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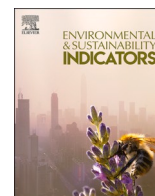
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Environmental assessment of mountain grassland farms with mixed cattle systems: use of bioeconomic simulations

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ABSTRACT

Management practices of cattle farming systems must be improved, particularly to increase the systems' feed self-sufficiency, food production and environmental performances. In mountain areas of the Massif Central (central France), mixed dairy/suckler cattle systems enable farmers to use grassland resources better and cope with economic fluctuations. Our objective was to estimate levels of ecosystem services provided by mixed dairy/suckler cattle systems as a function of the degree of mixing, along with their greenhouse gas emissions and energy use when their operation is optimized on an economic basis. The hypothesis was that mixed dairy/suckler cattle systems allow for controlled use of biomass, with better environmental performances than specialized systems (pure dairy or suckler herd) by maintaining grassland ecosystem services. Five herd-distribution scenarios were simulated using the Orfee bioeconomic optimization model. Environmental performances of the five systems were assessed according to three functional units (i.e., per farm, ha and kg protein produced). Mixed dairy/suckler cattle systems, which enabled larger herds, had higher greenhouse gas emissions per ha than specialized systems. However, because dairy cows produce more protein (milk and beef) than suckler cows, specialized dairy systems had the lowest greenhouse gas emissions and energy use per kg of protein. Specialized dairy systems had less advantage when dairy cows had less access to grassland. For the production of both milk and beef, mixed dairy/suckler cattle systems favour more sustainable use of biomass and tend to maintain a better combination of levels of ecosystem services for livestock production than specialized cattle farming systems.

1. Introduction

Unlike some mountainous areas on other continents, those in France are no longer 'wild'. They are home to agricultural and pastoral activities related to thousands of years of human presence. Because their climate and topography are not conducive to growing crops, permanent grasslands and herbivore farming systems predominate. The Massif Central is an area of medium-sized mountains in central France. Half of its mountain area is used for agriculture, and 80% of this area is covered by grasslands grazed by 4 million suckler and dairy cattle and 2.7 million sheep (Agreste, 2022). Mountainous farming systems face larger soil and climate constraints than lowland systems. Higher elevations have longer winters, steeper slopes that decrease fodder production and fragmented plots that increase distances between barns and grasslands, thus decreasing the area available for grazing dairy cows (Brunschwig

et al., 2006; Andrieu et al., 2007). Their extensively managed grassland-based systems, which have low stocking rates (≤ 1.19 live-stock units/ha of grassland area) and fertilization (mostly organic fertilization) (E.g., Farm BL22 (Cantal Chamber of Agriculture (2016))), provide many ecosystem services (ES) (i.e. values that humans place on ecosystems, and benefits that humans derive from natural resources (Wallace, 2007)) besides agricultural and cultural services, such as water supply and flow regulation, carbon (C) storage, erosion control and pollination in interaction with biodiversity (Bengtsson et al., 2019; Colas et al., 2019). These systems could play a key role in preserving biodiversity, which is currently decreasing globally (Singh, 2002). To achieve global C neutrality by 2050 (Allen et al., 2019), France needs to reduce its greenhouse gas (GHG) emissions by 80% compared to those in 2015 and increase C storage in soils to compensate for the remaining emissions (MTES, 2020). Cattle production represents ca. 9% of France's

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total emissions (CITEPA, 2022) but contributes to C storage in grasslands (Bamière et al., 2023). Actions in this sector are therefore particularly needed.

Mixed livestock systems (i.e. producing more than one breed or species of livestock) are gaining interest among researchers for application of agroecological principles, with integrated management of the types of production (Altieri, 1999; Dumont et al., 2013; Martin et al., 2020). Mixed livestock systems can help farmers decrease use of inputs and increase farm resilience by optimizing complementarities and synergies of livestock breeds or species (Diakité et al., 2019a, 2019b). In the Cantal department of the Massif Central, mixed dairy/suckler cattle farms represent 15% of ruminant farms (Agreste, 2022). In these systems, the suckler herd contains calves raised on their mothers' milk. Most calves are exported as weanlings to Italy for fattening. The dairy herd produces milk (some of which is used to make Protected Designation of Origin (PDO) cheese (Cayre et al., 2018)), calves (sold soon after birth) and cull cows. Previous studies showed that mixing suckler cattle and dairy cattle can increase grassland use (Diakité et al., 2019b), economic performance and resilience of farming systems compared to those of specialized systems (pure dairy or suckler herd) (Diakité et al., 2019a; Mosnier et al., 2022). However, the environmental performance of mixing suckler and dairy cattle has rarely been studied, particularly its relation with ES. Per kg of human-edible protein produced, dairy systems generally have a lower C footprint and use less land than suckler systems (Nijdam et al., 2012), but complementarity between the two herds can reduce their use of inputs (Diakité et al., 2019b) and thus modify the relative advantage of dairy production for certain indicators. Moreover, farmers can modify grassland management according to herd characteristics. The suckler herd has lower feeding requirements than the dairy herd, and these requirements are more likely to be satisfied by farm grasslands and fodder. Unlike dairy cows, which need to be milked every day, the suckler herd can graze on distant grasslands for several months without returning to the stable. As grassland management practices influence grassland vegetation, they may impact the ES that grasslands provide (Andrieu et al., 2007; Sollenberger et al., 2019). Trade-offs among environmental indicators are thus expected to occur as a function of the composition of the dairy/suckler cattle herd.

The study aimed to add to existing knowledge by assessing whether mixed dairy/suckler cattle herds can provide more ES than specialized systems and whether the percentage of each herd influences their environmental performances. The hypothesis was that mixed dairy/suckler cattle systems allow for more controlled use of vegetation biomass and have better environmental performances by maintaining grassland ES better than specialized systems.

