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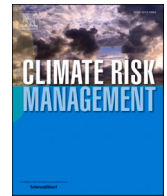
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Facing drought: exposure, vulnerability and adaptation options of extensive livestock systems in the French Pre-Alps

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ABSTRACT

Extensive livestock farming is a key activity in the Alpine region, contributing to the economy and maintaining typical landscapes, high biological and cultural diversity. With climate change, recent and unprecedented multi-year droughts are threatening these extensive production systems and the positive externalities they deliver.

This study aims to better understand the local exposure and vulnerability components that shape the drought risk in these systems, as a first step towards adaptation. We performed an original farm-level assessment, which to our knowledge has never been done in mountain livestock farming, combining climatic data with biophysical and socio-technical data derived from semi-structured interviews with farmers. We focused on three main types of mountain livestock farms in a drought-prone and traditional breeding area of the French Pre-Alps named the Vercors: (1) mountain grassland-specialised dairy systems, (2) mountain rangeland-based suckler systems and (3) middle-mountain rangeland-based suckler systems.

Our results show the extent to which the components of exposure (i.e. characteristics of drought hazards faced by farms locally) and vulnerability (i.e. sensitivity and strategies to cope with or adapt to drought) vary between farms and how different combinations of these components contribute to different patterns of the drought risk in relation to the different geographical, biophysical or socio-technical characteristics of livestock farms in the study area. Further, we identify the main environmental, socio-economic and institutional constraints that currently reduce the coping and adaptive capacity of farms. Finally, we discuss the combinations and drivers of concrete adaptation options in the specific context of extensive mountain livestock farming.

In addition to place-specific results offering an operational dimension for stakeholders in the case-study area, our study contributes to scientific advances by developing a methodological sequence broadly applicable on how to inform the risk of drought impacts in agro-pastoral livestock systems.

1. Introduction

Extensive livestock farming is a central activity in European mountains, recognized by decision makers and by society for its multifunctionality (Battaglini et al., 2014; O'Rourke et al., 2016; Faccioni et al., 2019). Mountain livestock farms are often based on

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low-input and extensive practices, and provide products with quality distinction in a context of natural handicaps, such as elevation, harsh climate and poor soils that limits other agricultural productions (Ripoll-Bosch et al., 2012; Battaglini et al., 2014; O'Rourke et al., 2016). They contribute significantly to the economy of mountainous regions and play a central role in their attractiveness, through the traditional use of semi-natural grasslands and pastoral areas that shapes typical landscapes and contributes to high biological and cultural diversity (Peringer et al., 2013; Bernués et al., 2014; Herzog and Seidl, 2018). However, with climate change, recent and unprecedented multi-year droughts are placing at risk these extensive production systems and the positive externalities they produce.

Droughts, defined as prolonged periods of insufficient precipitation, are considered one of the major threats to agricultural activities in mountains (Stephan et al., 2021). Mountains stands at the forefront of climate change impacts, facing reduced snowpack, significant increases in temperature and evapotranspirative demand and variable precipitation (Verfaillie et al., 2018; Hock et al., 2019; Castelli, 2021; Pepin et al., 2022; Scherrer et al., 2022). If a precipitation deficit occurs during the vegetative growing season and is combined with high potential evapotranspiration, this likely leads to an agricultural or soil moisture drought (Stephan et al., 2021). European mountains have suffered unprecedented impacts from agricultural droughts over the last decades (Stephan et al., 2021). In 2022, for instance, the drought-induced losses in forage production exceeded by far the quantities of forage traditionally purchased by livestock farmers in Switzerland (Calanca et al., 2022). Traditional mountain livestock farming is particularly at risk in the face of droughts because it relies heavily on rain-fed grasslands and rangelands to achieve forage self-sufficiency, and because its agricultural practices are constrained by an environment with natural handicaps (steep relief, harsh climate) or high conservation issues (e.g. high nature value lands) to respond to drought (Nettier et al., 2010).

In livestock systems, final risk of drought impacts remains difficult to quantify and predict as it results from multiple processes operating at different levels, from the plant-soil system to the socio-economic farm system (Finger et al., 2013; Deléglise et al., 2015; Cruz et al., 2018). As a first step towards adaptation in such multi-dimensional and complex systems (Urruty et al., 2016), it is essential to draw proper assessments of the drought risk, i.e. the ways drought impacts materialise from hazards triggered by climate variability and change to the biophysical and social vulnerability of systems (Hagenlocher et al., 2019). As defined by the IPCC (IPCC, 2018), climate risk is the potential for adverse impacts to a system and it results from the interaction of climate hazards, exposure and vulnerability of the system. Applying this framework to drought risk (UNDRR, 2019), drought hazard refers to the possible future occurrence of drought events of a certain frequency, duration and intensity and drought exposure refers to the presence of populations, their livelihoods and assets in drought-prone areas. In this framework, vulnerability is the propensity or predisposition of the system to be adversely affected due to its sensitivity when impacted by a drought hazard, combined with a lack of coping and adaptive capacity (IPCC, 2014). When applied to agricultural systems, the vulnerability concept is often operationalised through the assessment of biotechnical and social indicators, internal or external to the system, that are assumed to increase or decrease its ability to cope with or adapt to disturbances, as reviewed by Urruty et al. (2016). Referring to the concepts of adaptability and resilience developed for agricultural systems by Darnhofer et al. (2010), another way of informing about the coping and adaptive capacity of these systems is to identify the strategies that farmers can seize when facing stresses or shocks. They have been classified in two main domains: strategies that enable the farm to persist with no or marginal change on the one hand, i.e. coping measures (also described as absorption or buffer measures), and strategies that enable the farm to adapt through moderate to deep changes in its structure, organisation and functions on the other hand, i.e. adaptive and transformative measures respectively (Darnhofer et al., 2010).

