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ORIGINAL ARTICLE

Can traditional management practices help mountain livestock farms in the Spanish Pyrenees cope with climate change?

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Abstract

Livestock grazing systems constitute a traditional activity in mountain areas. They are adapted to vegetation growth cycles in meadows, forests and grasslands, and deliver ecosystem services such as open landscapes, wildfires prevention, biodiversity maintenance and quality products. Climate change poses a new challenge on mountain grazing systems by impacting on its natural resource base. We used the model NODRIZA to evaluate the potential impact of three scenarios of altered pasture quality and quantity due to climate change (optimistic, medium and worst) and a business-as-usual scenario (BAU) on four beef farms representative of the existing grazing systems in the Spanish Pyrenees. We explored the role of traditional management practices (e.g. modifying the grazing season and early weaning) to cope with these changes. Cow body condition score, feed self-sufficiency and gross margin were the indicators of farms functioning. The optimistic scenario improved all farming indicators during most of the modelled period and then declined—still above BAU levels—in the long term. The medium scenario resulted in an initial improvement of farming indicators and a decline to BAU levels in the long run. The worst scenario declined all indicators below BAU levels. The four case studies were impacted in the same direction but to different extent, farms oriented to fattened calves suffered higher impacts than those focused on weaned calves. Traditional adaptation actions succeeded to maintain cow body condition score steady, but they came at the expense of lower feed self-sufficiency and gross margin, becoming impractical to face climate change.

Keywords Modelling · Adaptation · Grassland · Feed self-sufficiency · Profitability

Introduction

Grazing livestock systems play a key role in mountain regions. These systems constitute an economic sector that ties people to marginal rural areas (Collantes and Pinilla 2004), are located in non-arable areas so they do not

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compete with land for human food, make a limited use of fuel-dependent inputs and are associated with the provision of ecosystem services, being considered by some as a sustainable way to produce animal food products (Franzluebbers and Martin 2022; Benoit and Mottet 2023). Mountain livestock systems obtain a major share of nutritional requirements of animals by grazing natural and semi-natural pastures (Muñoz-Ulecia et al. 2021). This management allows for a relatively lower dependence on off-farm feeds but tightens the well functioning of the farm to the availability and quality of natural resources, making them vulnerable to climate change impact on mountain grasslands. As a result, animal and livestock health and productivity can be negatively impacted by climate change in Europe, particularly in mountain regions (IPCC 2022). Moreover, the impacts of global change on ecosystems are expected to get worse over the coming decades (IPCC 2022), affecting the natural resource base of pasture-based livestock systems, particularly forage crops and grasslands (Weindl et al. 2015).

Meta-analyses have compiled the direct impact of expected climate changes on European pastures and grasslands (Dellar et al. 2018; Dumont et al. 2015). Most of them are based on short-term experiments in which the effects of increasing CO_2 concentration, increasing temperatures or reducing water availability are measured on biomass and nitrogen content—as an indicator of pasture quality—in pasture samples (Dumont et al. 2015). Dumont et al. (2015) found a general decrease of pasture quality with the increase of the CO_2 concentration ($-10 \pm 5\%$ in N content). Conversely, in mountain pastures, the warming effects combined with a reduction in water availability increased the forage quality ($+9 \pm 5\%$ in N content). However, extreme events (i.e. simulation of a 2-week heat wave at + 6 °C with a 3-month summer drought) decreased pasture biomass and quality (Niderkorn et al. 2014). Dellar et al. (2018) estimated an increase of 82.6% in biomass stimulated by higher temperatures in Alpine areas; however, when combined with dryer conditions, the biomass is expected to decrease by 20%. Few studies have explored the long-term effects of changes in CO_2 concentrations, temperature and water availability (Dumont et al. 2015). Cantarel et al. (2013) analysed the combined impact of these factors on mountain pastures over a 4-year experiment. Their results showed an initial increase in both biomass (+ 32%) and N content (+ 68.2%) in the first year of the experiment, followed by a sharp decrease during the last years of the experiment (reductions of 30% and 24% of the biomass in the third and fourth years; and 20.5% decrease in N content in the fourth year). The warming effects seem to counterbalance the stimulatory effects of elevated CO_2 concentrations on primary productivity (Cantarel et al. 2013).

We must also consider the indirect impacts of climate change on mountain pastures related to altering species composition and vegetation growth cycles (Campbell and Stafford Smith 2000; Dellar et al. 2018), which has already contributed to reducing 15% of grasslands' carrying capacity in Western Europe (Piipponen et al. 2022). Under warmer and dryer conditions, in the Pyrenees, changes in species composition have been shown to decrease forage quality (Sebastià 2007). The awareness of these impacts and the need to adapt to them, despite all uncertainty associated, has pushed researchers to investigate future scenarios via modelling.

Modelling studies have mostly focused on the impacts of different climate scenarios on livestock systems productivity, the impacts of livestock-associated emissions on climate change, the mitigation opportunities, or, less commonly, price variations effects (Diakité et al. 2019; Dono et al. 2016; Graux et al. 2011; Harrison et al. 2016; Moore and Ghahramani 2013; Qi et al. 2015; Rivington et al. 2007). Other studies have modelled the effects of different farm adaptation strategies to climate change in beef farming systems (e.g. Descheemaeker et al. 2018; Dynes et al. 2010; Martínez-Valderrama et al. 2021; Rotz et al. 2016; Tui et al. 2021). These strategies commonly included increasing the amount of feedstuffs offered indoors (on-farm-made or purchased), reorganizing calving dates and modifying stocking rates (Dynes et al. 2010; Chapman et al. 2012; Martínez-Valderrama et al. 2021). Although managing the grazing season is critical to adapt to the available resources in mountain beef farming systems, only some studies have focused on modifying the grazing length (Dynes et al. 2010; Harrison et al. 2017).