The mixed dairy/suckler cattle systems assessed in this study were simulated systems. Although analysing real farms assesses farm functioning under real-world conditions, it is difficult to disentangle effects of soil and climatic conditions, farm structure and management practices. It is also difficult to measure effects of changes in practices over the long term. Modelling allows impacts of practices to be tested when considering all other things equal and to consider current knowledge from multiple sources. Optimization models of livestock systems have the advantage of consistently adapting herd size and grassland management to new constraints. Simulations were performed using the Orfee bioeconomic model (Mosnier et al., 2017) to analyse optimal operating situations. The model optimized herd size, grassland management and animal diets for five percentages of suckler and dairy cattle by maximizing profit under biological, technical, structural and regulatory constraints. Simulations were based on two mixed dairy/suckler cattle systems in the Massif Central. The objective of this study was to explore the environmental performances (i.e. GHG emissions and non-renewable energy use) of changing the percentages of suckler and dairy cattle at the farm level to analyse trade-offs among three grassland ES and each farm's environmental performance in optimized operating situations.

2. Materials and methods

2.1. Description of the model

The Orfee (Optimization of Ruminant Farm for Economic and Environmental assessment) bioeconomic optimization model represents the annual production of a farm at equilibrium, which means that grassland management and animal production are the same every year under average climate conditions (Mosnier et al., 2017). It was developed to explore livestock systems in France that also produce cash crops. It was expanded in this study to optimize decisions about herd size, ration composition, grassland use and feed purchases on farms with heterogeneous grassland plots and to assess their environmental performance.

The optimization is based on maximizing a mean-variance objective function of farm profit. The profit equals the sum of operating revenues (sales plus subsidies) minus expenses related to operation of the farm, depreciation and maintenance of buildings and equipment, taxes, wages of salaried workers and family labour opportunity costs (excluding management) estimated as the French minimum wage (8.90 €/h in 2010). In this study, cattle breeds and the percentages of livestock units (LUs) (dairy/suckler cattle) of the herds were fixed, while the total number of LUs on the farm, the crop rotation, grassland management (i.e. mowing and/or grazing), crop production and consumption, animal rations, purchases of inputs and sales of products were optimized. Optimization was achieved under ranges of constraints related to animal energy and protein requirements, animal intake capacity, herd demography, farming operations, machinery, use of space, agricultural resources, and biotechnical and biological processes related to the cattle. Orfee is a static pseudo-dynamic optimization model that uses intermediate calculations at monthly time steps to compile balance sheets. It is implemented using the mathematical modelling platform GAMS (General Algebraic Modeling System) (McCarl, 2004). It has been adapted to consider geographic constraints and plot heterogeneity based on the French typology of permanent grasslands (Launay et al., 2011; Diakité et al., 2019b), in which grassland management and production differ by grassland type.

For simulations, the model uses data related to labour (e.g. number of annual worker units, number of permanent and temporary workers), soil characteristics (e.g. soil type, fertility), plot area and management mode, which is characterized by the distribution of calving, milking and grazing periods. Animal production data (e.g. livestock numbers, cattle breeds, biological and production characteristics) and economic data (e.g. subsidies, compensation for natural handicaps, suckler cow premiums, agri-environmental grassland premiums, labour costs, input prices) were used to perform the study. Prices for 2000–2015 were calculated as a reference price calibrated according to the farm type, multiplied by the index of price variation calculated by the French National Institute of Statistics and Economic Studies (INSEE, 2018). Structural data, such as the types of buildings and equipment were specified according to the farm type simulated.

2.2. Grassland typologies and ecosystem services

2.2.1. Regional and national typologies

To estimate the levels of ES associated with grassland types and then how management practices could change grassland types, it was necessary to combine two grassland typologies. The French national typology of permanent grasslands (Launay et al., 2011) was used to define scores associated with levels of ES, and the regional multifunctional typology of grasslands of the Massif Central (Galliot et al., 2020) was used to determine how a specific grassland type would change in response to management practices (i.e. mowing, grazing and fertilization). The national typology was created with the collaboration of 78 livestock farmers in 25 departments of 12 regions of France and based on a sample of 190 of 1500 preselected grasslands (excluding

Mediterranean rangelands) (Launay et al., 2011). The national typology defines 19 types of grasslands based on their botanical composition, biomass production and the feed value of this biomass. The main criteria used to cover the diversity of grasslands are practices (i.e. grazing alone, mowing alone, grazing and mowing), intensity of use (e.g. stocking rate, grazing duration, number of cuts), amount of inorganic or organic fertilization, livestock system (e.g. cattle/sheep, dairy/suckler, suckler) and geographic area. Values for seasonal changes in the botanical composition, biomass production and feed value are set as a function of possible ranges of these characteristics. The typology also assesses the contribution of each grassland type to ES related to floristic richness and diversity. The regional typology, which was developed by surveying 143 heterogeneous plots, provides information about the botanical composition of and changes in grassland types due to management practices (Galliot et al., 2020). It defines grassland types as a function of management practices and environmental characteristics. The simplified version of the regional typology used for the study contained 23 grassland types (Hulin, 2011), but the complete version of the typology (recently updated) contains 60 types (Galliot et al., 2020). Correspondences between the regional and national typologies were determined for each type of high-altitude grassland by comparing their dominant species and management practices (Appendix 1).