While the characterisation of the drought hazard components has recently been intensively investigated for the Alpine region (Jacob et al., 2022), the assessment of the final risk of impacts on mountain livestock farming still remains a challenge, due to exposure and vulnerability factors that need to be addressed locally (Stephan et al., 2023). For instance, drought impact at the grassland parcel level depends on biophysical and management aspects (e.g. soil and vegetation characteristics, number and timing of cuts or grazing, presence of irrigation, Deléglise et al., 2015; Calanca et al., 2022), which vary even between the different parcels of a mountain farm. At farm-level, final impacts of droughts hinge on biophysical, technical and socio-economic factors such as, for instance, the type and diversity of parcels in the farmland, the level of animal nutritional needs, the presence of water storage infrastructure or the farmer's expected income (Nettier et al., 2010). To help overcome this knowledge gap, we propose to address a farm-level approach to accurately capture and understand the climatic, biophysical and socio-technical human dimensions of drought risk in mountain livestock systems. In particular, we propose a mixed quantitative and qualitative approach to assess these different dimensions, with the aim of capturing the relationship between drought exposure and farmers' own perceptions of drought impacts and strategies for coping with or adapting to them. This is a crucial issue as farmers can decide to act and implement adaptation measures based on their own knowledge and conceptualisations of their opportunities and constraints (Käyhkö, 2019; Singh et al., 2020).

For this purpose, we performed an original assessment of exposure and vulnerability to drought of a diversified sample of mountain livestock farms. We conducted this work in the Vercors Regional Park (VRP), a mountainous region in the French Pre-Alps, at the crossroads between the Alpine and the Mediterranean climates, where droughts are a growing concern for human activities (François et al., 2019). Based on previous local studies (Nettier et al., 2010; Loucogaray et al., 2015), we focused on the three VRP typical farm types: (i) mountain grassland-specialised dairy systems, (ii) mountain rangeland-based suckler systems and (iii) middle-mountain rangeland-based suckler systems. Our methodology builds upon four complementary steps to assess the risk of drought impacts on these farms. First, we used climatic data and farm location to characterise the farms' exposure to drought hazards. Second, we assessed the farms' vulnerability through content analysis of semi-structured interviews with farmers that aimed to capture: (i) the sensitivity of farms, based on the degree to which farmers perceived the impacts of drought on their agro-pastoral resources, and, (ii) the strategies that farmers implemented or thought adequate for their farms to face droughts. Third, through a multivariate analysis that brought together these different components at farm level, we described the main patterns and drivers of drought risk in the VRP livestock farms. Fourth, we identified the main environmental, socio-economic or institutional constraints to the implementation of successful coping and adaptive strategies building upon farmers' experiences. Through this work, and starting from the hypothesis that mountain

livestock systems are likely to be differentially impacted by, and to differently respond to drought according to their geographical, biophysical and socio-technical contexts, we aimed to characterise (i) the extent to which the components of exposure and vulnerability vary between farms in the VRP, (ii) how different combinations of these components contribute to different patterns of the drought risk, and (iii) the main adaptation options to reduce farms' vulnerability to drought in the VRP.

2. Material and methods

2.1. Case study area characteristics

The study area covers the Vercors Regional Park (VRP) in the Western French Alps, Southeast of France (Auvergne-Rhône-Alpes region - NUTS2 level) (Fig. 1). VRP is a pre-alpine and calcareous mountain range consisting of a vast North-South plateau at an elevation of about 1000 m, surrounded by middle-altitude piedmonts and dominated by higher reliefs. The study area is around 206,000 ha, of which about 60 % is forest and 21 % is agricultural land according to Corine Land Cover 2018. Surface water is scarce due to the dominant karstic geology and draining subsoil.

VRP globally presents a mountain climate with average annual precipitations of about 1300 mm, falling mostly as snow in winter, and average minimum and maximum monthly temperatures respectively of 4.6 °C and 13.1 °C (1991–2020 averages, see Section 2.3 for meteorological data sources). Climate is modulated by a strong altitudinal gradient from valleys to highest reliefs, as well as by latitudinal and longitudinal gradients. Mediterranean climatic influences dominate in the south, while mountain influences are more important in the north and/or at high elevation (Bigot and Rome, 2010). Mean annual temperature, for instance, is 3.4 °C higher in the middle-altitude southern piedmonts than in the northern part of the plateau (1991–2020 average). Annual precipitation is also highly variable throughout the VRP: it is about 50 % higher in the north and/or at high elevation than on the southern edge (about 1600 mm compared to 1000 mm, 1991–2020 average).

