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# Mountain pastures increase the resilience of livestock farming to extreme events in the Ariège department, France

Andreas Mayer<sup>1</sup> · Claudine Egger<sup>1</sup> · Adeline Loyau<sup>2,3</sup> · Christoph Plutzer<sup>1</sup> · Dirk S. Schmeller<sup>3</sup> · Veronika Gaube<sup>1</sup>

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## Abstract

Mountain pastures are embedded in highly sensitive mountain ecosystems and provide forage for livestock during summer. In years when forage in the lowlands becomes scarce due to over-grazing and land degradation, or climate-related extreme events such as droughts, increasing stocking densities or expanding grazed areas in mountain pastures provide an additional and cost-efficient forage source. Their utilization highly depends on the management decisions of farmers and practices on their own agricultural land. To predict future land use and concomitant ecological impacts, it is crucial to understand the complex interplay between the decisions of farmers as well as the socio-economic and climatic environment. To understand these interactions, we use the agent-based part of the SECLAND model to analyze the future systemic feedback between climate change, land owner's decisions on land use, and land use change on agricultural land and mountain pastures in the department of Ariège, France. We develop three land use scenarios for a sustainability-driven, a business-as-usual, and a scenario driven by fossil-fueled economic growth. In all scenarios, 32–46% of farms cease to exist, while active farms intensify their land use. On mountain pastures, results show increasing stocking densities up to the maximum carrying capacity of 0.3 livestock units per hectare, especially under the scenario with strong climate change effects and increased extreme events. Additionally, these patterns are strongly shaped by farm succession, vegetation regrowth on unused mountain pastures, and the search for cost-efficient forage resources. Such high stocking densities on mountain pastures increase the pressure on the ecosystem through manure droppings and the introduction of alien microbes, calling for considerate management to avoid conflicting situations. Agent-based models such as that used in this study enable researchers to untangle the described complex interactions between grazing livestock, and the utilization of lowland and mountain pastures in European mountain agroecosystems.

**Keywords** Agent-based modelling · Mountain pastures · Livestock grazing · Climate change · Climate extremes

## 1 Introduction

Summer mountain pastures are complex socio-ecological systems. In mountainous regions in Europe, they provide forage for grazing

livestock during summer. In most cases, they consist of a mix of open grasslands, tree, or shrub vegetation types (Deléglise et al. 2019; Jäger et al. 2020). Grazing on mountain pastures is affected by the management decisions of herders, farmers, or institutional actors such as forest agencies or regional and national entities specifically devoted to pasture management (Nagy and Grabherr 2009; Herzog and Seidl 2018). Summer mountain pasture management is considered to be decisive for the maintenance of biodiversity, ecosystem services, and landscapes (MEA 2005; Girard et al. 2008; IPBES 2017; García-Ruiz et al. 2020). Well-managed mountain pastures are central for the provision of public goods and are a central cornerstone in agro-ecological and low input grazing livestock systems (Borsotto et al. 2014; Furtschegger and Schermer 2015; van der Ploeg et al. 2019), whereas most ecosystem impacts are related to inapt stocking densities in alpine meadows. High stocking densities may cause a range of negative impacts on plant and animal communities (Dumont et al. 2009;

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Jerneck et al. 2011; Negro et al. 2011), pollution, and loss of stored carbon (Abdalla et al. 2018; Mahefarisoa et al. 2021), while grassland abandonment increases the risk for landslides in topsoils (Tasser et al. 2003).

Climate change is an increasing threat to mountain ecosystems (Schmeller et al. 2018; Vicente-Serrano et al. 2021; Lemus-Canovas and Lopez-Bustins 2021), and hence also a threat to grazing livestock farmers in mountainous regions (Fuhrer et al. 2014). Farmers need to hedge against these impacts, e.g., through insurance (Vroege et al. 2019), adding cropland feed to ruminant livestock diets (Thornton and Herrero 2014; Mottet et al. 2017), or decreasing stocking densities (Stolze et al. 2019). All measures are prone to invoke additional or opportunity costs. As an alternative, underexploited mountain grasslands may become necessary for future livestock management strategies to counteract reduced forage availability. Consequently, summer mountain pastures may become more important in years when forage growth is curtailed in the lowlands and can thus increase the flexibility of farmers to cope with these forage shortages (Nettier et al. 2017; Herzog and Seidl 2018). However, considerate management needs to be implemented to avoid negative trade-offs with biodiversity, biogeochemical cycles, or hydrological processes (Tasser et al. 2005; Garcia-Pausas et al. 2017; Hilpold et al. 2018).

To predict future patterns of agricultural land and mountain pastures and concomitant ecological impacts, it is crucial to understand the complex interplay between the decisions of farmers and the socio-economic, biophysical, and climatic environment (Schirpke et al. 2017). The diversity and interactions of influencing factors need to be considered when modeling dynamic shifts of livestock between lowland grazing and the exploitation of summer mountain pastures. Rigolot et al. (2014) found that mountain pastures utilization increases the ability of farmers to cope with climate variability and that decisions about utilization are complex and made collectively. Herzog and Seidl (2018) conducted a series of interviews with farmers and extension officers to gain an overview of the main drivers of utilizing mountain pastures in Switzerland. They found that next to forage provision and health benefits for grazing livestock, benefits for labor requirements are important drivers for using mountain pastures in the Swiss Alps. Several studies have investigated the importance of land use for managing vegetation regrowth and keeping mountain pastures open (Tasser and Tappeiner 2002;

Gehrig-Fasel et al. 2007; Vandenberghe et al. 2007), an important strategy against future forage shortages. Nevertheless, research has shown that mountain pastures do also face strong impacts from climate change (Morán-Tejeda et al. 2017; Deléglise et al. 2019; Amblar-Francés et al. 2020), jeopardizing the potential of additional forage resources from mountain pastures. Lastly, while not directly related to the utilization of mountain pastures, the availability of farm succession through kinfolk or migrants from urban regions (i.e., neorurals, *néoruraux* in French, see (Viel 1984)) is essential for future land use patterns on lowlands, and in connection, on mountain pastures (Mailfert 2007; Lobley et al. 2010; Beckers et al. 2018).

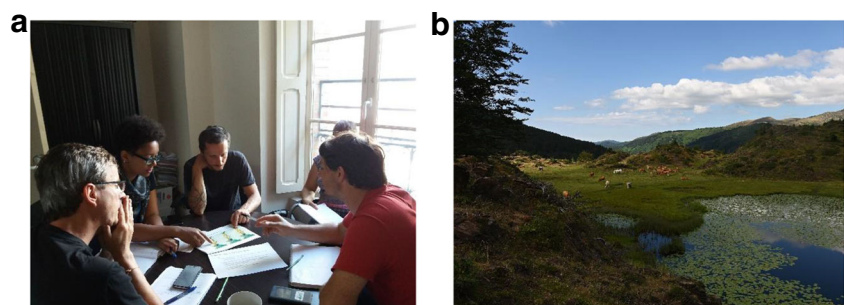
Here, we analyze for the first time the future systemic feedback between climate change, land manager's decisions on land use, and land use change on agricultural land and mountain pastures (i.e., estives) in the department of Ariège. The Ariège is a rural department in the French Pyrenees where relevant factors and dynamics to assess mountain pasture utilization exist, and where extensive research on the impacts from pollution, pathogens, microorganisms, and global change on mountain ecosystems have been conducted (Schmeller 2021a). We employ an agent-based model that is part of SECLAND (Dullinger et al. 2020), which was developed for a mountainous region in Austria. We employed this model to assess the linkages between active farms, land use, and the intensified utilization of mountain pastures to compensate for reduced domestic forage availability after climate-induced extreme events (e.g., droughts). This study builds upon previous research on the link between lowland farming and mountain grazing but significantly expands this research by systematically assessing mountain pasture utilization in three differing socio-economic pathways with an agent-based model that combines agricultural census data with results from qualitative interviews with land users and regional land use planners and decision-makers (Fig. 1).