2.2.2. Five grassland types considered

The national grassland types considered were those in areas where cattle grazing systems are established, particularly in mountainous areas:

- **G1:** These high-altitude grasslands with red fescue and bent grass are found on generally sloping areas 600–1600 m above sea level (a.s.l.) with acidic, dry soils of moderate fertility (based on indicator plant species). They are diversified grasslands with late phenology and low-to-moderate feed value and productivity, but which remains relatively stable during the growing season. These grasslands, which are exclusively grazed, are composed mainly of grasses. They were associated with summer grasslands.
- **G2:** These mixed high-altitude grasslands with little fertilization, aromatic species and red fescue are found 600–1200 m a.s.l. with neutral, dry soils of moderate fertility. These grasslands are composed mainly of tall grass and can be mowed and/or grazed. Their botanical composition has moderate productivity and high feed value, especially for regrowth.
- **G3:** These highly fertilized mixed high-altitude grasslands with English ryegrass and cocksfoot are found on generally sloping areas 600–1100 m a.s.l. with neutral, dry soils of moderate-to-high fertility. They are composed mainly of tall grasses. Usually mowed and then grazed, these tall grasses can be maintained by grazing alone if the appearance of ears and flowers is limited by grazing in spring. They contain early-phenology species from a variety of botanical families, with high productivity and high feed value, especially for regrowth.
- **G4:** These mixed high-altitude grasslands with common bluegrass and English ryegrass are found on areas 700–1100 m a.s.l. with acidic-to-neutral soils of moderate fertility. They are composed mainly of tall grasses. Usually mowed and then grazed, these tall grasses can be maintained by grazing alone if the appearance of inflorescences is limited by grazing from spring onwards. They are early-phenology legume-poor grasslands with very high productivity and high feed value, but which decrease rapidly in spring.
- **G5:** These high-altitude grasslands with aromatic flora, common bluegrass and perennial ryegrass are found on generally sloping areas 600–900 m a.s.l. with acidic-to-neutral soils of moderate-to-high fertility. They are composed mainly of tall grasses. Usually mowed and then lightly grazed, its vegetation can exclusively mowed. They contain early-to-medium phenology species, with

moderate productivity, high feed value in spring and average regrowth.

2.2.3. Four grass-use strategies considered

The grazing and mowing of grassland biomass was considered based on four grass-use strategies that covered the range of strategies encountered in cattle systems in the Massif Central:

- GS1: Year-round grazing (April to October)
- GS2: Late-spring or early-summer mowing (hay made at the end of June) + late-summer and autumn grazing
- GS3: Spring mowing (silage produced at the end of May, stored in silos or bales) + summer and autumn grazing
- GS4: Spring mowing (silage produced at the end of May, stored in silos or bales) + summer mowing (regrowth) + autumn grazing

These grass-use strategies were applied to the grassland types depending on the farm configuration and operation simulated by Orfee.

2.2.4. Three ecosystem services considered

Three ES provided by grasslands and described in the national typology (Launay et al., 2011) were considered:

- **Contribution to the maintenance of pollinating insects**, which corresponds to the percentage of plant species in the grassland that require insects to distribute their pollen. Launay et al. (2011) identified three levels: low (<5%), medium (5–25%) and high (>25%).
- **Floristic richness**, which corresponds to the number of plant species counted in the grassland during the botanical survey. Launay et al. (2011) identified three levels: low (≤ 25 species), medium (26–35 species) and high (>35 species).
- **Conservation of heritage floristic diversity**, which corresponds to the number of plant species in the grassland that grow in nutrient-poor environments. Launay et al. (2011) identified four levels: zero (<5 species), low (5–9 species), medium (10–19 species) and high (>20 species).

Launay et al. (2011) assigned a level or range of levels for each ES to each grassland type considered, which we converted into scores of 1.0 (low), 1.5 (low to medium), 2.0 (medium), 2.5 (medium to high) or 3.0 (high). The grassland types had the same scores for floristic richness and conservation of heritage floristic diversity (2.0 and 1.0, respectively), except for the particularly floristically rich G1 (3.0 and 2.0, respectively) (Table 1). In contrast, contribution to the maintenance of pollinating insects varied more among the grassland types (1.0–2.5).

2.2.5. Changes in grassland types due to management practices

A lack of information about the timing of changes in grassland types as a function of management practices forced us to ignore time and to rely on the grassland typologies (Fleury et al., 1988; Jeangros et al., 1991) to estimate these changes. Although grazing or mowing, amount

Table 1

Scores for ecosystem services associated with the five grassland types used in the assessment: G1: low-to-moderate feed value and productivity, G2: moderate productivity and high feed value, G3: high productivity and feed value, G4: very high productivity and high feed value, G5: moderate productivity and high feed value in spring.

Grassland type	Contribution to the maintenance of pollinating insects	Floristic richness	Conservation of heritage floristic diversity
G1	1.0	3.0	2.0
G2	1.5	2.0	1.0
G3	2.5	2.0	1.0
G4	2.0	2.0	1.0
G5	2.5	2.0	1.0

of fertilization, the date of mowing, following, trampling and under-use can influence grassland characteristics, only mowing alone or grazing alone were considered in this study. Based on the regional typology, we defined how grassland types would transition from one to another after mowing alone or grazing alone (Fig. 1). Although the grassland types have slightly different elevation ranges, their ranges overlap from 600 to 900 m. For G1, grazing alone keeps its vegetation in a stable state; although mowing alone would begin to change it to G2 and G5, it is exclusively grazed in the farming systems considered due to geographic constraints (i.e. slope, elevation, and distance from the barn). For G2, alternate grazing and mowing keeps its vegetation in a stable state, whereas grazing alone begins to change it to G1. For G3, grazing alone keeps its vegetation in a stable state, while mowing alone begins to change it to G4. For G4, grazing alone begins to change it to G3, whereas mowing alone begins to change it to G5. For G5, grazing alone begins to change it to G1 and G4 (assumed to be 50% each). Unfortunately, the national typology did not provide information about possible changes in G2 or G5 after mowing; thus, the assumption was that mowing alone kept the vegetation of G2 and G5 in a stable state. Based on these potential transitions, Orfee predictions of mowing alone and grazing alone in the grass-use strategies were used to determine manually the new distribution of areas of grassland types (Appendix 5).