The success of adaptation strategies focusing on infrastructure or off-farm feeds heavily depends on market fluctuations rather than the farming systems' particularities (Harrison et al. 2017). Conversely, herd management options tend to rely on both the specificities of the farming system and the regional socio-economic and environmental contexts (Dynes et al. 2010; Chapman et al. 2012; Harrison et al. 2017). It is worth noting that while modellers typically address the technological and economic aspects of adaptation, they often overlook the importance of behavioural, cultural and social factors that can significantly impact farm performance (Nielsen et al. 2020). These overlooked factors can profoundly impact the success of adaptation strategies, and a more comprehensive understanding is necessary for effective adaptation planning.

In this context, we explore the role of traditional management practices to cope with possible long-term effects of climate change on mountain pastures, focusing on beef farming systems of the Pyrenees. To do so, we modified the computational model NODRIZA (Villalba et al. 2006, 2010, 2012) to evaluate (i) the potential impact of three hypothetical scenarios of altered pasture quality and productivity due to climate change and (ii) the role of technically and socially feasible adaptation strategies on the performance of four characteristic beef farming systems in the Central Spanish Pyrenees. We analysed farm performance focusing on indicators related to farm economics, feed self-sufficiency and animal productivity.

Materials and methods

Study region and case studies

The region under study is the Spanish Central Pyrenees, specifically the valleys of Broto, Benasque and Baliera-Barrabés, in Huesca province, Aragón Autonomous Community. Each valley has socio-economic and biophysical particularities, which resulted in four different farming trajectories of evolution of beef farming systems in the last three decades (Muñoz-Ulecia et al. 2021). In a nutshell, three farming trajectories were specific to each of the studied valleys, and one trajectory was generic across valleys. The valley-specific trajectories maximised their output related to the most limiting production factor in each valley (i.e. agricultural area or labour availability). The fourth trajectory showed very few changes through time. These trajectories represent the heterogeneity of beef farms in the study region (Muñoz-Ulecia et al. 2021). One farm from each trajectory was selected as case study and included in our model to represent the existing diversity across mountain beef farming systems (Table 1). The animals (Parda de Montaña breed) spent around two-thirds of the year on pastures (mountain, meadows and forests) and were housed during the winter months. The pastures were mostly permanent meadows (where the most abundant species are typically *Dactylis glomerata*, *Festuca arundinacea*, *Trifolium repens*, *Poa pratensis*, *Lolium perenne*), forest pastures (*Pinus sylvestris* and *Pinus nigra* woodlands, with *Buxus sempervirens*, *Juniperus communis* and *Genista scorpius* shrubs, and herbaceous cover dominated by *Brachypodium* spp., *Bromus erectus*, *Festuca rubra*, *Carex* spp. and *Aphyllanthes monspeliensis*), and subalpine mountain pastures (grasslands of *Festuca rubra*, *Festuca skia*, *Bromus erectus*, *Nardus stricta*, *Trifolium alpinum*) (Casasús et al. 2002; Álvarez-Rodríguez et al. 2007). Cows calved in spring and autumn (in different proportions) and calves were sold at weaning (6–7 months) or fattened (10–12 months).

NODRIZA model

NODRIZA is a dynamic and stochastic model designed to simulate herd dynamics in beef farming systems. The model was developed using VB.NET language and object-oriented software development approaches. A detailed description of the model programming is available at Villalba et al. (2006, 2010, 2012). It considers the interaction of animal feeding, herd management and animal reproduction. NODRIZA can simulate the short, medium or long-term effects of various feeding strategies, use of natural resources and reproductive management; and evaluates the results in terms of technical and economic performance. The stochastic simulation considers animal variability within the herd and environmental variability between years, as has already been shown in previous studies (Villalba et al. 2006, 2010, 2012).

Feeding is considered on a batch basis, assuming that (on average) all animals consume the same amount of feed

Table 1 Main variables describing representative case studies

Variable	Type 1 – Large herd with small area 'Broto'	Type 2 – Small herd a low labour input 'Benasque'	Type 3 – Fattening and large area 'Baliera'	Type 4 – Small family farm 'Across-valley'
Herd size (cows)	104	46	200	31
Weaned calves sold	100	40	0	20
Fattened calves sold	0	0	160	0
Autumn calving's (%)[1]	50	75	65	50
Grazing season length (d)	259	236	243	243
Winter housing length (d)	106	129	122	122
Winter feeding	Hay, concentrates	Straw, concentrates	Straw, hay, concentrates	Hay, concentrates
Agricultural area, UAA (ha)[2]	27	25.1	100	23
Labour force (WU)	2	-0.5	4	1.2

All variables describing each farm used in the model are available in the Appendix, Table A1. [1]The rest of calving takes place during spring; this is an initial value that varies due to the dynamic modelling depending on stochastic variables and bull entry date, mating length and days to weaning. [2]Utilised agricultural area (UAA) is the sum of area used for cash crops, forage crops, pastures, grazing land and other agricultural uses, expressed in ha according to resource availability and animals' physiological state. The number and type of feeds (concentrates, dry forage or green forage), their energy value and the daily availability are inputs of the model. The key dates that define reproductive management are the weaning day and the mating period (defined by the entry and exit dates of the male in the group). The number of animals in the batch and their individual initial live weight (LW) and body condition score (BCS) at the start of the simulation are also model inputs. The physiological status defines the initial day of gestation and/or lactation of each cow. Some parameters are fixed, whereas others that differ for each cow are obtained with stochastic techniques. Stochastic parameters of the model have been adjusted from Villalba et al. (2010). Calves' selling prices and feedstuffs' prices are kept constant at 2018 values. As model outputs, NODRIZA provides a series of variables that we used to calculate indicators of (i) animal performance (BCS and LW of cow and LW of calves), (ii) feed self-sufficiency (energy obtained from grazing vs total energy intake) and (iii) economic performance (gross margin, incomes minus variable costs).

In this study, we parameterised NODRIZA with data from the four case studies and included the potential impact of climate change on natural forage quality and productivity. We ran 100 simulations per scenario and case study to represent variability both in the stochastic parameters and their linked variables (energy intake from natural and purchased inputs, costs and incomes). A visual representation of the model is available in Fig. 1.