## 2 Methods and study region

### 2.1 Study region

Our study is located in the French Département de l'Ariège, a mountainous area in the Pyrenees (Fig. 2). The Ariège is located

**Fig. 1** Researchers and stakeholders discussing the agent-based model used for this study during a field trip to the Ariège department in Summer 2018 (a), and livestock grazing nearby a pond on a mountain pasture (i.e., estive) in the Ariège department. Source: Dirk S. Schmeller.



in the eastern extremes of the oceanic precipitation regime and within the transition zone of Atlantic and Mediterranean climates. Annual average precipitation in the foothills is between 700 and 1000 mm/year, reaching up to 1800 mm/year in the high mountains. In the transition zone (“Piémont Pyrénéen”), the average temperature is between +5° in January and +19° in July. Climate projections predict increasing temperature anomalies in summer (+2°–+3.5° for RCP 4.5 and RCP 8.5, respectively) and autumn (same trend, but weaker than for summer) for the Pyrenees in general and also the Ariège (Serrano-Notivoli et al. 2019; Amblar-Francés et al. 2020).

The Ariège consists of three major geographical zones: extensive plains in the northern parts of the Département with large croplands; the transition zone with altitudes up to 1000 m and dominated by forests and grasslands, i.e., the region which is typically the most shrub-encroached due to complex land ownership and access, as well as topographical conditions; and the mountainous southern region (“Haut Pays Ariégeois”), encompassing regions from 800 to nearly 3000 m, where most of the summer mountain pastures are located. In the Ariège, most livestock systems are for meat production and grassland-based with a stocking density of 0.7 grazing livestock units per hectare (measured as the stock of grazing animals divided by the total forage area without mountain pastures) (Agreste 2016a).

## 2.2 Agent-based model

The agent-based part of the SECLAND model (SECLAND-ABM) has been developed to model spatially explicit land use scenarios at the landscape level. It is based on quantitative census data (spatially explicit agricultural and other census and statistical data), with additional qualitative data (semi-structured interviews with farmers and regional planners and decision-makers), allowing to integrate a broad range of data

sources into one land use model. The agent-based model is not spatially explicit *sensu stricto*. Due to restricted data availability (i.e., no parcel ownership data was available), geographic locations are represented by the allocation of farms to specific municipalities (for more details see Section 2.5.1). We applied an explanatory modeling approach (Lempert 2002; Matthews et al. 2007) by using an ensemble of three distinct scenarios of future socio-economic developments based on the IPCC-shared socio-economic pathways (SSPs; (O’Neill et al. 2017)). The here used, updated version of the agent-based model is described following the ODD protocol (Müller et al. 2013) (full description in Supplementary Table SI1).

## 2.3 Overview

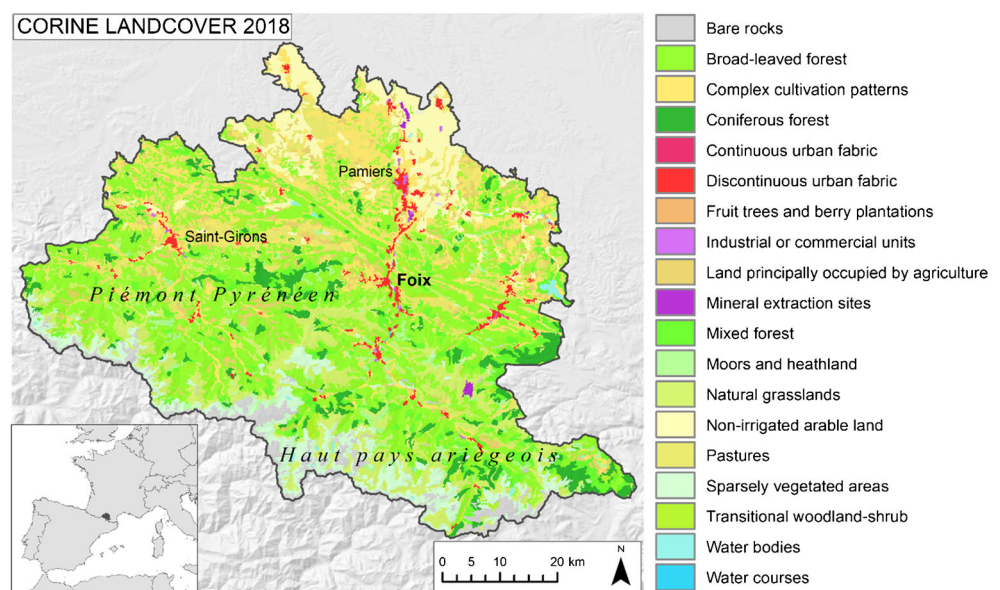
### 2.3.1 Purpose

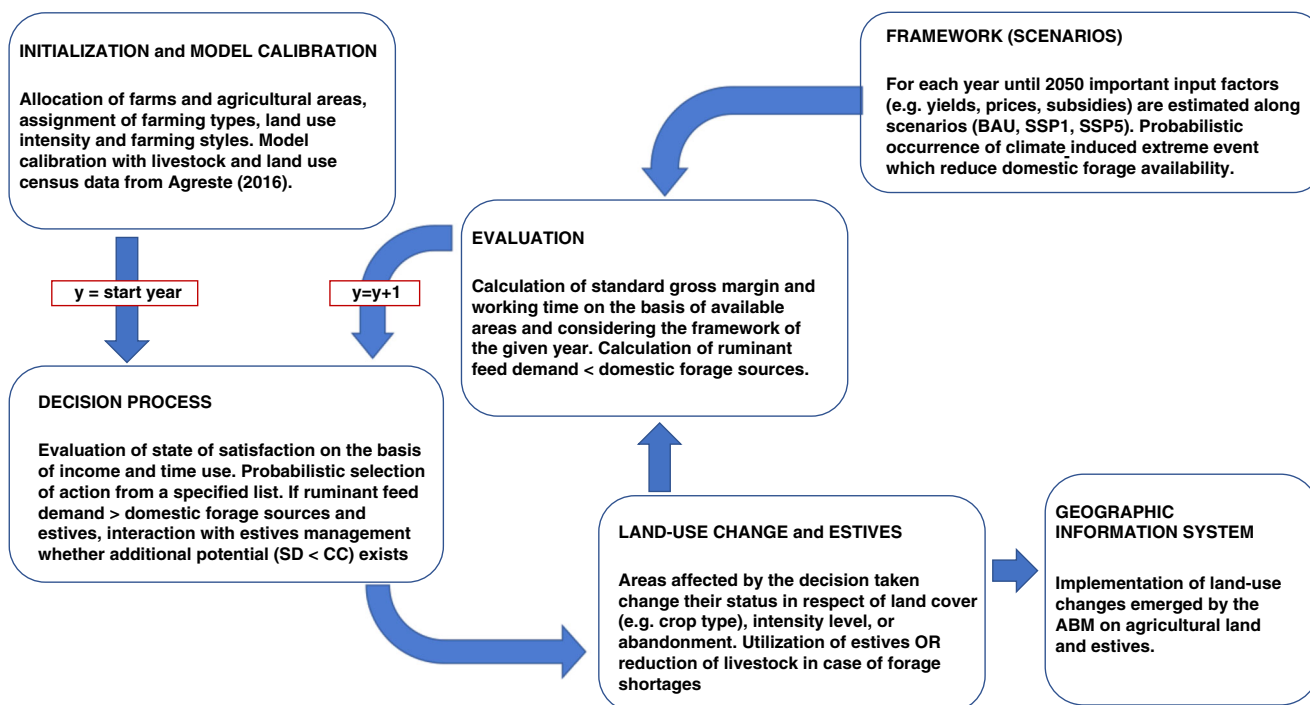
We aimed to analyze systemic feedbacks between climate change, land use decisions, and land use change in a mountainous region in the French Pyrenees until the year 2050 in annual time steps. The main focus of this study was to assess the impacts that farmers’ decisions have on lowland and mountain pastures utilization. Figure 3 provides a schematic overview of the purpose and the modeling process in SECLAND-ABM.