2.3. GHG emissions and non-renewable energy use

We refer in that research to net GHG emissions in addition to soil C storage as the Global Warming Potential indicator (GWPI). The GHGs considered were emissions of methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂) at all stages of agricultural production and for all inputs, from extraction of raw materials to farm exit gate (Mosnier et al. 2017). Indirect GHG emissions from purchased inputs (i.e. feed and litter produced off-farm, inorganic fertilisers, purchased animals) were estimated using life cycle assessment data (whose boundaries stopped at farm entrance gate) (Agribalyse® (Koch and Salou, 2014)). Emissions related to the construction of buildings, purchase of seeds, and use of pesticides, sprayers, and machinery involved in indirect GHG emissions were not included. Direct GHG emissions from petroleum fuel combustion were estimated using the Dia'terre® method (ADEME, 2010) v. 4.51.

Carbon storage in soils was considered simply, based on estimates by Soussana et al. (2010). We assumed that permanent grasslands stored 570 kg C/ha/year, temporary grasslands kept for 5 years had a net C

storage of 360 kg C/ha/year (950 kg C/ha/year being lost in the two years following grassland destruction) and that annual crops were a net source of 160 kg C/ha/year. Real storage is much more complex, as it depends on land-use history, the initial stock of soil C, soil, climate, agricultural practices, botanical composition and grassland age (Pellerin et al., 2021).

Enteric methane (CH₄) emissions were estimated using equations of Sauvant et al. (2011) and Sauvant and Nozière (2016) that considered the quantity and quality of feed, digestive interactions and animal size. CH₄ emissions from animal manure were estimated using the Inter-governmental Panel on Climate Change (IPCC) Tier 2 equation (IPCC, 2006), but with the quantity of volatile solids excreted daily estimated from the non-digestible organic matter ingested by cattle. See Appendix 2 for more details on how CH₄ emissions were estimated.

Nitrous oxide (N₂O) emissions included direct emissions from manure management and managed soils (Tier 1; IPCC, 2006), with emission factors set at 0.01 kg N-N₂O/kg nitrogen (N). Nitrous oxide emissions from manure management were calculated according to the Tier 2 equation (IPCC, 2006) and were proportional to the quantity of N excreted by cattle. N excretion was calculated monthly as the N contained in feed ingested by cattle minus the N contained in beef and milk. This excretion was allocated to manure management systems as a function of the time spent in a given barn or plot. Indirect N₂O emissions from N volatilization and leaching (NO₃) were also included. N leaching was estimated from a farm's N balance (Simon and Le Corre, 1992), which equalled N inputs (i.e. N in purchased animals, fertilisers and feed; N fixed by legume crops; N in crop residues and atmospheric N deposition) minus N outputs (i.e. N in animals, animal products and crops sold). One percent of the N volatilized during fertiliser application as NH₃ and NO (20% of N fertiliser content) was assumed to be transformed into N₂O (IPCC, 2006).

To aggregate emissions into CO₂ equivalents (CO₂ eq.), emissions of CO₂, CH₄ (non-fossil) and N₂O were converted into CO₂ eq. using 100-year-horizon Global Warming Potentials of the IPCC WGI AR6 (Smith et al., 2021) (i.e. 1, 27.2 and 273, respectively) and then summed.

Non-renewable energy use considered both direct use (i.e. petroleum fuel (35 MJ/L) and electricity (3.6 MJ/kWh in France) used for on-farm operations) and indirect use (i.e. to produce feed and fertiliser inputs, estimated by life cycle assessment) (Agribalyse® (Koch and Salou, 2014)).

To assess the environmental performance of the systems as a function of the main production factors and animal products (i.e. beef and milk), model predictions were expressed according to three functional units: per farm, per ha and per kg of animal protein produced. The quantity of beef produced from slaughtered animals was calculated by multiplying liveweight by 0.53 (i.e. the "kill out proportion") to estimate the carcass weight, which was then multiplied by an edible meat yield of 0.70 (Nijdam et al., 2012). Animal products were converted into protein assuming that beef contained 28.5% protein (Bauchart et al. 2008) and that milk had a density of 1.03 kg/L (Pagani et al., 2016) and contained 3.2% protein (Chatellier et al., 2013).

2.4. Two virtual farm types considered

Effects of herd composition were tested for two virtual mixed dairy/suckler cattle farm types located in the Massif Central in order to capture farm heterogeneity (e.g. herds; size; plot patterns; soil, climate and geographic conditions) and to better generalize model predictions to a wider range of farms in similar contexts. The characteristics selected for each farm type (Table 2) were based on farm types constructed from real farm data in an extensive network of commercial farms in France (INOSYS Livestock Network). They mirrored the coherent running of a well-run, profitable farm for a given system and context (Charroin et al., 2005). The farm types (Farm_1 and Farm_2), which were based on real farm data, were located on two different volcanic plateaus in the centre of the Massif Central (Cézallier and Planèze de Saint-Flour, respectively)