Future scenarios

We built three scenarios based on the literature representing the potential impacts of climate change in mountain pastures (Sebastià 2007; Cantarel et al. 2013; Dumont et al. 2015; Dellar et al. 2018): *CC_OPTIMISTIC*, *CC_MEDIUM* and *CC_WORST*. Using the current climate change projections available in the Worldclim database for the Spanish Pyrenees region in 2050, we confirmed that future conditions under a worst-case scenario (CMIP 6, Shared Socioeconomic Pathway 5–8.5, Global Climate Model BCC-CSM2-MR, Eyring et al. 2016) are similar to those described in the literature (Table 2). The scenarios vary in the climate effects on pasture productivity and quality and in the occurrence of extreme events during a 30-year simulation period. We distinguished between short-term effects during the first

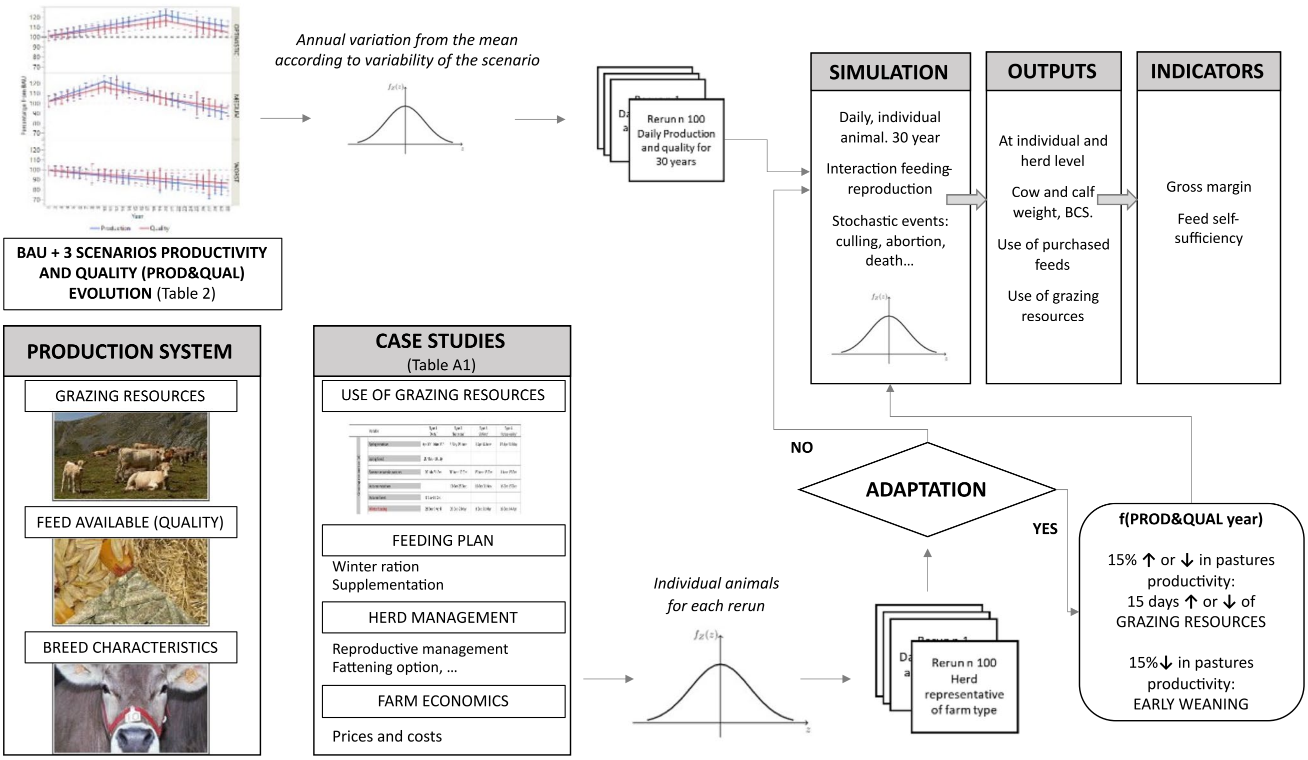

Fig. 1 Graphical representation of the model functioning. Scenarios represent climate change impact on natural pastures productivity and quality. Climate change and BAU scenarios are run 100 times to account for variability and stochasticity, including the grazing resources, feeds and breed characteristics for each of the case studies. This is measured individually for each animal in each day across a 30-year period. Adaptations include a 15% increase or reduction of the grazing season if pastures productivity increase or decrease a 15% or more, and early weaning if pastures productivity decrease a 15% or more. Adaptations are implemented when the threshold is reached

Table 2 Comparison between the expected conditions in the Spanish Pyrenees in 2050 (Shared Socioeconomic Pathway 5–8.5, Global Climate Model BCC-CSM2-MR) and the conditions of the experiments described in the literature

Variable	Regional projection (2050)	Cantarel et al. 2013	Dumont et al. 2015	Dellar et al. 2018
Atmospheric CO_2 concentration (ppm)	560	585 ± 144	363 ± 15	279 ± 81
Annual mean temperature	+ 3 °C	+ 3.5 °C	2.2 ± 1.5 °C	3.1 ± 1.7 °C
Annual rainfall	− 8%	NA	NA	NA
Rainfall in summer	− 17%	− 20%	− 48 ± 22%	81 ± 26%
Maximum temperature in summer	+ 5 °C	NA	NA	NA

decade, mid-term effects in the second decade and long-term effects in the last decade (Table 2). We also considered a differential effect of the summer season and extreme events, which reinforces the effects of climate change (both positive and negative), and interannual variability on the impacts of climate change that increases over time (Table 2). The values are consistent with the expected short-term (Dumont et al. 2015) and long-term (Sebastià 2007; Cantarel et al. 2013) effects of climate change for mountain areas. Since NODRIZA models pastures in energy terms, we explored the relationship between N content and the energy using data from INRA on mountain meadows (Agabriel 2007). We found a linear correlation between these variables ($R^2 = 0.639$, $n = 39$).