Around 1000 farms are included within the study area, contributing to its rural vitality, driving landscape evolution and supplying a diverse bundle of ecosystem services. According to the National Agricultural Census, cattle farming (dairy, suckler or mixed) dominates on the plateau in the northern and central parts of the study area, while specialised sheep farming dominates in the piedmonts in the south. In the piedmonts and valleys to the west of the study area, cereal, walnut and other fruit farming dominates, well ahead of mixed crop-livestock farming. Local agricultural products are recognised by various quality distinctions (Protected Designation of Origin (PDO), Protected Geographical Indication (PGI), organic farming, local labels of territorial embedding, etc.). The presence of a PDO cheese production area on the plateau of the VRP is directly linked to the dominance of dairy cattle farming in this part of the study area. Sheep production in the south benefits from a PGI for lamb meat. Agricultural land use is dominated by cultivated lands (crops and cultivated grasslands) on the flat part of the plateau and in the valleys bordering the study area, but,

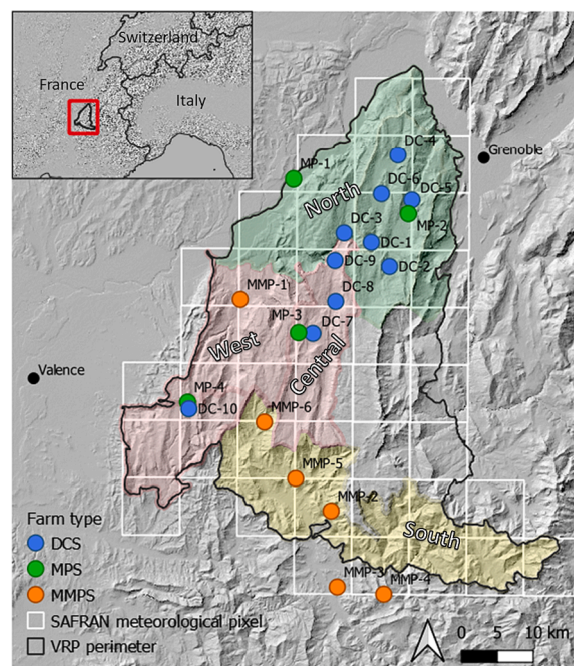


Fig. 1. Case study area and farms – Localisation of the 20 surveyed farms (plain dots) in the Vercors Regional Park (VRP). Dots represent the main buildings of the farms, where most of the farmland is concentrated. Farm type: DCS: grassland-specialised Dairy Cattle System; MPS: Mountain Pastoral suckler System; MMPS: Middle-Mountain Pastoral suckler System. White squares delineate the SAFRAN meteorological data grid (8 × 8 km – see Section 2.3). Main geographical VRP sub-regions are mentioned in white letters.

wherever the topography is more mountainous, semi-natural grasslands and rangelands (e.g. shrublands, woodlands and summer mountain pastures) are dominant. The agro-pastoral functions of semi-natural grasslands and rangelands (e.g. hay making, off-season grazing, summer grazing) depend on altitude, slope severity, access conditions and vegetation properties.

2.2. Case study farms characteristics

In the VRP, three dominant types of livestock breeding systems can be identified based on the typology from the French Livestock Breeding Institute (Nettier et al., 2010). These types differ mostly in terms of i) the main orientation of production (milk or meat) and ii) the specificities of the forage system, in particular the relative contribution of fodder stocks compared to grazing resources in the annual feed intake of herds, which is related to the length of the winter season as well as to the orientation of production. Building upon this typology, the authors' knowledge of the area and discussions with VRP managers, we selected a diversified sample of 20 livestock breeding farms and assigned each of them to one of the three main farm types. The selection of 20 farms aimed to take into account the relative prevalence of the three types in the different sectors of the VRP (e.g. dominance of dairy cattle systems on the plateau) and a certain diversity of situations within each type, representative of the reality of the VRP farms (Table 1, Fig. 1). The sample was made up as follow:

- (1) We selected ten farms affiliated to the mountain grassland-specialised dairy cattle system type (type DC). It represents dairy cattle farms in which fodder stocks usually represent more than 40 % of the yearly diet for herds. The ten farms are all located on the VRP plateau at an altitude ranging between 700 and 1100 m, in the northern, central or western parts of the study area, and four of them use a summer mountain pasture (only for young animals).
- (2) We selected four farms affiliated to the mountain pastoral suckler system type (type MP). It represents suckler farms (either sheep or cattle) in which fodder stocks represent between 20 and 40 % of the yearly diet for herds. Conversely to type DC, grazing of productive animals is not only based on semi-natural grasslands but also on rangelands (e.g. heathlands, summer mountain pastures). The four farms are spread over the VRP plateau, at an altitude around 1000 m (except for MP-1 farm, whose main buildings are in the valley but most of parcels are at a higher altitude), two of them are specialised in cattle breeding and two others in sheep breeding.
- (3) We selected six farms affiliated to the middle-mountain pastoral suckler system type (type MMP). It represents suckler farms (mostly sheep) in which fodder stocks represent less than 20 % of the yearly diet for herds due to a shorter winter season (relatively to types DC and MP) and to an extensive use of pastoral resources. The six farms are located in the western or southern parts of the study area, in the so-called "piedmonts" (i.e. middle-altitude foothills) ranging between 250 and 800 m. None of them use irrigation even for those located in the lowest altitude areas.

2.3. Agroclimatic characterization of farm exposure to drought

We informed the exposure of farms to drought using four indicators, namely the frequency, duration, average intensity and peak intensity of past drought events that occurred in the farmland area. We used the SAFRAN climate reanalysis dataset provided by the French National Centre for Meteorological Research (Vidal et al., 2010), which offers sufficient spatial resolution to account for the geographical aspects of farms (i.e. latitude, longitude and altitude). This dataset consists of meteorological parameters on a spatial grid of 8×8 km over the French national territory from 1960 to 2020, of which we used a subset of 42 pixels covering the case study area (Fig. 1).