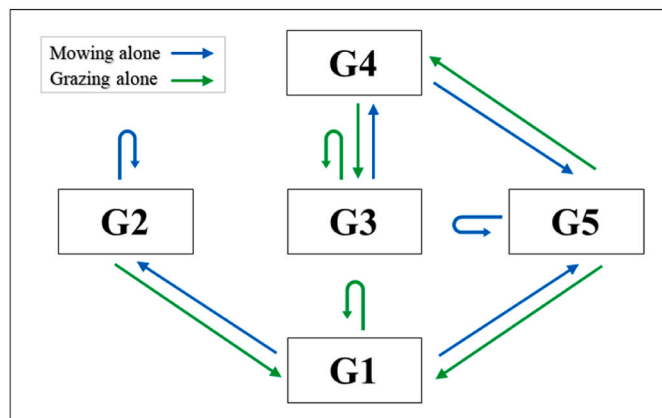


Fig. 1. Transitions between grassland types in France (G1 to G5) due to the influence of mowing alone (blue) or grazing alone (green) (arrows). Grassland types: G1: low-to-moderate feed value and productivity, G2: moderate productivity and high feed value, G3: high productivity and feed value, G4: very high productivity and high feed value, G5: moderate productivity and high feed value in spring. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Characteristics of Farm_1 (moderate size with summer grazing) and Farm_2 (large size with fragmented plots and some crops) (source: [Cantal Chamber of Agriculture \(2016\)](#)).

Characteristic	Farm_1	Farm_2
Dairy breed	Prim'Holstein	Montbéliarde
Suckler breed	Salers	Aubrac
Number of dairy cows	32	49
Number of suckler cows	35	40
Number of dairy cattle livestock units (LU)	44	72
Number of suckler cattle LU	44	55
Total LU	88	127
Percentage of LU in the dairy herd	50%	57%
Percentage of LU in the suckler herd	50%	43%
Stocking rate (LU/ha of grassland area)	1.26	1.19
Milk production by dairy breed (L/dairy cow/year)	5860	6433
Milk sold (kL/year)	180	300
Total annual work units	2.0	2.1
Useable agricultural area (ha)	70	112
Grassland area (ha)	70	107
Cereal-crop area (ha)	0	5
Temporary grassland (TG) area (ha)	0	33
G1 ^a (summer grassland) (ha)	29.5	0.0
G2 (ha)	5.5	20.0
G3 (ha)	15.0	25.0
G4 (ha)	12.0	15.0
G5 (ha)	8.0	14.0
Max. percentage of the area of TG grazed by dairy cows	100%	100%
Max. percentage of the area of G1 grazed by dairy cows	0%	0%
Max. percentage of the area of G2 to G5 grazed by dairy cows	70%	65%
Max. percentage of the area of G1 mown	0%	0%
Max. percentage of the area of TG and G2 to G5 mown	100%	100%
Maximum milk production (L/year)	180,000	300,000
Dairy calves born	Autumn	Autumn
Suckler calves born	Winter	Autumn

^a Grassland types: G1: low-to-moderate feed value and productivity, G2: moderate productivity and high feed value, G3: high productivity and feed value, G4: very high productivity and high feed value, G5: moderate productivity and high feed value in spring.

that have different soil and climate conditions, geographic constraints and plot patterns. Farm_1 represented a medium-sized farm (70 ha) with equal percentages of dairy and suckler cattle (Prim'Holstein and Salers breed, respectively) that contained only grasslands on less fragmented plots (Table 2). In contrast, Farm_2 was a large (112 ha), modernized farm with 57% dairy cattle and 43% suckler cattle (Montbéliarde and Aubrac breed, respectively) that contained grasslands and 5 ha of cereals on fragmented plots to supplement its purchases of concentrate feed (Table 2). The farms differed slightly in animal productivity, with Farm_2 producing 10% more milk per cow per year (Table 2). The main geographic constraint was the slope for Farm_1 and the distance from the barn for Farm_2.

2.5. Experimental design

For each farm, the experimental design for simulations tested five scenarios, each of which had a herd distribution defined by the percentage of the farm's LUs in a dairy (D) herd: 100D for a dairy-only herd, 75D for a dominant dairy herd, 50D for a balanced dairy/suckler herd, 25D for a dominant suckler herd or 0D for a suckler-only herd. For each scenario, the management practices that Orfee set to optimize farm profit were used to predict a new distribution of grassland types based upon their original distribution. From this new distribution of grassland types, the farm's overall score for each ES equalled the average of the scores of the grassland types on the farm weighted by the areas of the grassland types.

3. Results

Orfee's predictions of the grass-use strategies applied to grassland types (Appendices 3 and 4) determined the optimized distribution of grassland types (Appendix 5), which influenced predicted levels of ecosystem services, animal production, feed consumption and environmental performances.

3.1. Ecosystem services

For each farm type and ES, the ES score differed only slightly among the scenarios (maximum difference of 0.027 and 0.190 for Farm_1 and Farm_2, respectively) (Fig. 2). Differences among scenarios were larger for Farm_2 due to its larger size, lower stocking rate and more fragmented plots, which allowed for more flexibility in farming practices in time and space. Maintenance of pollinating insects decreased as the percentage of dairy cattle decreased (from 100D to 0D) because dairy cattle rely more on mowing, which allows more grassland plants to bloom for pollinators, whereas suckler cattle rely more on grazing. In contrast, scores for floristic richness and conservation of heritage floristic diversity increased as the percentage of dairy cattle decreased, because the increased grazing favours floristic richness and diversity. Thus, replacing dairy cattle with suckler cattle created a trade-off, which was stronger for Farm_2, which improved floristic richness and diversity but decreased maintenance of pollinating insects.