In *CC_OPTIMISTIC*, both the productivity and the quality of pastures increased in the short and mid-term by 20% and 15%, respectively (with an annual increase of 1% in productivity and 0.75% in quality, Table 3). In the long-term, the warming effects reached an inflection point, negatively affecting both parameters. During the last decade, the pasture productivity and quality were reduced by 10%. We included an extreme event in this scenario (i.e. a pulse disturbance in the year 25 of the simulation that lasts a year), which increased the variability of the pasture quality and productivity by 75%.

The *CC_MEDIUM* increased, in the short-term, the pasture productivity and quality by 20% and 15%, respectively (Table 3). An inflection point occurred after the first decade. During the mid and long term, the productivity and quality dropped by 30% and 20%, respectively. This scenario included two extreme events (in the years 12 and 25 of the simulation).

In the *CC_WORST*, the negative effects of climate change appeared from the beginning, slowly but continuously over time. During this scenario, the pasture productivity and quality decreased by 20% and 15%, respectively (Table 3). In this scenario, there were three extreme events (in the years 8, 12 and 25 of the simulation).

In addition, we considered two management scenarios: (a) *BAU* (*business as usual*) where no action to adapt is taken and (b) *ADAPT*, where two common management strategies (detailed below) are introduced. Combining climate and

Table 3 Description of the climate change scenarios, including the yearly change in pastures quality, productivity and variability

			Yearly variation (%)[1]					
			OPTIMISTIC		MEDIUM		WORST	
Simulation decade	Grazing resource		Mean	CV	Mean	CV	Mean	CV
1–10 years	Spring/autumn	Quality	0.75	0.10	1.50	0.10	− 0.50	0.15
		Productivity	0.10	0.15	0.20	0.10	− 0.67	0.15
	Summer	Quality	0.10	0.20	0.20	0.20	− 0.10	0.25
		Productivity	0.15	0.25	0.25	0.20	− 0.10	0.25
11–20 years	Spring/Autumn	Quality	0.75	0.10	− 0.10	0.15	− 0.50	0.15
		Productivity	0.10	0.10	− 0.15	0.15	− 0.67	0.15
	Summer	Quality	0.10	0.20	− 0.15	0.25	− 0.10	0.25
		Productivity	0.15	0.20	− 0.20	0.25	− 0.10	0.25
21–30 years	Spring/autumn	Quality	− 0.10	0.15	− 0.10	0.15	− 0.50	0.20
		Productivity	− 0.10	0.15	− 0.15	0.15	− 0.67	0.20
	Summer	Quality	− 0.15	0.25	− 0.15	0.25	− 0.10	0.30
		Productivity	− 0.15	0.25	− 0.20	0.25	− 0.10	0.30

[1] Yearly variation in mean Quality and Productivity and Coefficient of Variation (CV) of Quality and Productivity. The initial value for both parameters is 100 and 5 for Mean and CV respectively

management scenarios results in seven different scenarios. The *BAU* (without the effects of climate change) is the simulation used as reference or baseline to measure the impact of climate change, while the *BAU* in each climate scenario is used as baseline to measure the role of the adaptation strategies.

Adaptation strategies

We considered two of the most frequent actions farmers take to face yearly fluctuations in the region: modification of the grazing calendar and early weaning (Blanco et al. 2008a; Muñoz-Ulecia et al. 2019). The modification of the grazing calendar was included in the model by increasing or reducing the grazing season 15 days when pasture productivity increases or decreases by 15% or more, respectively. Early weaning has been proposed as a strategy to reduce the nutritional requirements of beef cows to maintain lactation and therefore enhance the recovery of LW and BCS on pasture, given that dry cows can make a better use of relatively low-quality pastures (Casasús et al. 2002). Therefore, early weaning was included when pasture productivity declined 15% or more. Minimum calf age for early weaning was established at 90 days. Adaptation actions were automatically implemented when conditions fulfil the thresholds stablished; therefore, both actions could be implemented simultaneously.

Results

Differences across case studies—BAU scenario

Our results show that all case studies have different functioning for the indicators under analysis (BCS in Fig. 2, feed self-sufficiency in Fig. 3 and gross margin in Fig. 4). *Baliera type* is the only one where calves are fattened on-farm, and it is characterised by having the highest cow BCS (around 3.5) (Fig. 2), a feed self-sufficiency around 63% (Fig. 3) and a farm gross margin around 25,000 €/year (Fig. 4). *Benasque type* presents the lowest cow BCS (around 2) (Fig. 2), feed self-sufficiency (62%) (Fig. 3) and an average gross margin equal to *Baliera type* (Fig. 4). *Broto type* presented a cow BCS of 2.5 (Fig. 2), the highest feed self-sufficiency (67%) (Fig. 3) and the highest farm gross margin (60,000 €/year) (Fig. 4). Finally, the *Across-valley type* presented average BCS around 2.5 (Fig. 2), feed self-sufficiency above 66% (Fig. 3), but the lowest gross margin (below 20,000 €/year) (Fig. 4). When considering gross margin per cow, we observe that *Baliera type* presented the lowest value (around 125 €/cow), while the other three types presented values around 550–650 €/cow.

Impact of climate change scenarios across case studies

OPTIMISTIC climate change scenario All case studies improve their performance during the first two decades while there is a decline during the third decade. Regarding BCS and feed self-sufficiency, all farming types show a similar trend due to increasing quality and availability of natural resources (Figs. 2 and 3). *Baliera type* presents the highest BCS and feed self-sufficiency values, but also the smallest increase since baseline values were already high. Still, all indicators remain above BAU levels except for gross margin in *Baliera type*, with values similar to BAU scenario (Fig. 4).