We computed the Standardized Precipitation and Evapotranspiration Index at a three-month time scale (SPEI-3), an indicator recommended for drought characterization (Vicente-Serrano et al., 2010; WMO and GWP, 2016), particularly relevant to detect seasonal droughts in agriculture (Potop et al., 2012). For each pixel, we used the *spei* function of the "SPEI" package (Beguería and Vicente-Serrano, 2017) in R 3.6.1 (R Core Team, 2019) with a monthly water balance as input over the 1960–2020 time series. Prior to SPEI computing, the water balance was calculated as the difference between Precipitation and Potential Evapotranspiration (PET), where PET is estimated by using the *penman* function of the "SPEI" package and according to Penman-Monteith equation.

We defined a drought event as a period in which SPEI-3 is continuously negative after SPEI-3 being inferior or equal to -1 (Potop et al., 2012). We only considered drought events that occurred between March and October, each year. This period corresponds to the main growing season for vegetation in the VRP. Outside this period, possible snow cover on the ground reduces the relevance of computing PET and therefore of using the SPEI-3. Each drought event can be defined through its duration (number of months from the beginning to the end), its average intensity (mean SPEI-3 value over the event duration) and its intensity at peak (min SPEI-3 value over the event duration). When SPEI-3 at peak was below -1.5 , we classified the event as "severe or extreme". To accurately link drought hazards to farmer's experiences, we analysed drought data for each farm from the pixel corresponding to the location of the main farm building where most of the farmland is located. We paid particular attention to drought hazards that occurred in the four years prior to this study (2017–2020) because (1) a preliminary analysis of the climate dataset identified this period as one marked by several severe drought events in the VRP, and (2) it was a recent period and therefore easier for farmers to remember and refer to during the interviews.

2.4. Interviews with farmers to assess the vulnerability to drought

Following our conceptual framework, vulnerability of farms to droughts results from their sensitivity on the one hand, informed by the degree and nature of drought impacts perceived by farmers on the agro-pastoral resources they use, combined with the successful

Table 1

Characteristics of the case study farms.

Farm code	1. Grassland-specialised dairy cattle system										2. Mountain pastoral system				3. Middle-mountain pastoral system					
	DC-1	DC-2	DC-3	DC-4	DC-5	DC-6	DC-7	DC-8	DC-9	DC-10	MP-1	MP-2	MP-3	MP-4	MMP-1	MMP-2	MMP-3	MMP-4	MMP-5	MMP-6
Geographical sector	North	North	North	North	North	North	Central	Central	Central	West	North	North	Central	West	West	South	South	South	South	South
Altitude (m)	1000	1100	740	1100	1000	1000	850	850	940	900	250	1000	1000	1000	270	650	500	800	600	650
Working unit	2	2	1	2	2	2	1.5	4.5	2	1.5	2	2	2	3	3	1	2	2.5	1	1
Off-farm work	Yes	Yes	No	No	No	Yes	No	No	No	No	No	No	Yes	No	No	No	No	Yes	Yes	No
Herd	Dairy	Dairy	Dairy	Dairy	Dairy	Dairy	Dairy	Dairy	Dairy	Dairy	Suckler	Suckler	Suckler	Suckler	Suckler	Suckler	Suckler	Suckler	Suckler	Suckler
	cows	cows	cows	cows	cows	cows	cows	cows	cows	cows	cows	ewes	ewes	cows	ewes	ewes	ewes	ewes	ewes	ewes
Number Cows/Ewes	50	60	28	86	52	50	38	36	55	40	40	700	240	200	1050	170	400	150	185	250
Production	Milk	Milk	Milk	Milk	Milk	Milk	Milk	Cheese	Milk	Milk	Meat	Meat	Meat	Meat	Meat	Meat ¹	Meat	Meat ²	Meat	Meat
Value added products	Yes ¹	Yes ¹	Yes ¹	Yes ¹	Yes ¹	Yes ¹	No	Yes ^{1,2}	Yes ¹	Yes ²	Yes ³	Yes ^{3,4}	Yes ⁴	No	Yes ⁴	Yes ⁵	Yes ⁵	Yes ⁵	Yes ⁵	Yes ⁴
Organic farming	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	No	No	Yes	No	No	Yes	No	Yes	Yes	No
Distribution channel	Local ¹	Local ¹	Local ¹	Local ¹	Local ¹	Local ¹	Long ²	Local ³	Local ¹	Local ¹	Local ³	Local ^{3,4}	Local ⁴	Long ⁵	Local ^{3,4}	Local ⁴	Local ^{3,4}	Local ³	Local ³	Local ⁴
Farmland area (ha)*	110	135	51	114	101	90	67	83	128	208	70	90	100	350	205	110	62	110	150	79
% Grain crops	0	11	0	0	5	0	12	8	0	2	7	0	0	9	3	5	0	13	0	19
% Cultivated grasslands	27	59	0	30	19	17	56	26	10	20	3	17	15	23	7	18	33	13	0	8
% Permanent grasslands	73	30	100	70	76	83	32	66	90	0	90	83	20	6	50	5	0	22	7	23
% Rangelands	0	0	0	0	0	0	0	0	0	78	0	0	65	63	39	73	67	52	93	51
Transhumance to summer pasture	No	Yes ¹	Yes ¹	Yes ¹	No	No	No	Yes ¹	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No

Production: ¹ secondary production: Cereals; ² secondary production: Cereals and PDO goat milk.Value added products: ¹ Protected Designation of Origin Bleu du Vercors-Sassenage; ² Protected Geographical Indication Saint-Marcellin; ³ Park market certification;⁴ Quality certification Label rouge; ⁵ Protected Geographical Indication Agneau de Sisteron.Distribution Channel: ¹ Local dairy factory; ² Industrial dairy factory; ³ Direct selling; ⁴ Local farm cooperative; ⁵ Long distribution circuit.