### 2.3.2 Entities

The main agents were 2333 active farms (each represented by a farmer with specific socio-demographic and normative characteristics) in the base year (2016) who cultivated 91.826 ha of agricultural land, calibrated with census data from Agreste (2016a). We defined three distinct farming types based on

**Fig. 2** Overview of the Ariège department, southern France. Map based on CORINE land cover data, available at <https://land.copernicus.eu/pan-european/corine-land-cover/clc2018> (CLS 2018).





**Fig. 3** Overview of the modeling process and data processing in SECLAND-ABM. SD, stocking density; CC, carrying capacity.

the main contribution to the farm gross margins: (1) cropland farms, (2) livestock farms with primarily milk, or (3) meat production. To reflect the high share of organic farming in the Ariège (Agence Bio 2016), farms were classified either as conventional or organic. Furthermore, production systems were differentiated from low to high land use intensity systems, defined by cropland or grassland yield levels. The medium land use intensity class was calibrated with biomass harvest data from the French agricultural census (Agreste 2016a), with census data-derived thresholds until 2050. The (min) and (max\*1.2) regional crop-specific yield values between 2000 and 2014 have been used as the lowest (level 1) and highest (level 5) values until 2050. Farmland was divided into six land use categories: food crops, forage crops, temporary grassland, and three permanent grassland categories based on the slope (<25°, 25°–35°, and > 35°, see (BAB 2021) for reference). Slope and elevation are important factors, determining how mountain grasslands are used (Taillefumier and Piégay 2003; Bender et al. 2005; Mottet et al. 2006). Permanent grasslands have decreasing biomass output per hectare with increasing steepness, restrictions for land use change, and steep and remote areas have had a higher probability for abandonment (Vacquie et al. 2015; Hinojosa et al. 2016; Lavorel et al. 2017). Livestock numbers were calibrated with reported numbers from census data based on forage output from lowland grasslands and forage crops, utilizing feeding and energy requirements per ruminant livestock type (milk/beef) from (BAB 2021). Approximately 18,000 livestock units have been allocated to mountain pastures in

the base year, in line with reported data from the Federation pastoral de l'Ariège (2022). We use the concept of farming styles from Schmitzberger et al. (2005) to represent four different idle types of agents in the agent-based model, with different preferences and value systems: yield optimizer (mainly oriented towards maximizing yields), traditionalist (prefer well-established management and have low willingness to change), idealist (agriculture considered a way towards self-realization), and innovative (high flexibility and willingness to change). The agricultural land rental market and mountain pastures are represented by one non-farm agent in each case in the agent-based model, interacting with farmers through lease/rent and the provision of areas for grazing livestock, respectively.

### 2.3.3 Process overview and scheduling

Farmers invest labor to cultivate their farmland and livestock from which they generate agricultural income. Farming intensity levels were assigned with specific labor input demand per land use plot and livestock unit, and delivered specific gross margins and subsidies. Farmers evaluate their well-being based on criteria concerning the total farm income and farm labor hours (workload). Depending on their satisfaction with the farm income and workload, farmers evaluate whether to continue as active farm and current management practices or whether they need to change/adapt (see Table 1). Farmers select from a range of actions to adapt on-farm practices to reduce

workload and/or increase income and off-farm practices concerning farm management. We defined the latter as using mountain pastures for livestock grazing. The range of decisions and probabilities in Table 1 were derived from the participatory process during a field trip in July/August 2018.

## 2.4 Design concepts

### 2.4.1 Background, individual decision making of farmers, and adaption

Farmers are bounded rational agents (Groeneveld et al. 2017) and rather than profit-maximizing, they seek to achieve and maintain well-being, defined as the balance between income and workload. We thus set three well-being criteria: absolute thresholds for the farm income (minimum annual income between 15,000 and 20,000 EUR) and/or workload (maximum annual workload between 1800 and 2000 h/cap/year), as well as a threshold for relative income (income per agricultural working hour > 1 standard deviation of the average value of farms within the same farming type) to account for relational income comparison among peers. Farmers needed to reconsider their land use management every year based on their (dis-)satisfaction with income and workload. In line with literature (Deléglise et al. 2019) and information from interviews with farmers and regional decision-makers, we parametrized farmers' decisions in the agent-based model, taking into account differences based on farming type and farming

style of a farmer. In our model, one decision out of a set of eleven decisions with pre-defined probabilities was taken by each farmer depending on the (dis-)satisfaction of farmers with income and workload (see Table 1).

### 2.4.2 Interaction and emergence

Farmers interacted with the dynamic municipality rental market and the estives management agent each time a decision which required interaction (e.g., expansion of farmland, land abandonment) was taken. Interaction with the municipality rental market happened if farmers leased out or rented farmland. If farmers required additional forage sources, they tried to send livestock to the mountain pastures. They communicated with the estives management agent (who is responsible for all mountain pastures in the study region) and received feedback on whether there is enough capacity for additional grazing livestock. If stocking densities on mountain pastures allowed for additional livestock, farmers gained additional forage resources but had to invest additional labor. If stocking densities on mountain pastures did not allow for additional livestock, farmers reduced their domestic livestock until they fell below the maximum carrying capacity (CC) on their farmland after climate-induced extreme events. The decision to send more livestock to mountain pastures was taken based on the impacts from climate-induced extreme events which reduced lowland forage availability. The resulting land use patterns arise from the interaction of scenario settings (i.e., socio-economic developments) and the decision making of farmers.

**Table 1** Land use decisions on the farm for individual farmers, one decision per year. Farmers take land use decisions based on their satisfaction with income and workload, probabilities depend on farm type, farming style, and scenario.

Action	Description
Nothing	Farmers change nothing.
Termination	Farmers abandon all farming activities and pass all areas to the municipality rental market.
Intensification on land and livestock	Farmers increase the land use intensity by +1 level, and livestock accordingly.
Extensification on land and livestock	Farmers decrease land use intensity by -1 level, and livestock accordingly.
Expansion of farmland	Farmers acquire additional farmland (max. +25% of current farm size) from the municipality rental market (only if land is available from farms which lease out land or have abandoned farming). Cropland farms only acquire cropland, livestock farms all land categories.
Reduction of farmland	Farmers send farmland (max. -25% of current farm size) to the municipality rental market. Farms first reduce permanent grassland, then temporary grassland, and last cropland.
Land use change	Farmers change crop cultures on cropland, e.g., switch forage crops to crops and vice versa.
Land abandonment	Farmers temporarily give up 25% of permanent grassland (slope classes 2 and 3).
Switch to organic production	Farmers switch from conventional to organic production.
Increase of livestock	Farmers increase livestock units by +25%.
Reduction of livestock	Farmers decrease livestock units by -25%.

## 2.5 Details

### 2.5.1 Initialization

No data that links individual land parcels and farmers were available. We thus used available census data on the community, regional, or department level to build average farms per community (including a certain fluctuation range for farm size, livestock units, and age of farm head) which we aligned with total census data, e.g., number of farms, land use, and livestock units.