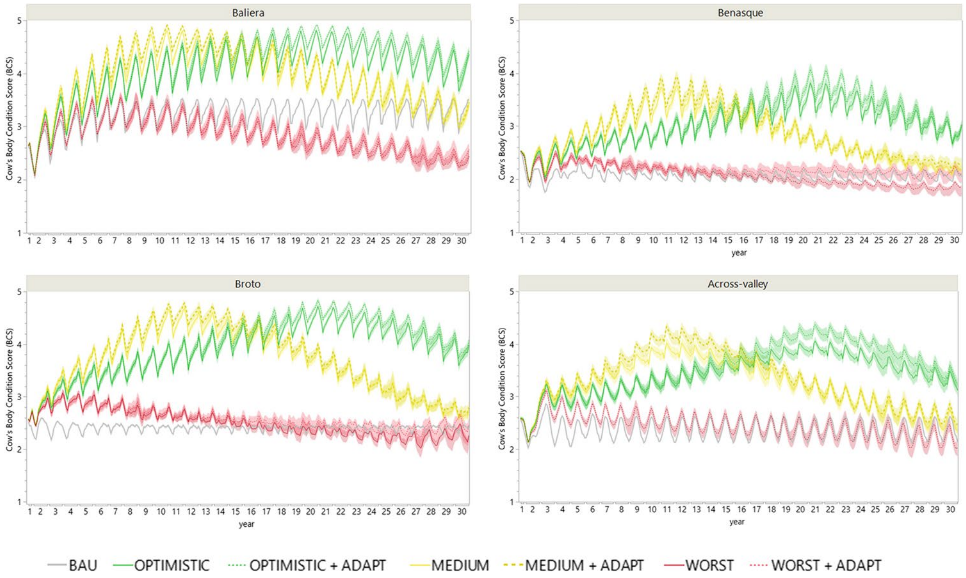

Fig. 2 Cow body condition score per case study under different climate change and adaptation scenarios. Lines represent the daily average BCS of the 100 runs for each scenario. Dashed light-colour lines refer to scenarios with adaptation actions (modifying grazing period length and early weaning). Bands are the confidence interval of the mean (95%). Baliera represents fattening farms with large area; Benasque represents small herd and low labour input; Broto represents farms with large herd and small area; Across-valley represents small family farms

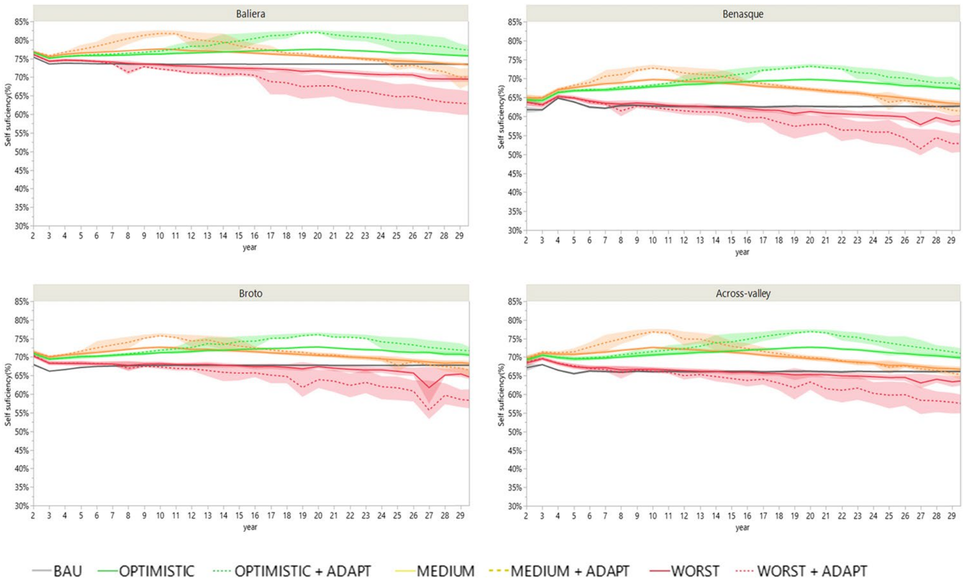

Fig. 3 Feed self-sufficiency per farming type under different climate change and adaptation scenarios. Lines represent the average self-sufficiency of the 100 runs for each scenario. Dashed light-colour lines refer to scenarios with adaptation actions (modifying grazing period length and early weaning). Bands are the confidence interval of the mean (95%). Baliera represents fattening farms with large area; Benasque represents small herd and low labour input; Broto represents farms with large herd and small area; Across-valley represents small family farms

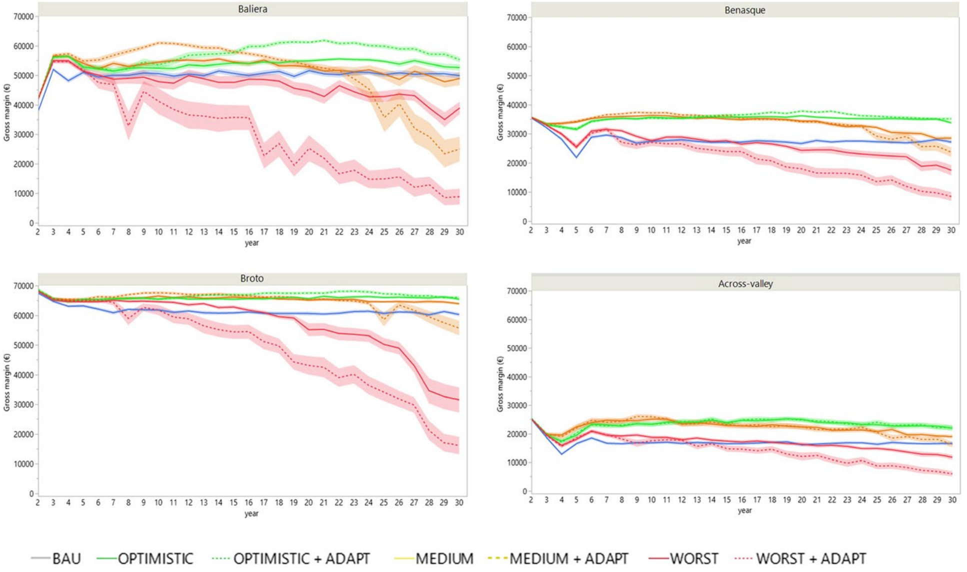

Fig. 4 Gross margin per case study under different climate change and adaptation scenarios. Lines represent the average gross margin of the 100 runs for each scenario. Dashed light-colour lines refer to scenarios with adaptation actions (modifying grazing period length and early weaning). Bands are the confidence interval of the mean (95%). Baliera represents fattening farms with large area, Benasque represents small herd and low labour input, Broto represents farms with large herd and small area, Across-valley represents small family farms

MEDIUM climate change scenario Animal weight and feed self-sufficiency improved during the first decade and then decreased, reaching similar results to BAU scenario for all case studies (Figs. 2 and 3). Gross margin, however, remained with little changes across the whole simulation with values slightly above BAU scenario, except for *Benasque type*, which showed a gross margin higher than BAU scenario during most of the time (Fig. 4).