*Farmland area does not take into account collective summer mountain pastures or collective communal grazing lands.

Transhumance to summer mountain pasture: ¹ only for young animals not yet in dairy production.

strategies farmers have implemented to persist or adapt, on the other hand. In our framework, the combination of strategies farmers have implemented can be seen as manifestations of farms' coping and adaptive capacity (Smit and Wandel, 2006; Urruty et al., 2016), i.e. respectively, the capacity to temporarily absorb or buffer disturbances while the farm remains in its original configuration in the long-term, and the capacity to adapt practices and farm's structure or organisation to anticipatively address disturbances (Darnhofer et al., 2010).

We collected information during interviews with farmers conducted between March and October 2021. The semi-structured nature of the interviews allowed flexibility in items discussed and depth of discussions. Our limited sample size allowed for extensive discussions with farmers (interviews lasted approximately two hours) and in-depth content analysis after transcription. Interviews addressed the three following points:

- (i) the farm's general biotechnical and social characteristics (production system, farmland, buildings and equipment, labour organisation, history, plans for the future, etc.) and its functioning, with an emphasis on the management of the forage system (grazing management in an average year, harvesting dates, purchases, etc.),
- (ii) the farm's sensitivity to droughts, expressed as the nature and level of drought impacts experienced by farmers, with a focus on the 2017–2020 period. We asked farmers to rate impacts of droughts on a four-level scale (no impact, low, moderate, high impact) for each of the agro-pastoral resources they might use (i.e. cereal crops, sown grasslands, semi-natural grasslands, rangelands including summer mountain pastures, different types of water resources, different groups of animals according to their physiological needs, etc.). As farmers very rarely reported impacts on cereal crops and animals, these two categories do not appear in the results,
- (iii) the strategies already adopted by farmers in order to persist or adapt to drought. We asked farmers about the reasons for adopting these specific measures and to comment on possible constraints to activating these measures. We then rated, with farmers, the relative importance of the different measures, for the farm to have successfully coped with or adapted to drought, on a four-level scale (none, marginal, moderate, essential). We also asked farmers about the measures they might consider in the future and the possible constraints and levers to their activation.

To characterise the measures mentioned by farmers in step iii), we relied on distinction between coping versus adaptive measures proposed by Darnhofer et al. (2010). Following an inductive approach, we grouped the measures into seven categories, namely purchases, use of security stocks, extension of farmland, changes affecting mowing surfaces and/or management, changes affecting grazing surfaces and/or management, changes in herd management, changes in water management. Subsequently, we grouped factors explicitly mentioned by farmers as constraining the implementation of specific measures into several categories of constraints through an inductive analysis.

2.5. Multivariate analysis of exposure and vulnerability components at farm level

To identify the patterns of drought risk in VRP farms, we performed a hierarchical clustering after a principal component analysis (PCA) of farms (PCA individuals) according to their exposure and vulnerability components (PCA variables). 18 PCA variables derived from the data collected above were used as follows:

- Four quantitative variables describe farms' exposure to drought: frequency, duration, average intensity and intensity at peak of droughts, averaged over 2017–2020 (see section 2.3);
- Three categorical variables summarise farms' sensitivity to drought, i.e. each variable is the global impact of drought described by farmers on: (1) fodder stocks, (2) grazing resources and (3) water resources. They were rated on a four-level scale by averaging the different impacts related to the same resource category, when needed (section 2.4, step ii);
- 11 categorical variables summarise the different categories of measures activated by farmers in response to drought, with a distinction between coping and adaptive measures, and rated on a four-level scale (section 2.4, step iii).

Main variables were standardised (i.e. centred and scaled) prior to analysis in the PCA function in "FactomineR" package in R. Main characteristics of farms (see Table 1) were included in the analysis as supplementary variables to help interpreting the results but did not contribute to the construction of the principal components. A hierarchical clustering was then performed using the Ward's criterion on the information contained in the first five dimensions of the PCA (default method in the HPCP function in "FactomineR" package). These analyses were performed using R 3.6.1 (R Core Team, 2019) with packages FactomineR (Le et al., 2008) and factoextra (Kassambara and Mundt, 2020).

3. Results

3.1. Degree of farm exposure to drought

Our analyses revealed important differences in drought frequency and intensity between farms according to their location in different VRP sub-regions.

The eight farms located in the northern part of the VRP were the least exposed to drought hazards. These farms were exposed to only one severe drought during the 2017–2020 period (Fig. 2A) and, in average during this period, to less intense events than

elsewhere in the study area (min SPEI-3 > -1.4 for 6 farms, Fig. 2B). In average over 2017–2020, drought event duration was between 4 and 5 months according to farms (data not shown).

All other 12 farms, located in the central, western and southern parts of the VRP, either in the middle-altitude piedmonts or on the plateau, were more exposed to drought hazards. Over the 2017–2020 period, drought frequency was high, with 2–4 severe or extreme droughts occurring during this period (Fig. 2A). Drought intensity at peak followed an altitudinal gradient: farms located in the piedmonts were exposed to more severe droughts than farms located on the plateau (Fig. 2B). Like in the northern part, duration of drought events was between 4 and 5 months, in average during this period (data not shown).