We derived information on the number of active farms and grazing livestock (measured as grazing livestock units – GLU, i.e., expressed in equivalents of one adult dairy cow producing 3000 kg of milk annually) for each municipality from the French annual agricultural statistics (Agreste 2016a) and spatially explicit agricultural land use data for the study region from the RICA FADN database of the EU (European Commission 2021). We combined the detailed spatial data with the aggregated census data to link land use with data on farms (per community) in the Ariège. Furthermore, we calculated region-specific ( $n=3$  Arrondissements) metrics to define average farms and applied standard deviations to increase heterogeneity based on the following equation:

$$\text{farm factor } x_{ijk} = \text{avg}.x_j + (\text{scalefactor } x_{jk} \times a \times b \times \text{std } x_k)$$

for farm  $i$ , municipality  $j$  and arrondissement  $k$

with  $\text{avg}.x_j$  being the average of the given factor on the municipal level, the scale factor accounting for differences between municipality and arrondissement,  $a$  being +1 or -1 giving direction for the deviation from the average, and  $b$  reflecting a deviation percentage from the arrondissement's standard deviation  $x_k$ . For grasslands, we left a buffer of 20% additional forage area for each farm, in line with information from interviews with farmers and Nettier et al. (2017). For municipalities with just one farm, these values were

initialized. Areas of municipalities with no active farms were allocated to the municipality rental markets. The resulting farm characteristics were sum checked (on municipal level) and corrected if necessary. Where no data for individual farms and farmers was available, we randomly assigned individual farms. Results are presented for the years 2016 to 2050 in the remainder of this manuscript to allow for model calibration of the ABM within the first 2 years.

### 2.5.2 Input data

We gathered behavioral data for all agents using a set of semi-structured, qualitative interviews with farmers and local to regional experts and decision-makers. We used a short survey for every interview to note down socio-economic and demographic factors of the farm manager (e.g., age, workload, successor) and the farm (e.g., farm size and type, livestock numbers, farmland use). We additionally guided the interviewees through a set of topical areas (Table 2) but let them emphasize topics that were particularly important to them.

Due to the small sample size of semi-structured interviews with farmers ( $n=10$ ), we likely have not sampled the total farmer population representatively, but we nevertheless put special emphasis on covering a broad diversity of interviewees (see Table 2 and Supplementary Table SI3) and investigating the complex and interrelated motivations behind the decision making of farmers. Upscaling of behavioral traits to the total population was based on probabilities of farm characteristics derived from local agricultural census data (Agence Bio 2016; Agreste 2016a). For agent-based models which aim to understand farmers motivations and values, such an approach is more appropriate than large samples of questionnaire-based farmer information, and thus a common method used in the agent-based modeling community (Janssen and Ostrom 2006; Valbuena et al. 2008; Smajgl et al. 2011).

FADN and RICA provided data on average gross margins per farm type and farm size in the Midi-Pyrénées which we used to calculate the gross income per agricultural

**Table 2** Interview partners and topics that were covered during five local stakeholders and ten farmer interviews conducted in July and August 2018.

Interview partners	
Local decision-makers and experts	Mountain pasture management, forestry, forestry/climate, rural history, national park
Farmers	Grazers farming (5 meat, 2 dairy); mixed farming (1), crops/vegetables farming (1)
Topics	
Socio-demographic	Farm succession, subsidies, available workforce, part-time/full-time, prices
Farm management	History of farm/region, changes in the production system, land ownership, land use intensity, conventional/organic practices, production system
Climate change	Perception, impacts, adaptation
Mountain pasture management	Stocking density, meadows/pastures, attractiveness, constraints

activity for each farm, and RICA also contains a high-resolution agricultural land use map (plot level) to locate farming activities (Agreste 2016b; European Commission 2021). Since no extensive data on time use for agricultural land management in the Ariège was available, we used labor requirements from an Austrian case study (Dullinger et al. 2020). For further details on data sources, see Supplementary Table S14.

### 2.5.3 Scenarios

To assess future land use patterns and mountain pasture utilization in the Ariège, we developed three distinct socio-economic scenarios (Table 3). These scenarios are in line with the shared socio-economic pathways SSP (Riahi et al. 2017), a business-as-usual (BAU) socio-economic development, a green and sustainability-oriented scenario with favorable conditions for agriculture and low climate change impact linked to SSP1 (van Vuuren et al. 2017), and a scenario which is driven by unconstrained economic growth with unfavorable conditions for agriculture and strong climate change impacts, similar to SSP5 (Kriegler et al. 2017). For crop and grassland yields, we assumed a substantial closure of yield gaps between conventional and organic agriculture (de Ponti et al. 2012), and reinforced inputs of technology and capital (SSP5), and sustainable intensification in SSP1 (Poux and Aubert 2018; Scherer et al. 2018), which can additionally increase agricultural yields, albeit more input of labor and capital will be necessary. Changes in climate are also an increasing driver for severe weather extremes such as heatwaves, droughts, and intense precipitation (Heinrich et al. 2014; Diffenbaugh et al. 2017; Myhre et al. 2019). Due to their direct effect on local farms, the consideration of extreme events is particularly

important on a regional level (Gobiet and Truhetz 2008). Therefore, we implemented stochastic extreme events that negatively affect the farm income with varying severity depending on the scenario assumptions in the agent-based model. We additionally assumed across all scenarios: vegetation regrowth on 4% of unused mountain pastures, and the acquisition of new farms through neorurals if <25 ha of farmland pro community was available.

### 2.5.4 Model evaluation

To account for the stochastic elements in the ABM, we compiled 100 model runs and selected the medium run for active farms for further analysis. We followed elements of the ABM evaluation recommendations, a framework for model transparency (Augusiak et al. 2014; Schulze et al. 2017), and the ODD protocol (Grimm et al. 2006, 2010; Müller et al. 2013).

## 3 Results

### 3.1 Agricultural land use and active farms

In the base year 2016, 91,826 ha of agricultural land have been cultivated in the Ariège (Figure 4(a)). Until the year 2050, agricultural areas decreased to 63,000 ha in the BAU scenario (−31%), with a slightly slower reduction in SSP1 (67,000 ha, −28%), and a more dramatic reduction in SSP5 (49,000 ha, −45%). The negative trajectories are particularly driven by the interplay of insufficient farming income or/and disproportionate workload, the two factors affecting decisions in the agent-based model. Only SSP5 showed a significantly different trend, while results in BAU and SSP1 within 100 Monte-

**Table 3** Scenario assumptions underlying the agent-based model about yields, prices, subsidies, income, working hours, workload, extreme events, and carrying capacity of mountain pastures. Scenarios assessed: business-as-usual (BAU), a sustainability-driven scenario (SSP1), and a

scenario driven by rapid economic growth (SSP5). *CL* cropland, *GL* grassland, *AWU* agricultural working units, *LU* livestock units, *CC* carrying capacity.

SCENARIOS	BAU	SSP1	SSP5
Yields	15–20% increase	10–15% increase	25–30% increase on CL, +25% on GL
Agricultural gross margins	Constant	Constant, + for organic	Reduced
Agricultural subsidies	Constant	For change to organic	Decreased
Non-agricultural income	Constant	Increase	Increase
AWU/per ha or LU	Slight increase	Slight increase	Strong increase
Maximum of accepted workload	Constant	Change according to farming style	Constant
Minimum of required agricultural income	Constant	Change according to farming style	Higher
Climate-related extreme events	Low probability of occurrence, whole region affected; moderate reduction of gross margins	Very low probability of occurrence, whole region affected; minor reduction of gross margins	High probability of occurrence, whole region affected; strong reduction of gross margins



Carlo simulations partly overlapped. Summer mountain pastures, i.e., estives, showed a stronger decline than total agricultural land (Figure 4(e)). Mountain pastures decreased by nearly two-thirds, with similar patterns across all three scenarios. This trend is stronger in steep and remote mountain pastures, which were only used if the maximum stocking intensity was reached in better suitable ones, else vegetation re-growth progressed.

The strong decline of agricultural areas in SSP5 was mainly driven by a massive reduction in forage areas for grazing livestock, including permanent grasslands (−53%) as a response to missing subsidies (Figure 4(b)). Forage crops and temporary grasslands (Figure 4(c)), i.e., cropland forage areas, also showed a considerable, albeit smaller reduction in SSP5 (−20%). While the area for permanent grasslands in BAU and SSP1 also decreased, cropland forage areas increased slightly in BAU (+5%) and more strongly in SSP1 (+17%), driven by a shift in cropland production from food to forage crops. Across all scenarios, the share of cropland forage areas in total agricultural land increased from 14% in 2016 to 17% in SSP5, 22% in BAU, and 24% in SSP1. Croplands that were not primarily used to feed livestock and which were the dominant land use in the northern fringes of the Ariège had a similar trend across all scenarios, ranging at approximately 18,000 ha in 2050, still a reduction of 40% of total croplands that were cultivated in 2016 (Figure 4(d)). Only in SSP5 the share of cropland for food crops in total agricultural land slightly increased from 32 to 34%.