3.2. Animal production and feed consumption

Mixed dairy/suckler cattle systems grazed more grass than specialized systems. System 50D grazed the most grass and consumed the most grass overall (grazed and mowed) on Farm_1, whereas system 25D did so on Farm_2 (Table 3). The quantity of grass consumed overall increased as the percentage of suckler cow and herd size increased. The quantity of concentrate feed increased as the percentage of dairy cows or herd size increased: farm resources were used more efficiently, but additional resources were also required, which could partly offset the production benefits. As expected, specialized dairy systems produced the most milk, whereas specialized suckler systems produced the most beef. Because dairy herds produce more protein than suckler herds, specialized dairy systems produced the most protein despite having the smallest herd.

3.3. GHG emissions and non-renewable energy use

Emissions of CH₄ and N₂O per farm increased as herd size increased, as they are driven mainly by the basal metabolism of animals (Table 3). System 50D, which had the largest herd, also had the highest GHG emissions per farm and per ha. Per kg of protein produced, GHG emissions increased as the percentage of dairy cattle in the herd decreased. Most GHG emissions were CH₄ (59–69%), with relatively equal percentages of CO₂ (16–23%) and N₂O (14–23%). Emissions of CO₂ due to purchased feed were highly correlated with non-renewable energy use. The energy used in electricity depended mainly on the quantity of milk produced, due to the milking process, and increased as the percentage of dairy cows in the herd increased. The energy used in petroleum fuel increased as the quantity of grass mowed increased, which depended on herd size and the quantity of grass grazed (Table 3). The energy used for purchased feeds increased as milk production increased, due to its higher feed requirements, and decreased as the percentage of grassland area mowed increased. Specialized suckler systems used the least energy per farm and per ha, but the most per kg of protein, as dairy cows produce more protein.

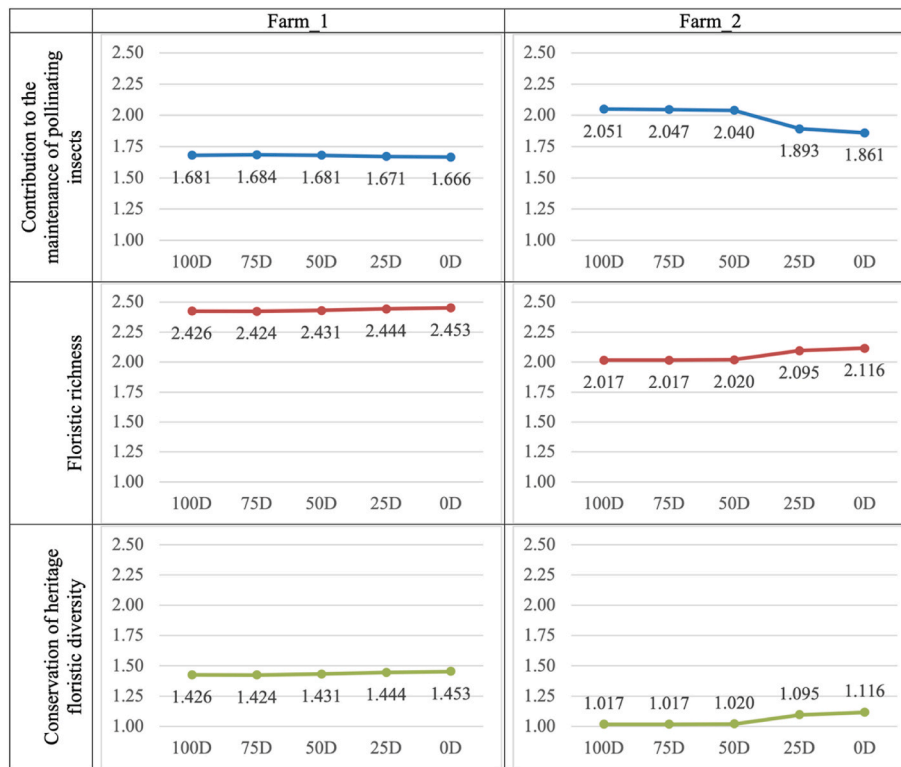


Fig. 2. Levels of ecosystem services predicted for Farm_1 (moderate size with summer grazing) and Farm_2 (large size with fragmented plots and some crops) by scenario after farm operations. Scenarios: 100D = dairy cattle herd, 75D = 75% dairy cattle, 50D = 50% dairy cattle, 25D = 25% dairy cattle, 0D = suckler cattle herd.

Table 3

Annual animal production, feed consumption and greenhouse gas (GHG) emissions and non-renewable energy use according to three functional units for Farm_1 (moderate size with summer grazing) and Farm_2 (large size with fragmented plots and some crops) by scenario^a. Bold text indicates the best value by farm.