WORST climate change scenario All indicators worsened for all case studies, reaching levels below BAU values. *Baliera type* showed the greatest decline in BCS, while the other three systems presented values close to BAU. Regarding feed self-sufficiency, *Baliera type* also showed the highest decline, while the other farms also presented marked reductions. All case studies showed lower gross margins, but *Broto type* showed the highest decline. *Baliera type* reached negative values for gross margin, while *Across-valley type* had a limited reduction (Fig. 4).

Adaptation strategies effect

In the OPTIMISITIC scenario, early weaning did not take place (Fig. 5) and grazing season length was extended during the first and second decade to lately reach BAU levels at the end of the third decade (Fig. 6). This action resulted in higher feed self-sufficiency and gross margin than scenarios without adaptation, but similar cow BCS (Figs. 2, 3 and 4). In the MEDIUM scenario, early weaning only occurred during the third decade (Fig. 5), while grazing

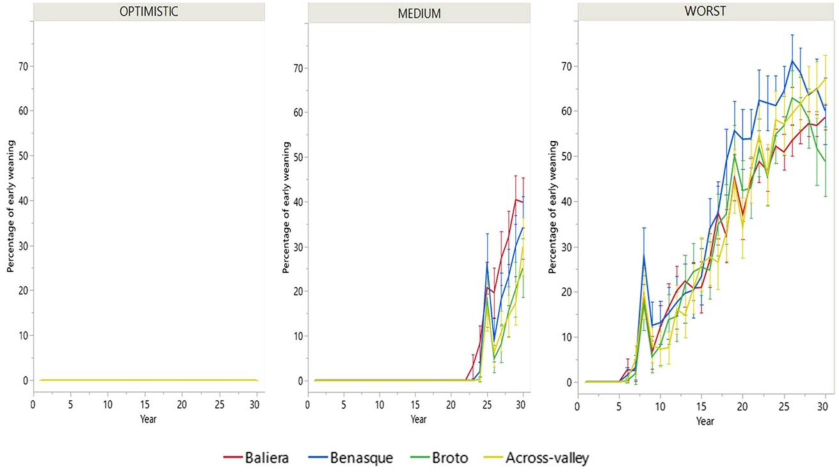

Fig. 5 Percentage of early weaning under each scenario per study case. Lines represent the average gross margin of the 100 runs for each scenario, bars represent the 95% confidence interval. Baliera represents fattening farms with large area; Benasque represents small herd and low labour input; Broto represents farms with large herd and small area; Across-valley represents small family farms

season modification implied an enlargement during the first decade followed by a shortening in the second and third decade, reaching values below BAU (Fig. 6). These changes positively impacted all indicators during the first two decades, but these effects were counterbalanced in the third decade (Figs. 2, 3 and 4). In the WORST scenario, both early weaning and grazing season shortening started during the first decade and were maintained throughout the simulation (Fig. 6). These actions worsened all farming indicators, reaching values below scenarios without adaptation actions (Figs. 2, 3 and 4).

Discussion

The climate change-livestock interface has received increasing attention in the last decades due to livestock both impacting and being impacted by climate change. We contribute to this research field by modelling different climate change scenarios in real farm conditions, i.e. how they could be impacted by climate change and the potential coping capacity of traditional management strategies.

Climate change impact on mountain grazing farms and adaptative actions effect

Climate change entails high risks for food security globally; therefore, adequate adaptation actions are essential to avoid or mitigate the impact of potential food crises (IPCC 2019). In the particular case of European mountain areas, livestock systems are characterised by a large use of mountain pastures during spring, summer and autumn (Veysset et al. 2019; Muñoz-Ulecia et al. 2021). Thus, the impact of climate change on pastures will result in alterations of livestock productivity during these periods. Our results show that under the OPTIMISTIC climate change scenarios (enhanced pasture quality and productivity), benefiting livestock farms. A longer grazing period on quality-improved grasslands resulted in higher feed self-sufficiency and lower feeding costs, improving farm economic performance. However, this optimistic scenario starts a decreasing trend in the last decade of the simulated period, pointing out a potential worsening in the long term. In fact, our OPTIMISTIC scenario may be unrealistic, as a recent study shows that grasslands carrying capacity in Western Europe has already showed a decreasing trend in the last decade (Piipponen et al. 2022).

Under the MEDIUM scenario, climate change could first boost pasture quality and productivity during a brief period of time, to follow a decreasing trend later (Cantarel et al. 2013; Dumont et al. 2015). We found that the initial pasture enhancement served to improve farm performance, which was maximised by increasing the grazing period. When climate change negatively affected grasslands, farms returned to BAU levels in cow BCS, feed self-sufficiency and gross margin. That is, changes in pasture quality and productivity of -5 and -10%, respectively, did not impact the normal functioning of the mountain farms modelled. This may be due to high quality and productivity of grasslands in the region (Casasús et al. 2007; García-González et al. 2008; Reiné et al. 2014). For these same reasons, when adaptation actions were taken, climate change impacts were boosted instead of alleviated. Since grasslands were providing abundant and high-quality feed to animals, the shortening of the grazing season resulted in a decline of feed self-sufficiency and gross margin. Yet, early weaning helped to maintain these declines to a minimum by reducing cow nutritional requirements. In fact, Blanco et al. (2008b) described that early weaning allowed dry cows to graze on low-quality resources without affecting the performance or the economic margin obtained from their calves from weaning to slaughter, and therefore advised it as a strategy to optimise both the herd technical performance and an adequate management of pastures.