The reduction in agricultural land indicates fewer active farms in the Ariège in the future. In the base year 2016,

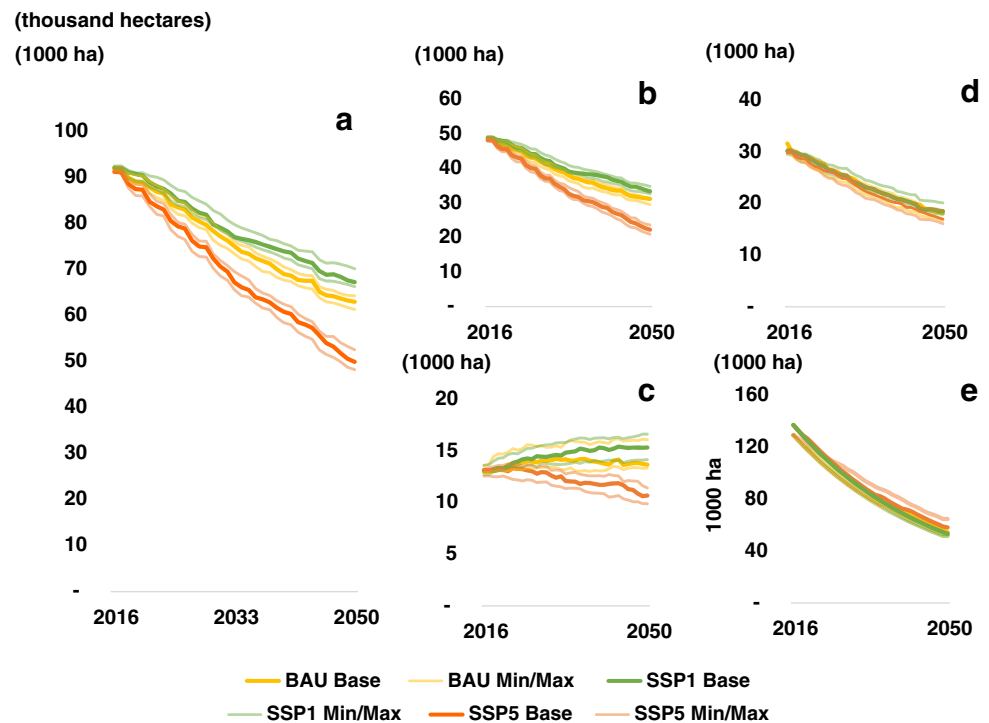
2333 farms were active in the Ariège, of which 76% have been conventional and 24% organic. Across all scenarios, the number of active farms decreased to 1450 (−38%) in BAU, to 1579 (−32%) in SSP1, and to 1255 (−46%) in SSP5 (Table 4), a slightly stronger reduction than total agricultural land. Consequently, average farm sizes increased in BAU and SSP1, but remained at a comparable level in SSP5. Organic farms increased most in SSP1 due to favorable conditions for organic farming, and all scenarios supported a majority of organic farms by 2050.

The trend of a reduction of active farms of nearly 40% until 2050 in the BAU scenario underestimated the historic trend from 1970 to 2010 by approximately 20%; however, historic data showed a reduction of the trend of farm abandonment since the year 2000, thus increasing the fit of the agent-based model (for further results on model evaluation see Supplementary Figure SII).

### 3.2 Farmers' decisions

Agricultural land use and the utilization of mountain pastures were driven by the management decisions of active farms (Figure 5). In BAU and SSP1, the majority of farmers (65% and 73%, respectively) were content with both their income and their workload when taking land use decisions over the whole period from 2016 to 2050, while in SSP5 only 36% were satisfied with both, and nearly half (47%) of all decisions were taken because farmers did not reach the critical income thresholds. This was considerably higher than in BAU and SSP1 (20% and 14%, respectively) (Figure 5).

**Fig. 4** Agricultural land use between 2016 and 2050 for three scenarios. Business-as-usual BAU (yellow), a sustainability-driven scenario (SSP1-green), and a scenario driven by rapid economic growth (SSP5-orange) in thousand hectares (1000 ha). (a) total agricultural land use (without mountain pastures), (b) permanent grasslands, (c) areas for forage crops (e.g., forage maize) and temporary grasslands, (d) cropland for food crops (e.g., cereals, oil crops), (e) mountain pastures. Semi-transparent lines indicate the lowest and highest values from 100 Monte-Carlo simulation runs.



**Table 4** Farm indicators for the number of all, conventional (conv), and organic (org) farms, and for average farm sizes in the base year and for 3 scenarios (Business-as-usual (BAU), shared socio-economic pathway 1 (SSP1), and shared socio-economic pathway 5 (SSP5) for 2050. Numbers in brackets indicate the lowest and highest values from 100 Monte-Carlo simulation runs.

	2016	2050 BAU	2050 SSP1	2050 SSP5
Farms (all)	2333 (2324–2330)	1450 (1407–1500)	1579 (1546–1611)	1255 (1207–1305)
Farms (conv)	1782 (1766–1814)	530 (487–572)	363 (330–400)	447 (422–504)
Farms (org)	551 (517–562)	920 (880–950)	1216 (1165–1265)	808 (750–842)
Avg. farm size (ha)	40	43.4	42.6	40

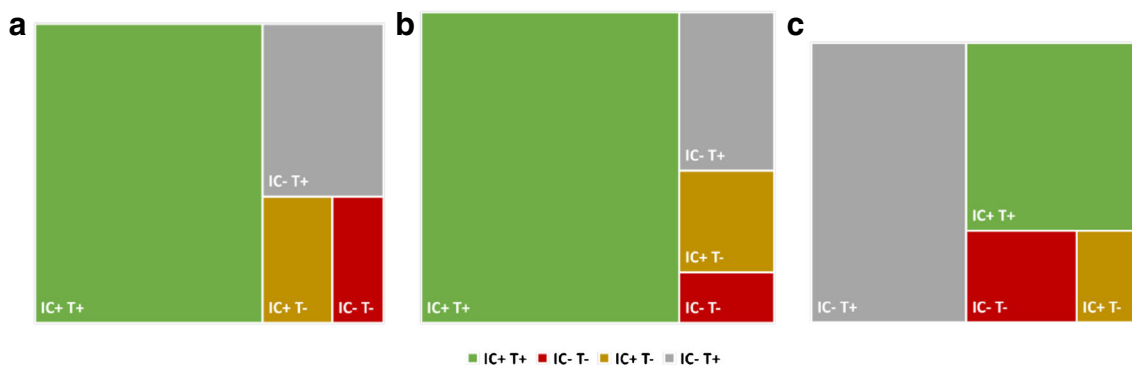
Farmers were under stronger pressure to secure an income in SSP5, where all farming subsidies were constantly reduced until 2026 and then cut completely. An additional 11% of farmer decisions were taken because they were discontent with both income and workload, a major driver for the abandonment of farming activity. Only one-third (36%) of decisions were taken because income and workload were within the accepted range. In the BAU and SSP1 scenario, insufficient income was the major driver of farmer dissatisfaction, with more farmers struggling with their income in BAU (26% compared to 18%, respectively). The workload was in fewer cases a constraint, opening up possibilities to increase activities through farm enlargement, more livestock, or the utilization of summer pastures. In SSP5, 20% of decisions were based on excessive workload, a ratio higher than in BAU (15%) and SSP1 (13%). In an SSP1 scenario with environmental subsidies and support for the transition to organic farming, the highest absolute and relative numbers of farmers with high life quality (i.e., IC+ and T+) were observed. In SSP5, the opposite pattern appeared, and 11% of all decisions were taken because of insufficient income and excessive workload, a critical pattern for the continuation of farming.