Characteristic	Farm_1					Farm_2				
	100D	75D	50D	25D	0D	100D	75D	50D	25D	0D
Utilized agricultural area (UAA) (ha)	70	70	70	70	70	112	112	112	112	112
Livestock units (LU)	65	73	80	82	80	113	125	137	132	128
Animal liveweight produced (t)	9.0	11.8	14.9	17.5	19.1	18.1	25.9	34.3	39.7	44.7
Milk produced (kL)	264.7	221.9	162.3	83.9	0.0	500.3	415.0	310.3	150.4	0.0
Quantity of protein produced (t)	9.7	8.6	6.9	4.6	2.0	18.4	16.4	13.8	9.1	4.7
Grass mowed (t DM)	143	150	155	162	172	344	320	284	289	269
Grass grazed (t DM)	144	174	196	179	170	199	260	306	339	311
Grass mowed and grazed (t DM)	287	324	351	341	342	543	580	590	628	580
Concentrate feed consumed (t)	62	63	61	44	20	93	106	118	69	42
Energy from electricity (GJ)	190	165	130	82	29	358	308	247	143	46
Energy from petroleum fuel (GJ)	97	101	105	107	109	243	215	198	197	185
Energy from purchased feeds (GJ)	200	206	198	147	74	245	295	329	179	101
Energy from inorganic fertilisers (GJ)	131	125	116	110	103	437	636	626	653	624
Energy used (GJ)	618	597	549	446	315	1283	1454	1400	1172	956
Energy used per unit protein (MJ/kg protein)	63.9	69.7	79.2	96.6	156.3	69.7	88.6	101.1	128.1	202.1
Energy used per ha (GJ/ha UAA)	8.8	8.5	7.8	6.4	4.5	11.5	13.0	12.5	10.5	8.5
Carbon dioxide (CO ₂) emissions (t CO ₂ eq.)	51	52	50	43	32	99	126	129	111	96
Methane emissions (t CO ₂ eq.)	144	152	158	151	139	347	374	393	359	337
Nitrous oxide emissions (t CO ₂ eq.)	31	32	33	31	29	86	125	134	134	132
GHG emissions (t CO ₂ eq.)	226	236	241	225	201	532	625	656	604	565
Carbon storage (t CO ₂ eq.)	40	40	40	40	40	51	51	51	51	51
GWPI ^b (t CO ₂ eq.)	186	196	201	185	161	481	574	605	553	514
GWPI per unit protein (t CO ₂ eq./kg protein)	19.3	22.9	29.0	40.0	79.9	26.1	35.0	43.7	60.4	108.7
GWPI per ha (t CO ₂ eq./ha UAA)	2.6	2.8	2.8	2.6	2.3	4.3	5.1	5.4	4.9	4.5

^a Scenarios: 100D = dairy cattle herd, 75D = 75% dairy cattle, 50D = 50% dairy cattle, 25D = 25% dairy cattle, 0D = suckler cattle herd.

^b The Global Warming Potential indicator (GWPI) included GHG emissions and soil C storage.

4. Discussion

4.1. Ecosystem services

Orfee predicted a trade-off among the three ES. Systems dominated by suckler cows had lower maintenance of pollinators but higher floristic richness and diversity, which by increasing the nutritional quality of grassland vegetation, can be considered as a favourable trade-off from the viewpoint of cattle production. From other viewpoints, the importance of maintaining pollinators may depend on the local context.

Although Orfee operates on a monthly time step, it is a static model, and the scores associated with the ES provided by grassland vegetation were based on the most common practices (i.e. mowing, grazing and fertilization) rather than considering a wider range of management practices and their effects (e.g. changing the date of mowing, fallowing, trampling, under-use). The results should therefore be taken with caution, as understanding the changes in ES that grasslands provide requires considering more management practices in a dynamic system and over a long period. Indeed, Orfee cannot consider with sufficient accuracy the timing or trajectory of changes in biodiversity and in the area of grassland types due to management practices. Thus, grassland typologies that cross-reference environmental factors and/or practices by estimating changes caused by the most common practices were used (Fleury et al., 1988; Jeangros et al., 1991). The typologies help to consider differences, even large ones, in biodiversity among plots on the same farm. The fact that the ES results for two farm types with contrasting plot patterns and herd compositions were consistent with each other, even though only the most common practices were considered, supports the relevance of this approach.

A trade-off among the three ES requires preserving biodiversity using productive management methods, such as grazing by suckler cows that favours floristic richness and diversity. Angerer et al. (2021) also found that in the Alpine mountain (Italy), beef cattle systems have a satisfactory environmental performance and particularly negative biodiversity damage potential.

Preservation of grassland biodiversity is also promoted through the territorial organization of PDO systems, which are also designed to protect environmental sustainability (Alain et al., 2014). In Italy, for example, PDO systems favour the sustainability of mountain livestock farms that use traditional dual-purpose breeds to produce milk and/or meat (Battaglini et al., 2014).

4.2. Animal production and feed consumption

As they had the most LUs, mixed dairy/suckler cattle systems (i.e. 75D, 50D and 25D) tended to be the most intensive, with some of the highest stocking rates and largest consumption of concentrate feed. Optimizing farm profit resulted in similar grass use per LU, which had more mowing and grazing depending on whether the farm contained more dairy or suckler LUs, respectively. The results follow the logic that floristic diversity is favoured mainly by grazing and often mowing at an optimal threshold; however, when stocking rates are too high and/or mowing pressure too high, floristic diversity tends to decrease (Jouven et al., 2007).

It is important to consider farm structure because it strongly influences the interaction between stocking rates and grassland productivity (Loiseau, 1991), and this interaction makes it possible to define areas where self-sufficient livestock production can be reconciled with sustainable use of grassland (Balent et al., 1999). Many criteria thus need to be considered when determining modes of operation that favour maintenance of ES.

Other kinds of mixed livestock systems could have been considered, such as mixed sheep and cattle farming systems or those that combine 'low-productive' and 'high-productive' cattle breeds in mixed dairy/suckler cattle systems. For example, compared to high-productive cattle, low-productive Highland cattle gained more weight (Pauler et al., 2020a)

and consumed more thistles and woody plants (Pauler et al. 2020b), which increased plant species richness, grassland quality and decreased the workload needed for grassland management (Pauler et al., 2019).

4.3. GHG emissions and non-renewable energy use

Estimating GHG emissions and non-renewable energy use is essential for assessing the environmental sustainability of farm operations. Mixed dairy/suckler cattle systems tended to have the most LUs, consume the most grass, and emit the most GHGs per farm and per ha. Mosnier et al. (2022) predicted with Orfee that mixed dairy/suckler cattle systems had GHG 1–2% lower than those of specialized dairy systems, but this potential effect would likely be offset by intensification, which increases indirect GHG emissions due to purchased inputs.