A comparative analysis between past (1961–1990) and recent (1991–2020) periods confirmed the contrast in drought exposure between farms located in the north and all others (data not shown). Indeed, the frequency of drought hazards has remained more or less stable in the northern part between past and recent periods (−2 to +0 events per decade) when it has significantly increased elsewhere (+3 to +6 events per decade), although the increase was less pronounced at higher altitudes than at lower ones.

3.2. Nature and level of farms' sensitivity to drought

The interviews revealed that recent droughts in the VRP mostly impacted forage resources while, comparatively, less impacts were reported on water resources, except for the specific case of water resources on summer mountain pastures (Table 2).

We found that the sensitivity of forage resources to drought (i.e. reduction in fodder stocks and grazing resources, long-term degradation in grassland potential) varied widely between farms (Table 2) and identified three explanatory factors to this variation. Firstly, sensitivity appeared to be geographical sector dependent: low to moderate impacts were mostly reported by farms in the northern and southern sectors, while mostly high impacts were reported by farms in the central and western sectors. Secondly, local pedoclimatic conditions on the farms, revealed by in-depth investigation during the surveys, emerged as an additional determinant of farms' sensitivity. When farm parcels had deep soils or were located on northern slopes or in the flat and humid parts of the VRP plateau, drought impacts on forage at farm level decreased compared to situations with a predominance of parcels located on superficial soil and/or on steep slopes. Thirdly, sensitivity varied according to the type of livestock system: middle-mountain pastoral systems reported none to moderate impacts from drought on grazing resources, while grassland-based dairy systems and mountain pastoral systems frequently reported high drought impacts on grazing resources (Table 2).

3.3. Nature and importance of farms' strategies to cope with and adapt to drought

The interviews then revealed the nature and importance of farms' strategies to persist and adapt to drought, as well as their variations between farms. Globally, we found that farmers adopted measures that mostly target the management of the forage system (i.e. purchases, mowing management, grazing calendar, etc.), the management of the herd or the management of the water resource (Tables 3A and 3B). Interestingly, farmers did not rely on a single measure and rather favoured a combination of several measures, both

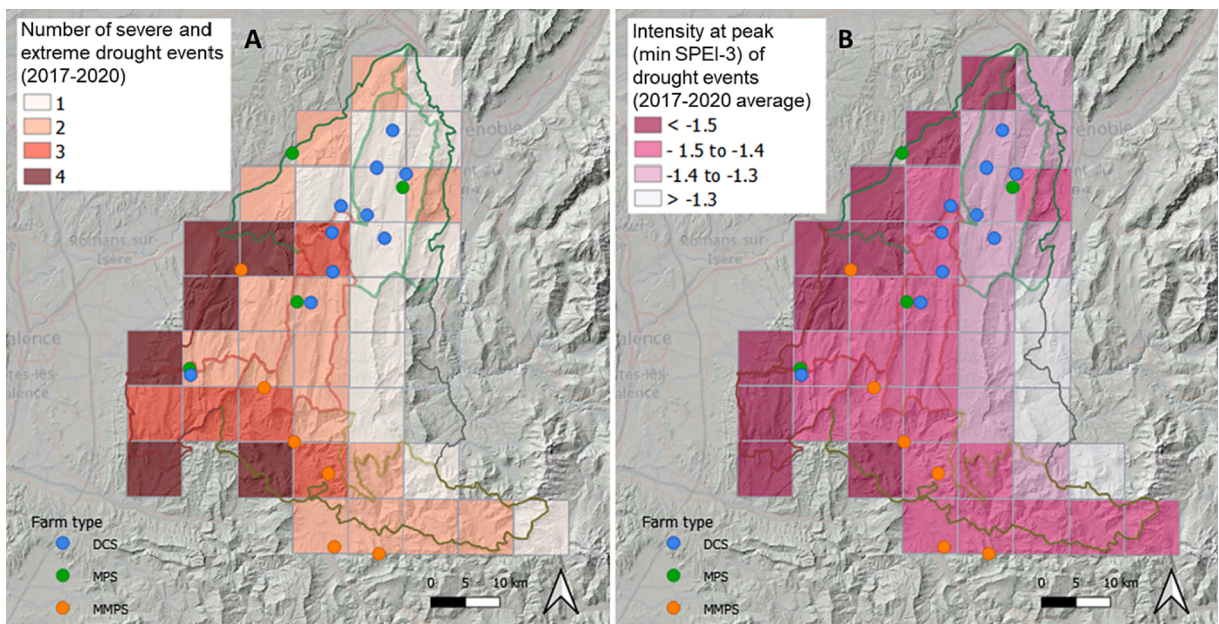


Fig. 2. (A) Number of severe and extreme drought events during the 2017–2020 period and (B) intensity at peak (min SPEI-3 value) of drought events in average over 2017–2020, for each of the 42 meteorological pixel covering the VRP. Plain dots indicate the location of the 20 surveyed farms and plain lines delineate the main geographical VRP sub-regions (refer to Fig. 1 for colour code).

Table 2

Nature and level of impact of droughts that occurred in the 2017–2020 period on agro-pastoral resources of farms in the VRP. 0: none; ‘+’: low impact; ‘++’: moderate impact; ‘+++’: high impact; NA: *not applicable*.