### 3.3 Carrying capacity of grazing livestock and mountain pastures utilization

The majority of agricultural land in the Ariège is used to provide forage resources for domestic grazing livestock. In

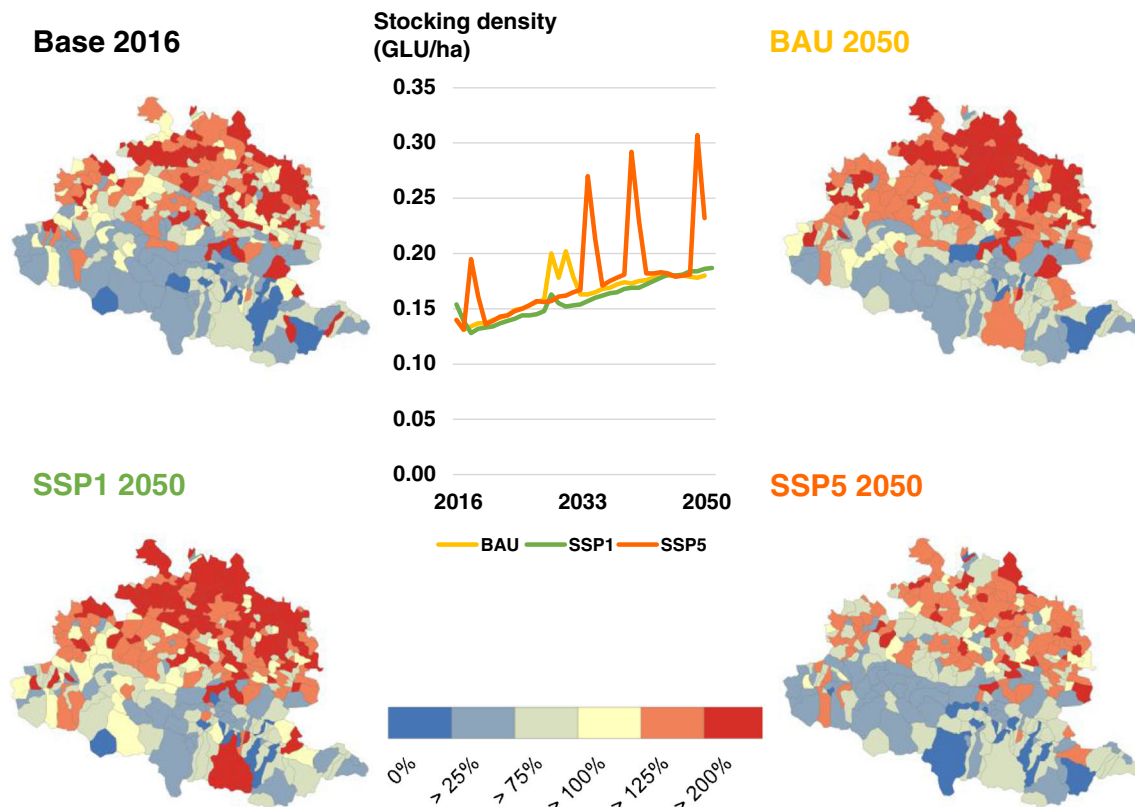
2016, suckler cow husbandry was the most widespread live-stock system in the Ariège. Of the total 46,000 grazing live-stock units (GLU) in the Ariège in 2016, approximately two-thirds were raised for meat production and the remainder for milk production. Until 2050, GLUs decreased in all scenarios, with a stronger reduction for meat than for milk livestock due to higher gross margins in dairy systems while workload remained within acceptable dimensions. In total, our model showed that between 31,000 (BAU and SSP1) and 35,000 (SSP5) GLUs will remain in the Ariège in 2050. Stocking densities per forage area (i.e., grassland and forage crop area) have been approximately 0.8 GLU/ha in the lowlands on average in the Ariège in 2016 (Figure 6). The reduction of roughly one-third of GLUs will, however, not compensate for the reduction of agricultural lands, leading to increasing stocking densities in the lowlands across all scenarios from 1 GLU/ha in SPP1 to nearly 1.6 GLU/ha in SSP5 (for additional results see Supplementary Figures SI2–SI4).

In 2016, approximately 18,800 GLUs were sent to mountain pastures for grazing, resulting in a stocking density of 0.15 GLU/ha. In the year 2050, domestic forage deficits will particularly increase in northern communities of the Ariège, but due to the overall reduction of active farms and livestock, fewer livestock will be on the mountain pastures than in 2016 in all socio-economic scenarios. The reduction was similar in BAU and SPP1 (50% reduction in both scenarios), and a less pronounced



**Fig. 5** Farmers’ satisfaction with income and workload (IC+T+), grey: discontent with income, content with workload (IC–T+), brown: content with income, discontent with workload (IC+ T–), red: discontent with income and workload (IC– T–). Largest to smallest share from bottom left clockwise.

Green: content with income and workload (IC+T+), grey: discontent with income, content with workload (IC–T+), brown: content with income, discontent with workload (IC+ T–), red: discontent with income and workload (IC– T–). Largest to smallest share from bottom left clockwise.



**Fig. 6** Utilized carrying capacity per community in the Ariège for the base year (2016) and three scenarios in the year 2050. Business-as-usual (BAU, top right), a sustainability-driven scenario (SSP1, bottom left), and a scenario driven by rapid economic growth (SSP5, bottom right). Utilized carrying capacity is shown as required feed demand of total grazing livestock units (GLU) in the percentage of total forage output from temporary and permanent grasslands, and forage crops per

community. Values >100% indicate higher forage demand than domestically produced, which corresponds to those communities that need to send their livestock to mountain pastures to compensate for domestic forage deficits. The line chart shows the development of stocking densities on mountain pastures between 2016 and 2050 for the same three scenarios. SD, stocking density.