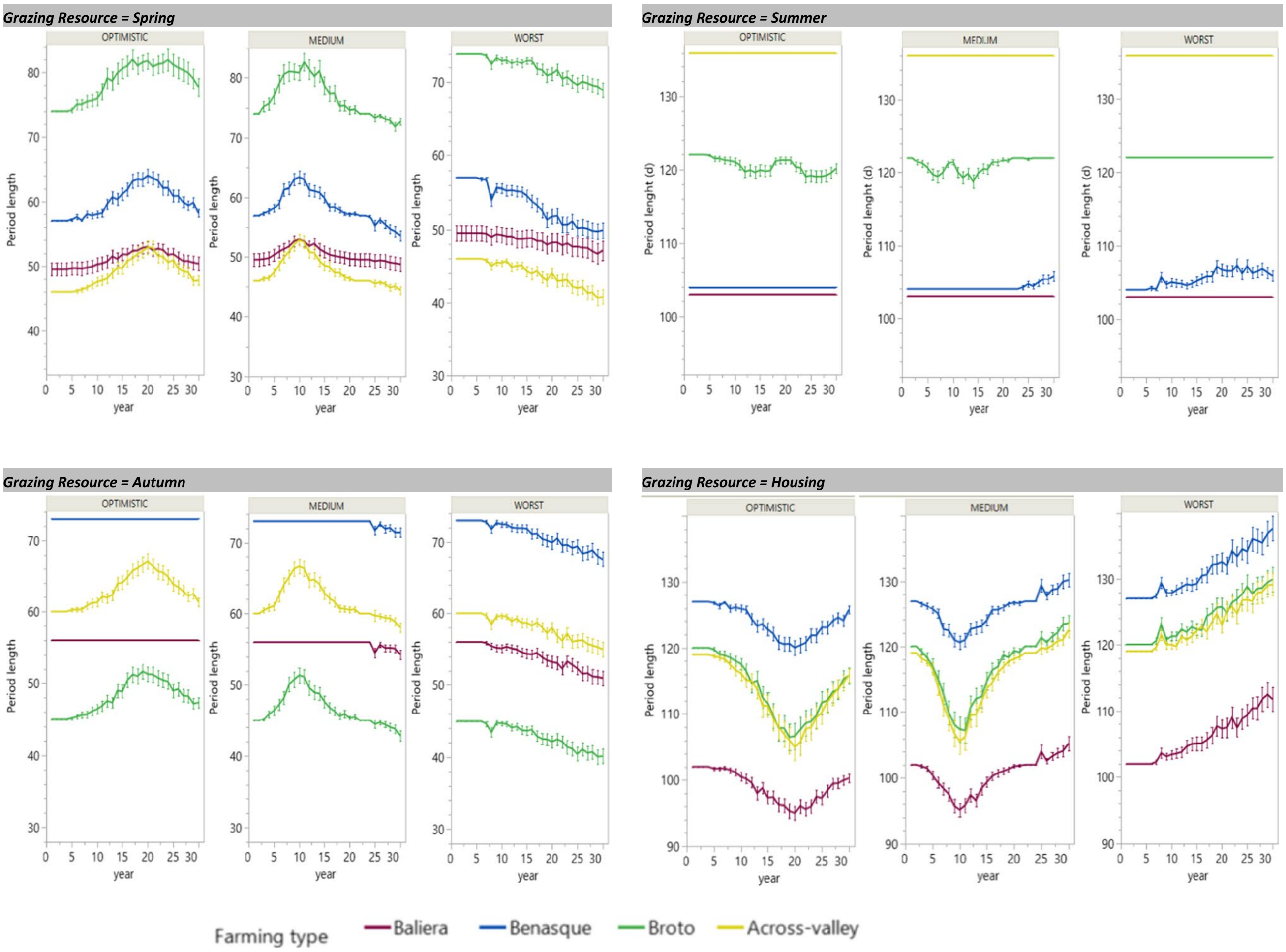

Fig. 6 Grazing season modification under each scenario per study case. Lines represent the average gross margin of the 100 runs for each scenario, bars represent the 95% confidence interval. Baliera represents fattening farms with large area; Benasque represents small herd and low labour input; Broto represents farms with large herd and small area; Across-valley represents small family farms

When climate conditions worsened (WORST scenario), all farming indicators declined. As a cascade effect, small changes in cow BCS resulted in farms decreasing their feed self-sufficiency, which impacted their gross margin. Adaptation actions were successful to fulfil the requirements of the herd and maintain cow BCS within BAU levels; however, they resulted in a more profound decline of the other farming indicators. This is due to both a lower quality of pastures and a shortening of the grazing period when conditions become too harsh. Similar results have been found in other world regions (Dynes et al. 2010; Harrison et al. 2017). The consequences of these results are of high importance in the context of mountain agroecosystems since their high dependence on natural resources could become a disadvantage. Past dynamics in the Pyrenees characterised by a continuous process of grazing land abandonment and afforestation (Lasanta et al. 2000), together with poor-quality pasture, could suggest a lack of enough available land to maintain current stocks leading to a loss of feed self-sufficiency at the regional level. Controversially, those farming systems that contribute less to climate change (or even help mitigating it) (Manzano-Baena and Salguero-Herrera 2018; Manzano and White 2019) and provide multiple ecosystem services (Bernués et al. 2019) could become the losers of a warmer climate.

Mountain farms of the Spanish Pyrenees have already adapted to increasing feeding costs by early weaning (Blanco et al. 2008a, b). Our results show that early weaning resulted in an improvement of cow BCS and a reduction of feeding costs when climate conditions forced farms to reduce grazing and increase off-farm feed use. Moreover, it also resulted in a decrease of income due to the lower weight of calves. Therefore, the combination of modifying the length of the grazing season and early weaning may be a well-suited strategy to maintain the well functioning of the herd and to adapt to sporadic events. These strategies could even be applied separately or in a staggered manned, i.e. early weaning could be prioritised in lactating cows, and in case of a further reduction in feed availability the grazing season could be shortened. However, in the context of climate change, they may decrease mountain farm income and increase their dependence on external animal feeds, worsening their feed self-sufficiency and economic profitability. In this regard, market prices for inputs and outputs will play a central role in engaging farmers into different management actions (Lehtonen 2015), as well as the economic support of public policies. Regarding the effect of extreme events, we found that they only impacted in the WORST scenario, and farms were able to recover after the disturbance.