System type	Farm	Geographical sector	Forage resource				Water resource	
			Forage stocks: hay, silage, wrapping (semi-natural hay grasslands, sown grasslands, annual forage crops)	Grazing resources on farm (semi-natural grasslands and rangelands around farms)	Grazing resources on summer mountain pasture	Long-term degradation of semi-natural grasslands/rangelands	Water resource on farm (springs and streams on farm and parcels around)	Water resource on summer mountain pasture (springs, water reservoirs)
1. mountain grassland-specialised dairy cattle	DC-1	North	++	++	NA	0	++	NA
	DC-2	North	++	++	0	+	0	0
	DC-3	North	++	0	+	+	0	++
	DC-4	North	+	+	0	0	+++	++
	DC-5	North	++	+++	NA	++	++	NA
	DC-6	North	+	++	NA	+	0	NA
	DC-7	Central	+++	+++	NA	+++	0	NA
	DC-8	Central	+++	+++	0	0	+	++
	DC-9	Central	+++	+++	NA	+++	++	NA
	DC-10	West	+++	+++	NA	+	0	NA
2. mountain pastoral suckler	MP-1	North	+++	+++	++	+++	+	++
	MP-2	North	++	++	+++	++	0	+++
	MP-3	Central	++	+++	NA	+++	0	NA
	MP-4	West	+++	+++	+++	+++	0	+++
3. middle-mountain pastoral suckler	MMP-1	West	++	+	0	+	0	0
	MMP-2	South	++	++	++	++	0	0
	MMP-3	South	+	+	+	0	0	0
	MMP-4	South	++	+	0	0	0	++
	MMP-5	South	NA	0	0	+	+	++
	MMP-6	South	0	+	NA	0	+	NA

for coping with drought impacts (Table 3A) and for adapting to the likely reduction and/or greater variability of forage and water resources in the future (Table 3B).

Regarding the management of the forage system, while some coping measures were common to all farm types (e.g. shifting grassland use from mowing to grazing to regain grazing surface), other measures were preferentially used by certain categories of farms. For instance, contrary to the other farm types, dairy farmers often declared relying on previous year residual forage stocks to supplement animals during the drought period (i.e. security stocks) (Table 3A). In contrast, middle-mountain pastoral farmers preferentially mentioned relying on the extensive use of buffer areas (i.e. extensive grazing areas which are not used every year or not at the same intensity, and which are flexible in the timing and duration of grazing) or on the exceptional grazing of extra lands outside contracted or owned properties (Table 3A). In addition, for a large part of mountain farms located on the VRP plateau (i.e. either dairy or suckler), extraordinary feed purchase was often an important or essential coping measure contrary to farms located in the piedmonts (i.e. middle-mountain pastoral farms).

We found that responses were more homogeneous across farms' types when considering long-term adaptation measures in the management of the forage system (Table 3B). Many farmers reported that they had increased the area of their farmland (i.e. mechanisable lands or private and/or collective grazing surfaces) or were planning to do so, with constant livestock units (Table 3B). At the parcel scale, most of adaptive measures were related to a fine-tuned technical management of grasslands and pastoral areas aiming at securing or improving productivity (e.g. sowing of resistant specie and species-mix in cultivated grasslands, advance in hay making date to secure the first cut and open the possibility for a second one, fine scale rotational grazing). Regarding herd management, some farmers mentioned they have shifted the lambing or calving periods to avoid animal high nutritional needs during periods of low grazing resources or they have reduced the number of young animals (i.e. the ones intended for cull animal replacement) to decrease forage needs on the farm while keeping about the same animal production capacity (Table 3B). Only one farmer explained having being obliged to significantly reduce the number of animals in production. Regarding watering of livestock, adaptive measures have been taken, or are planned, particularly by pastoral farms and for the transhumance period on summer mountain pastures (Table 3B). In these farms, water storage equipment has become essential to continue using the current farmland or to better balance grazing pressure between sectors.

3.4. Constraints to the implementation of adaptation measures

The interviews revealed constraints to the implementation of coping or adaptive measures (Tables 3A and 3B). Some constraints were common to all geographical sectors and farm types. They include the biophysical limits of mountain settings ('physical limit') which restrict the mechanisation and the potential for cultivated grasslands and crops; workload ('work organisation reason') which limits, for instance, the total area that can be mown at peak mowing times; and the competition for agricultural land ('land pressure'), which strongly limits the extension of farmland (Table 3B). Similarly, the systematic purchase of external fodder and feed was not an option for the majority of farmers, as it was deemed not financially viable in the event of recurrent droughts and despite existing government aids. In the specific case of dairy farms, which had a slightly higher purchasing capacity and made more use of purchases than other farms, the PDO specifications restricting the origin of feed supplies appeared an additional regulatory constraint to purchases. In these farms, technical constraints to grazing management were higher than in pastoral farms. For example, coping measures involving spatial mobility of herds (e.g. grazing of buffer areas) were not implemented to face drought due to daily milking on farms and the high and constant nutritional needs of herds for a regular milk production.