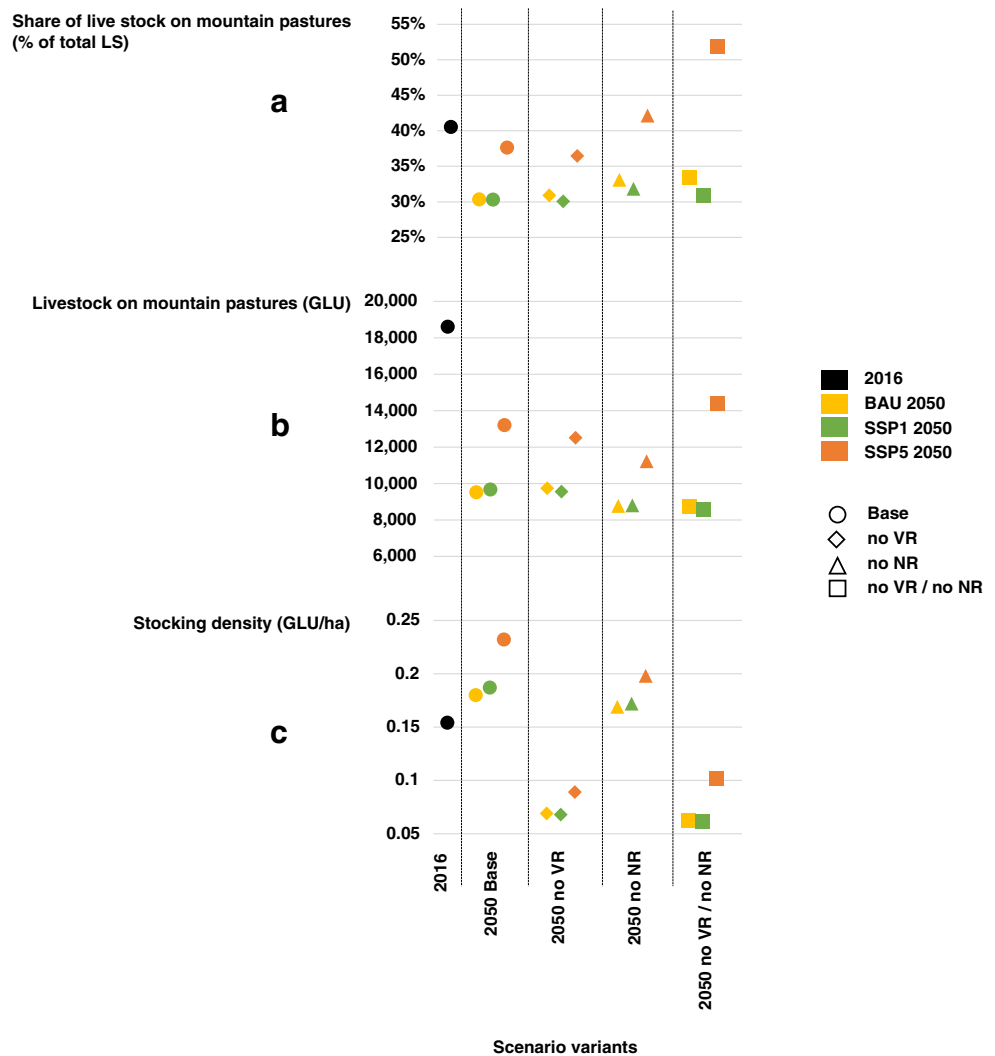
reduction in SSP5 (30% reduction). In combination with grazing area loss through vegetation regrowth on temporarily abandoned mountain pastures, stocking densities, however, increased constantly until 2050 until 0.18 GLU/ha in SSP1 and BAU, and to 0.2 GLU/ha in SSP5. While all scenarios showed similar general trends in the development of stocking densities until 2050, the intense spikes in individual years, most pronounced in BAU and SSP5, indicate higher stocking densities through additional livestock on the mountain pastures. This is a direct consequence of the exploitation of mountain pastures' grazing potentials to compensate for forage shortages induced through climate-related extreme events in the lowlands. Hence, stocking densities increased slightly in individual years in SSP1, more distinctively in the BAU scenario (<0.2 GLU/ha), and much more in SSP5, where stocking densities reached 0.3 GLU/ha in three individual years until 2050. In these years, mountain pastures might be used at or even above the maximum carrying capacity to buffer for forage shortages in lowlands in the SSP5 scenario.

### 3.4 Assessing the impact of ecological and social parameters for the utilization of mountain pastures

The utilization of mountain pastures is driven by complex interactions between social and ecological parameters. We here assess the impact of the accessibility to lease agricultural land on the rental market for new farmers, i.e., to become a neorural, and vegetation regrowth on temporarily abandoned mountain pastures: for total livestock, stocking density on mountain pastures, and the share of grazing livestock on mountain pastures. To test whether results are scenario-dependent, both factors were assessed across all three scenarios (BAU, SSP1, SSP5).

Across all scenario variants in the year 2050, SSP5 showed the highest shares of livestock grazing on mountain pastures (Figure 7a), and the exclusion of neorurals increased this share in all scenarios, when compared to the base scenario. Additionally, all scenario variants had a larger impact in SSP5 than in BAU and in SSP1, indicating a higher dynamic between lowland agriculture and mountain pastures in a scenario with unfavorable conditions for

**Fig. 7** Scatter diagrams showing the impacts of scenario variants without vegetation regrowth on temporarily abandoned mountain pastures, and the exclusion of the possibility of acquiring abandoned farmland through new agents, i.e., neorurals, in the agent-based model. Variants include a base scenario including vegetation regrowth and neorurals (Base), the exclusion of vegetation regrowth (no VR) or neorurals (no NR), or the exclusion of both factors (no VR/no NR). Assessed indicators are (a) the share of livestock on mountain pastures (in % of total livestock), (b) grazing livestock units (GLU) on mountain pastures, and (c) stocking density on mountain pastures (GLU/ha) for the base year and three scenarios in 2050 Business-as-usual (BAU), shared socio-economic pathway 1 (SSP1), and shared socio-economic pathway 5 (SSP5).



farming. The effects of the exclusion of vegetation regrowth only had a minor impact on the share of livestock on mountain pastures.

The overall trend of fewer livestock on mountain pastures in 2050 was visible throughout all scenario variants (Figure 7b). The exclusion of one or both factors was generally leading to fewer livestock on mountain pastures, except in SSP5, where in a variant with the exclusion of vegetation regrowth and the exclusion of neorurals, more livestock was grazed on mountain pastures in 2050. Overall, the exclusion of vegetation regrowth had only a neglectable impact on the total livestock on mountain pastures, indicating that more area to be grazed did not increase total livestock numbers on mountain pastures.

Excluding vegetation regrowth and neorurals decreased stocking densities on mountain pastures across all scenarios (Figure 7c), with vegetation regrowth having a considerably stronger impact than neorurals. If all mountain pastures remained potential areas to be grazed by livestock (no VR), stocking densities decreased by more than 60%

in comparison to a base scenario in 2050. The exclusion of neorurals (no NR) showed a reduction of under 10% for BAU and SSP1, and a reduction of 17% in SSP5. Interestingly, the combined effects (no VR and no NR) led to the highest reduction of stocking densities in BAU and SSP1, whereas in SSP5, they were even slightly higher than in the scenario variant with only the exclusion of vegetation regrowth (i.e., 5%).

## 4 Discussion

We have shown in this study that only a socio-ecological perspective allows to understand the complex interactions which drive livestock grazing on mountain pastures, and to model future trajectories of land use in mountain regions in Europe. We used quantitative census data and supplemented it with qualitative information gathered through interviews with regional stakeholders to parametrize an agent-based model for a mountainous region in the French Pyrenees, the Ariège

department. Using the satisfaction of farmers with income and workload as the decisive criterion for their management decisions, we quantified future land use patterns resulting from the interaction of farmers with the socio-economic, biophysical, and climatic environment until the year 2050 for three different scenarios in annual resolution. Our model suggested a strong reduction in the number of active farms of nearly 50% in the 34 years assessed under a business-as-usual (BAU) scenario, and a slightly lesser reduction in the utilized agricultural area and grazing livestock, with significant differences between the three scenarios. Furthermore, results showed that mountain pastures are used as a buffer for lowland forage shortages, with higher utilization in a scenario with unfavorable conditions for agriculture and strong climate change. Our results extend past trends of agricultural land use in the Ariège, which is in line with trends across European mountain cattle farming systems (García-Martínez et al. 2009), and in general within European farming systems, where a similar trend is already ongoing (Renwick et al. 2013) and may accelerate until 2050.

When interpreting the results of this study, several caveats need to be considered. The limited number of interviews did not allow for a representative sample of farmers in the Ariège, and thus the parametrization of farmer types was based on randomized allocation instead of a representation of the underlying distribution. Nevertheless, data from qualitative interviews to parametrize agents' behavior is a common approach in agent-based modeling. Gathering representative samples of behavioral data of farmers would require substantial resources, thus qualitative interviews with farmers and decision-makers have become widely applied in inter- and transdisciplinary agent-based models (Polhill et al. 2009; Ghorbani et al. 2015; Reilly et al. 2021). Furthermore, data constraints did not allow for a spatially explicit representation of land ownership and mountain pasture utilization in the Ariège. We, therefore, calibrated farms with the total number of utilized agricultural area and livestock per community, and addressed mountain pasture utilization only per community instead of a spatially explicit representation of land use, since this was the finest level of information on agricultural census data available. We employed these approaches to overcome data gaps, in line with the current methodology applied in agent-based models (Heckbert et al. 2010; Filatova et al. 2013). Farmers' satisfaction was implemented in the agent-based model as the combined result of sufficient income and manageable workload as proxies for economic and social dimensions of farm decisions (Ellis 1993; Newig et al. 2008; Gaube et al. 2009), differentiated by normative and value-based types of farmers (Schmitzberger et al. 2005). We did not, however, take into account legacy effects through learning and adaptive behavior, an important next step to be implemented in the agent-based model (Darnhofer et al. 2010). This would also allow to overcome the current parametrization

between climate-induced extreme events and additional utilization of mountain pastures, which is currently happening in the same year, thus underestimating the complexities of shifting livestock from lowlands to mountain pastures. Adequate, quick, and flexible management needs to be ensured to realize mountain pastures' buffer function. Lastly, further research on the viability and impacts of adding alternative sources for livestock forage acquisition in the agent-based model are necessary to improve the robustness of scenarios dealing with the decision making of farmers in mountain regions.