Results per kg of protein did not enable us to assess how the GHG emissions of each breed were influenced by the presence of the other breed. Nevertheless, they highlighted that better resource use may induce farmers to intensify their system to make it more profitable, thus decreasing the benefits of more complete grazing of grasslands. These results also show the advantages of dairy cows, which have lower GHG emissions per kg of protein produced (Faverdin et al., 2022). Furthermore, because specialized dairy systems can provide some beef as a co-product, they can be considered multifunctional as most of the livestock systems in mountain areas with large areas of grassland (Bernués et al., 2011). However, protein from milk is not exactly the same as protein from beef; thus, specializing in dairy production may not be effective if it does not satisfy the demand for beef (Zehetmeier et al., 2012).

Replacing dairy cattle with suckler cattle on dairy farms can increase grazing and thus decrease the purchase of inputs and GHG emissions of mixed dairy/suckler cattle systems. Grazing also fertilizes grasslands with animal manure and urine while decreasing energy use for fertilizing, mowing and conditioning grass (Peyraud et al., 2010). Decreasing the percentage of dairy cattle in mixed dairy/suckler cattle systems is thus more useful for decreasing GHG emissions per farm and per ha, although they increase per kg of protein. Because the two farm types differed in environmental performances per ha as the percentage of dairy cattle increased, due to their differing geographic constraints and plot patterns, it is difficult to generalize these results per ha from a single farm type to other farms outside the Massif Central. In contrast, because the two farm types had the same trend in environmental performances per kg of protein as the percentage of dairy cattle increased, due to the relative production of milk and beef, these results per kg of protein can be generalized to other farms outside the Massif Central.

Non-renewable energy use per kg of protein estimated in this study was not directly comparable to results of other studies, which usually calculated it per unit of milk or beef. Per L of milk, the two specialized dairy systems used 2.3–2.5 MJ, which falls within the range of studies reviewed by Upton et al. (2013). Per kg of liveweight, the two specialized suckler systems used 16–21 MJ, which also falls within the range of previous studies (Angerer et al., 2021).

Energy use per farm and per ha increased as the percentage of dairy cattle increased because dairy systems require more energy than suckler systems, in order to milk cows, cool milk and heat water (Upton et al., 2013). However, as milk production results in more protein per cow, energy use per kg of protein decreased as the percentage of dairy cattle increased. This effect was smaller for Farm_1, which had a larger percentage of grasslands that could not be grazed by dairy cows or mowed. Thus, dairy cows in specialized dairy systems produced protein with more energy efficiency than they did in mixed dairy/suckler cattle systems.

The best trade-offs among levels of ES, grass use and energy use occurred in the mixed dairy/suckler cattle systems. Overall, mixed systems with suckler and dairy cattle allow farmers to improve grazing performance while maintaining their ES. Given the characteristics of specialized systems and the results of our assessment, which optimized farm operations for profit, specialized systems are less suitable than

mixed dairy/suckler cattle systems for improving resilience, environmental (Table 3) and economic (Appendix 7) performances. Resilience and economic performances were previously assessed using Orfee (Diakité et al., 2019a). Ultimately, studying farms under optimal operating situations helps estimate minimum environmental impacts of a range of viable mixed farming systems in the Massif Central.

4.4. Framework of the Orfee model

Because Orfee was not designed to consider transition between grassland types due to the management practices applied, the transitions were determined analytically by using the regional and national typologies together. Adding the ability to consider these transitions to Orfee will be a future research challenge. In any case, this study is one of the first to investigate ecosystem services along with GHG emissions and non-renewable energy using a bioeconomic optimization modelling system. Adding an additional objective function to optimize an environmental variable, such as GHG emissions per farm, at the same time as profit would increase the value of this approach. Doing so would require updating all of Orfee's IPCC-based emissions factors and equations to the most recent versions. The multi-objective optimization model that will result may provide more accurate results for assessing the environmental performance of farming systems.

5. Conclusion

Assessment of environmental performance (GHG emissions and non-renewable energy use) depends greatly on the structure, production potential and main specialization (milk, beef or both) of a livestock system. The hypothesis was that mixed dairy/suckler cattle systems allow for controlled use of biomass, with better environmental performances than specialized systems (pure dairy or suckler herd) by maintaining grassland ES. No single system configuration outperformed the others for all indicators of ES, feed consumption, GHG emissions and non-renewable energy use. Environmental performance of systems can be assessed only by considering functional units (e.g., per farm, per ha, per kg protein produced). Thus, systems with the best trade-offs among levels of ES, GHG emissions and non-renewable energy use cannot be identified without also considering production objectives. The study shows that mixed dairy/suckler cattle systems tend to have larger herds. However, more protein is derived from milk in dairy cattle systems than from beef in suckler cattle systems. The GHG emissions per ha appear higher for mixed dairy/suckler cattle systems, but due to the higher protein production of dairy cows, specialized dairy systems have better environmental performances per kg of protein produced. However, these performances are lower on farms in which dairy cows have less access to grasslands for grazing. The influence of the percentage of dairy cattle in the herd on ES depends on the percentage of grassland areas grazed or mowed. The relative advantage depends on the ES considered, but systems dominated by suckler cows tend to favour more sustainable grass use and better trade-offs for livestock production among the main ESs. In general, intensification should remain moderate to tend toward sustainable grass use. Overall, mixed dairy/suckler cattle systems were not necessarily the most favourable in this study, partly because it is economically optimal to increase the size of their herds. However, when the farm objective is to produce both milk and beef and supply the ES assessed, mixed dairy/suckler cattle systems tend to offer a good compromise. It would be useful to assess the systems under real dynamic operating conditions to understand better how ES and the use of grassland resources vary over time.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.indic.2023.100259>.

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