Farm heterogeneity helps understanding the diverse impacts of climate change

The adaptation actions led to similar results across case studies for cow BCS and feed self-sufficiency but contrasting outcomes for gross margin. Climate change impact on cow BCS was offset by adaptation actions in all case studies when compared to scenarios without adaptation. This improvement was due to a longer grazing period when pasture quality increases (OPTIMISTIC and the beginning of MEDIUM scenarios), but also to a shorter grazing period when pasture quality decrease (WORST scenario). Similarly, feed self-sufficiency increased thanks to adaptation actions when climate improves pasture quality and productivity but worsened under harsh climate conditions. The lower quality and productivity of pastures during the grazing season resulted in a lower net intake of energy. The impact of adaptations on gross margin followed a common trend, but *Baliera and Broto* experienced a more drastic reduction. On the one hand, the reduction of the grazing period in harsh climate conditions implied a higher dependence on off-farm feedstuffs that had to be purchased. On the other hand, early weaning resulted in lower income from selling calves. These effects were visible in MEDIUM and WORST scenarios in *Baliera*, given that their production orientation was focused on selling fattened calves at 10 to 12 months.

Therefore, despite the diverse case studies within the same region and farming system—mountain grazing livestock—, farms presented different projections for the future, being the major driver of the differences in product orientation. The *Baliera type*, which was the only one fattening calves on-farm, experienced greater impacts in animal performance, feed self-sufficiency and economic profitability. Moreover, when adaptation actions were considered, *Baliera type* presented a negative economic margin. Therefore, our results contrast with other studies where increasing barn feeding presented positive outcomes to alleviate the decreasing quality of pastures (Dynes et al. 2010; Lieffering et al. 2016). Yet, the lack of profitability of on-farm fattening in the Pyrenees is already a reality (García-Martínez et al. 2009; Muñoz-Ulecia et al. 2021) and farm economic margin is highly dependent on the support of the Common Agricultural Policy (Muñoz-Ulecia et al. 2021). Those farms where calves are fattened on-farm, therefore, may require adaptations beyond management strategies considered here. For instance, some farms in Northern Italy have focused on fattening calves born and reared in France rather than sourcing them from the national suckler herd (Berton et al. 2017). The other three case studies focused on selling calves at weaning to be fattened elsewhere. These case studies, particularly *Benasque* and *Across-Valley*, suffered a lower impact of climate change, but still were severely affected. In other words, the type of marketed product (weaned vs. fattened) may modulate but not eliminate climate impacts on farm economics.

In this regard, our results point to the need of other adaptation actions to face climate change beyond those currently implemented. Designing effective adaptation strategies is therefore critical and requires a long-term contextualised perspective (Nguyen et al. 2014; Dono et al. 2016) that, in some cases, may go beyond modifying farming management and require more transformative actions like changing product orientation or breeds, integrating livestock species or seek for alternative pasture areas (Aguilera et al. 2020; Benoit et al. 2020; Steiner et al. 2020; Dumont et al. 2022). Market prices and public economic support, therefore, will be determinant in maintaining the profitability of mountain farms. Although product prices have remained almost unchanged in the last thirty years (Ríos-Núñez and Coq-Huelva 2015), input prices are influenced by energy price (Ciaian and Kancs 2011; Lucotte 2016; Kalogiannidis et al. 2022). Thus, the current energy crisis across Europe is raising concerns about the viability of systems highly dependent on imported products (Abay et al. 2023; Zhou et al. 2023), which suggest that transiting towards more industrial systems may reduce the direct impact of climate change, but could come at high risk due to market instability.

Limitations of the modelling approach

The results must be read in the context of the limitations imposed by the study. In our model, we did not consider several effects on grasslands associated to climate change, such as pollinator behaviour and modifications of vegetation composition, or the increase of pests, among others. All these factors can influence the reconfiguration of ecosystems (Chapin et al. 1997), but their high complexity and uncertainty pose challenges to elaborate future scenarios. Moreover, we did not include the direct impact of climate change on animal yields (e.g. heat stress).

There are other management options that farmers could implement (e.g. production system transition, changing breeds or species) that we did not include in our study. We did not intend to consider the wide range of possible actions, but to measure the effect of those currently used. The rationale of our approach is that climate change is progressive, and so farmers do not suddenly perform drastic or transformative modifications. Therefore, farmers are more likely to perform adaptative actions where they feel confident, rather than transformative ones that could entail uncertain results and higher risks (Burton et al. 2008; Brown et al. 2019).

Conclusion

Under the optimistic scenario of climate change where natural pasture quality and productivity could be enhanced, cow body condition score improves, as well as the feed self-sufficiency and gross margin of farms by increasing the length of the grazing season.

The medium climate change scenario results in an improvement of farming indicators in short term and then return to current levels in long term. Adaptation actions result in a worsening of farm feed self-sufficiency and gross margin due to the shortened length of the grazing season.

The worst climate change scenario severely impacts on the functioning of farms from the beginning. Under this scenario, traditional adaptation actions help to maintain herds nutritional state, but at lower farm feed self-sufficiency and gross margin. Therefore, grazing farming systems in the region need alternative adaptation strategies to face the declining pasture quality and productivity under climate change.

Differences between farms can help understand which factors may boost or alleviate climate change impacts. Our results indicate that farms focused on on-farm fattening will suffer more. However, the type of marketed product (weaned vs. fattened) modulates but does not eliminate climate impacts on farm economics. Consequently, adaptation actions may require more profound changes at the farm and regional level.

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Data availability All neccessary data is already provided in the article.

Declarations

Conflict of interest The authors declare no competing interests.

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