Farming systems in the Ariège are located within a highly fragmented and diverse agricultural landscape. A general trend towards land use intensification and abandonment of remote and steep areas in the so-called transition zone between lowlands and mountain pastures has been observed in the Pyrenees (Mottet et al. 2006) and in the Alps (Cocca et al. 2012; Faccioni et al. 2019). In our model, land use intensification was further enforced by the removal of stocking density restrictions for receiving subsidies. For scenario SSP5, our model suggested a drastic increase of the grazing livestock density from 0.8 to 1.4 GLU/ha. Nevertheless, the utilization of mountain pastures was not necessarily following a similar trajectory. Mountain pastures could provide important forage resources in addition to lowland grassland and cropland forage areas for grazing livestock (Eychenne 2008; Rigolot et al. 2014; Nettièr et al. 2017; Herzog and Seidl 2018). In our study, we tested whether mountain pastures increase a farmer's resilience to domestic forage losses by using an agent-based model. When forage provision was curtailed due to extreme climate events (i.e., droughts), more livestock was sent on mountain pastures for grazing, hence increasing stocking densities. Droughts, such as they happened in the Ariège in 2003, 2018, and 2019, and which are predicted to happen more often in the future (King and Karoly 2017), further increased stocking densities on mountain pastures if they were used as an additional forage resource, pushing stocking densities towards 0,3 GLU/ha in individual years until 2050. Results from this study are in line with findings from similar studies (Rigolot et al. 2014; Nettièr et al. 2017; Herzog and Seidl 2018; Deléglise et al. 2019), and add a quantitative outlook for three long-term scenarios until 2050.

Using mountain pastures as an additional forage resource is not the only, but the preferred option for livestock farmers in the Ariège to increase forage supply. Interviews have shown that buying additional forage on markets is not a relevant strategy, especially for organic farmers which mentioned higher forage costs and limited supply. Furthermore, farmers mentioned that if forage shortages in the Ariège occur, also nearby regions will be affected. For them, estives provide an attractive and low-cost additional forage resource for grazing livestock. Such an approach benefits farmers twofold through reduced forage costs and through the opportunity to gain

higher prices for meat and dairy products from extensive and pasture-based livestock systems (van der Ploeg et al. 2019).

The results from our study suggest that in drought years more pressure from grazing will be put on mountain pastures and will then cause intense unbalances in the C:N:P stoichiometry in the soil, with consequences for plant composition (He et al. 2020). If livestock has access to water bodies, these unbalances will also occur there, increasing pressures on amphibians. Consequently, increasing grazing pressure on mountain ecosystems will incur changes in food webs, nutrient cycling, and biogeochemical cycles, thereby likely impacting water quality (Schmeller et al. 2018) with unexpected effects on wildlife and human well-being as a consequence of pathogen emergence (Bernardo-Cravo et al. 2020; Schmeller et al. 2020). Thus, careful management and long-term planning of mountain pasture utilization, close monitoring of impacts, and control of farming practices are essential, specifically in years in which mountain grassland feeding capacities, are strongly needed. These may, however, also be the years under which these ecosystems are already under high stress from climate change impacts, leading to reduced carrying capacities (Kampmann et al. 2008; Jäger et al. 2020; Lemus-Canovas and Lopez-Bustins 2021). Therefore, farmers must seek for additional forage resources to increase their resilience without risking negative ecological impacts on mountain pastures, e.g., through creating grassland buffers on farmers' permanent grasslands (Nettier et al. 2017).

Grazing on mountain pastures is considered a cost-effective way to counteract domestic lowland forage shortages, and their utilization is influenced by the complex interrelations between social, ecological, and climatic driving forces (Dressler et al. 2019). We tested the impact of vegetation regrowth on mountain pastures and access of neorurals to acquire farms in the agent-based model by removing one or both factors in all scenarios and found a strong influence of both factors on mountain pastures' capacity for forage provision and utilization patterns. Advancing vegetation regrowth on temporarily abandoned or unused grazing areas reduces buffer capacities for shortages in lowland forage supply, and can substantially increase stocking densities on mountain pastures. Declining forage potential has the strongest impacts in a scenario with higher probabilities for the occurrence of climate-induced extreme events (King and Karoly 2017; Myhre et al. 2019), where additional demand to compensate for forage shortages in lowlands in combination with reduced forage potential on mountain pastures can substantially increase stocking densities. Thus, keeping mountain pastures open is central for grazing livestock densities and concurrent ecological pressures (Dumont et al. 2007; Machaca et al. 2018). Néoruraux farmers have a long tradition in the Ariège (Viel 1984; Mailfert 2007), and if this tradition is maintained in the future, the decline in active farms and utilized farmland might be slower than predicted by models without considering

neorurals. Results from this land use modeling assessment show that in scenarios which include neorurals in the Ariège, a lower share of livestock is sent to mountain pastures across all scenarios, indicating that less abandonment of lowland agricultural land reduces the demand for additional forage from mountain pastures, beyond the share of livestock which is rearing on mountain pastures as an integral part of traditional farming systems in mountain regions.

Adapted management strategies with a high degree of flexibility are necessary to respond to changing demand, and to manage vegetation regrowth from temporary under-grazing in high mountain pastures and the concomitant long-term reduction of forage areas, since both, over- and under-grazing, are leading to degrading mountain pastures (Tasser et al. 2003; Wang et al. 2020). Thus, mountain pasture utilization needs to be embedded in a broader research and management strategy on alternatives to counteract domestic forage shortages, especially since mountain ecosystems do have a higher sensitivity to global change (Huber et al. 2005; Zamora et al. 2017; Schmeller 2021b).

## 5 Conclusions

The agricultural and land use system in the Ariège, as a model for the French Pyrenees and likely other European mountain ranges, will have to face significant changes in the future: These changes are driven by the interaction of climatic, biophysical, and socio-economic changes (Schirpke et al. 2017) and farmers' decision structures that shape individual responses. Future agricultural and environmental policies need to consider the complex interactions between these factors to design sustainable and viable conditions for farming in mountain ecosystems and not to the detriment of the latter. Further assessments of changes of mountain pastures under climate change and impacts of livestock on montane aquatic ecosystems are needed to provide guidelines about supported numbers of livestock units per mountain region. Therefore, our study can help to disentangle the complex interplay which shapes future land use and contribute essential knowledge for developing a good communication strategy that is needed to reduce the probability of conflictual situations and to find the best possible compromise supported by the multiuser group active in mountains.

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**Code availability** Not applicable.

**Authors' contributions** Conceptualization: A.M., V.G., C.E., C.P.; methodology: A.M., V.G., C.E., C.P.; field work: A.M., C.E., D.S., A.L.; analysis: A.M., V.G., C.E., C.P.; writing—original draft: A.M.; writing—review and editing: all authors; funding acquisition: A.M., V.G., D.S..

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Research involving human participants** The study was conducted according to the guidelines laid down in the 1964 Helsinki Declaration and its later amendments.

**Informed consent** All study participants gave informed consent to participate in the study.

**Consent for publication** The authors affirm that human research participants and all persons recognizable on figure 1 provided informed consent for this publication.

**Conflict of interest** The authors declare no competing interests.

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