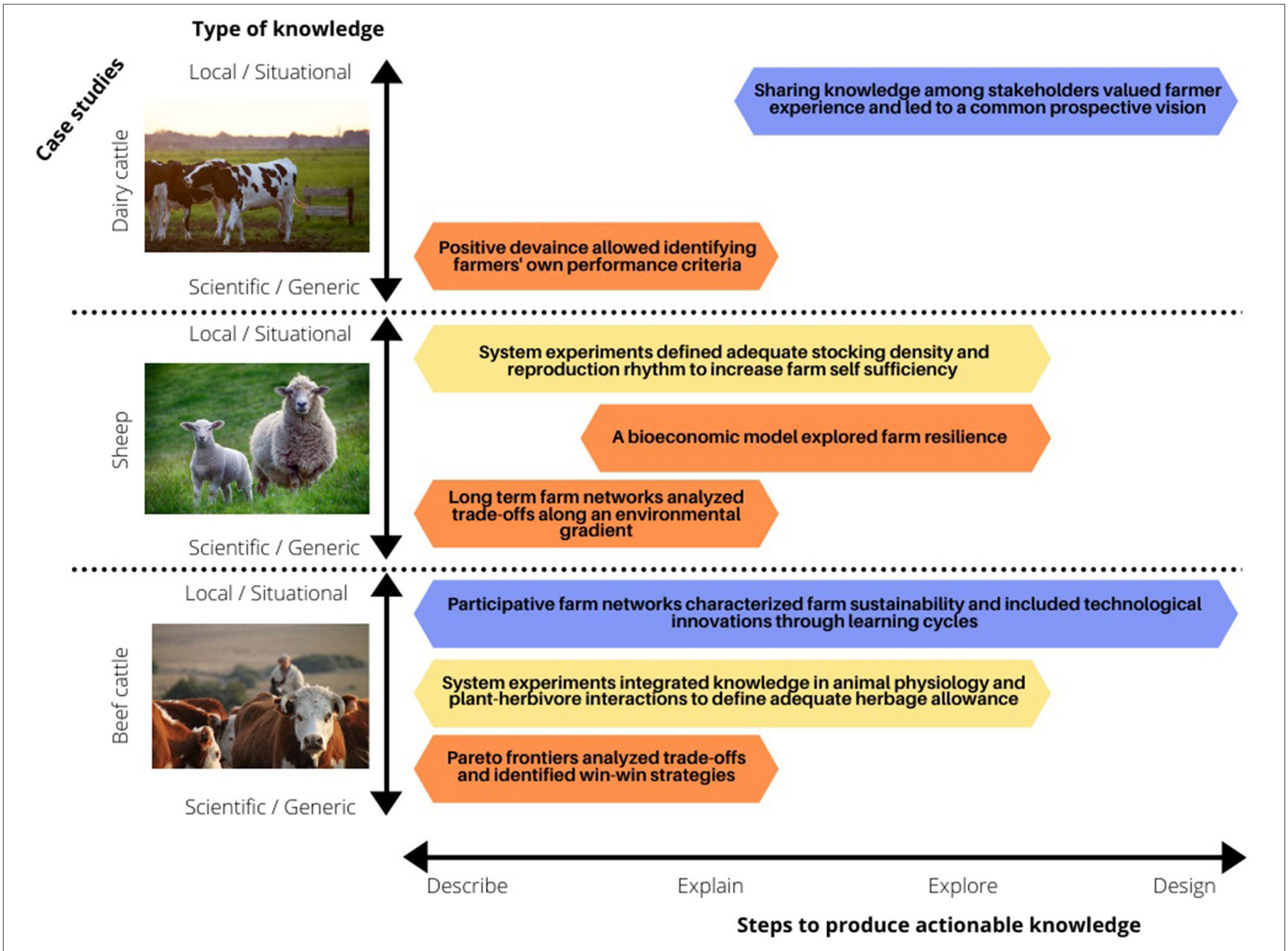

FIGURE 5 | In each production (dairy cattle, sheep, beef cattle), the different case studies from this article were reported along two axes according to the steps used to produce actionable knowledge (describe, explain, explore, design) on the X-axis and the type of knowledge that is being used (scientific—generic vs. local—situational) on the Y-axis. Box colors indicate the research approach: brown for trade-off analysis in farm network data, yellow for long-term system experiments, and blue for co-innovation.

this and rather subsidizes technical assistance around production programs focused on single products or outcomes.

In France, a crucial step in how farmers and researchers collaborated to formalize a common prospective vision for a PDO cheese area was the use of games that summarize the ecological and socioeconomic dimensions of livestock farming. Playing activity facilitated interactions as participants challenged each other's reasoning and conclusions in a safe environment despite their different and sometimes conflicting priorities and values (Dernat et al., in review). Participants taking the perspective of others more accurately were better able to explore different points of view (Johnson and Johnson, 2009) and to reach a common goal even if they did not have the answer individually. Playing allowed the discovery of unexplored options (e.g., switch to a full-hay diet) within the system and can facilitate appropriation by farmers of complex concepts such as ecosystem services. Emerging options promoted a more balanced portfolio of rural vitality and ecosystem services based on the valorization of the ecological and cultural value of local grasslands.

Crafting actionable knowledge in agricultural systems can be based on learning cycles, in which learning is conceived as a process resulting from the combination of system observation and diagnosis phases and transforming experience (Kolb, 1984; Kolb and Kolb, 2005; Cerf et al., 2012). Rossing et al. (in review) described their experiences with co-innovation and identified three dimensions of working: adoption of a complex system approach, creation of a social learning setting, and dynamic monitoring and evaluaton. In each of these dimensions, the research approaches described here provide support for systemically rethinking systems, whether to describe phenomena, explain them, explore alternatives, or select new designs for implementation (cf. Giller et al., 2008). Trade-off analyses are clearly focused on the "describe" (identifying outliers from Pareto frontiers or positive deviant approaches) and "explain" steps, while models allow the exploration of topics that are difficult to observe such as system resilience (**Figure 5**). System experiments allow to integrate scientific knowledge in the redesign process but are mainly focused on the "explain" and "explore" steps. Research that aimed to improve the sustainability of Uruguayan family farms through a co-innovation process accounted for the whole learning cycle, including the adoption of new technologies on the farms. Conversely, the focus was on farmer own experience rather than on the use of scientific knowledge in the French PDO cheese production area, researchers supporting the process by providing tools to facilitate collaboration between stakeholders. The last two case studies confirm the diversity of co-innovation approaches that aim to promote the development of agroecology (Lacombe et al., 2018). Overall, the greater the involvement of farmers as designers of their production system, the more informative the local and situational knowledge (**Figure 5**). Group learning and the structured co-innovation approach provided positive changes in grazing systems. Knowledge sharing between researchers, farmers, and other stakeholders allows the use of science-based analytical approaches and/or local knowledge in a systemic way and generates actionable knowledge to improve farm economic results while providing ecosystem services and various societal benefits.

ETHICS STATEMENT

Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

BD, PM, MB, and WR conceived of the project idea and agreed on manuscript structure and case studies. BD, PM, MB, SDe, and WR reviewed the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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