3.5. Exposure and vulnerability patterns of VRP livestock farms

The multivariate analysis provided a synthetic view of the different components of farms' exposure and vulnerability to drought (Fig. 3). The hierarchical clustering on principal components further classified farms in three groups (as reported in Fig. 3):

- Farms of the first group are characterised by the lowest drought exposure (significant negative contribution of exposure variables to this group). They are also characterised by a mixed strategy to both persist and adapt to drought, based on the use of security stocks and the extension of the farmland area (significant positive contributions of these two variables to this group). This group is composed of grassland-specialised dairy cattle farms located in the northern part of the VRP plateau.
- Farms of the second group displayed jointly a high exposure to drought (in particular the intensity of drought events contributes positively and significantly to this group) and a low sensitivity (negative contribution of two sensitivity variables to this group). These farms are characterised by a strategy essentially based on coping measures related to the flexibility of grazing management (significant positive contribution of this variable to this group), in relation to supplementary variables indicating a high ratio of rangelands within farmlands and the use of a summer mountain pasture during a large part of the year. Another feature of these farms is that they did not rely on external purchases (significant negative contribution of this variable). This group is composed of middle-mountain pastoral suckler farms, located in the western or southern parts of the VRP and at lower altitude than farms located on the plateau.
- Farms of the third group were not homogeneously exposed to drought (no contribution of drought exposure variable to this group) but had a high sensitivity (significant positive contribution of two sensitivity variables to this group). These farms are also characterised by the importance of purchase of external forage to cope with drought (significant positive contribution of this variable to this group) and by limited coping measures concerning grazing management (significant negative contribution of this variables to this group).

Table 3A

Nature and importance of coping measures implemented by farmers to buffer immediate impacts of droughts in the VRP. 0: not implemented (i.e. not relevant or not necessary); '+': marginal measure; '++': moderate measure; '+++': essential measure; NA: not applicable.

A			Nature and importance of coping measures								
System type	Farm	Geographical sector	Purchases	Security stocks	Mowing management	Grazing management	Extension of farmland	Herd management		Water management	
			Extraordinary purchase (hay, straw, cereals, cut of standing grass from a non-livestock farmer, ...)	Distribution of hay to compensate for the lack of grazing resources	Areas usually mowed are used for grazing at the expense of harvesting for stocks	Increased grazing of buffer areas (e. g. woodlands, off-season pastures, oversized sectors in summer pastures)	Exceptionnal grazing of lands outside the farm (e. g. cereal regrowth, orchards, walnut groves, forest areas)	Temporary decrease in animal body condition and/or production to reduce forage needs	Earlier sale of cull animals to save forage resource on the farm	Carrying additional water tons to compensate for the drying up of springs / increased animal needs	Purchase of water from the drinking water system
1. mountain grassland-specialised dairy cattle	DC-1	North	0	+++	++	NA	0	0	+	0	0
	DC-2	North	0	+++	++	0	0	0	0	+	0
	DC-3	North	0	+++	+	0	0	+	0	0	0
	DC-4	North	++	++	+	0	0	0	+	0	++
	DC-5	North	+++	+	++	NA	0	+	0	0	+
	DC-6	North	+	++	0	NA	0	++	0	0	0
	DC-7	Central	+++	+	++	NA	0	0	+	0	0
	DC-8	Central	+++	+	++	0	0	0	0	+	0
	DC-9	Central	+++	+	++	0	0	++	+	+	0
	DC-10	West	+++	+	++	0	0	+	0	0	0
2. mountain pastoral suckler	MP-1	North	+++	0	+	0	0	0	0	++	++
	MP-2	North	+++	0	0	0	0	++	+	0	0
	MP-3	Central	+++	0	+	0	+	++	+	++	0
	MP-4	West	+++	0	++	0	0	+	0	0	0
3. middle-mountain pastoral suckler	MMP-1	West	0	0	0	++	+++	0	0	0	0
	MMP-2	South	0	++	++	+++	0	+	0	0	0
	MMP-3	South	++	0	++	++	+++	+	0	0	0
	MMP-4	South	+	0	++	+	0	0	0	0	0
	MMP-5	South	0	0	NA	+++	0	0	0	0	0
	MMP-6	South	0	0	0	+++	0	0	0	+	0

Table 3B

Nature and importance of adaptive measures implemented by farmers for long-term anticipation of future droughts in the VRP. 0: not implemented (i.e. not relevant or not necessary); '+': marginal measure; '++': moderate measure; '+++': essential measure; NA: not applicable. When measures were not implemented due to explicitly mentioned constraints by farmers, these measures are referenced as *Excluded (Excl.)* and the nature of constraint is indicated in brackets (EC: economic reason; RE: regulatory constraint; LP: land pressure; WO: work organisation reason; PH: physical limit; WP: wolf predation; SR: sanitary reason; TF: technical functioning reason). When measures were not implemented but already planned, they are referenced as *Planned*.

B			Nature and importance of adaptive measures											
			Purchases	Extension of farmland	Mowing surface management		Grazing surfaces and management			Herd management			Water management	
System type	Farm	Geographical sector	Systematic compensatory feed purchase (e.g. through cash flow provisioning)	Extend in the farmland area to increase the security stocks / to gain grazing flexibility (e.g. new lease agreements)	Sowing drought-resistant species and high-diversity seed mixes to secure harvests from cultivated grasslands	Conversion of permanent grassland and/or faster cultivated grassland turnover	Revalorisation of grasslands (finer hay and grazing management) to improve the forage quality and quantity	Improvement of rangelands and mountain pastures (e.g. clearing of shrubs, adapted grazing pressure)	Noticeable changes in summer mountain pasture management to increase or preserve the resource	Offset of calving and lambing period to reduce the need for forage stocks	Reduction in the number of young animals to decrease forage needs	Reduction in the number of animals in production on the farm	Improved water supply and/or storage capacity on farm	Improved water storage capacity on summer mountain pasture
1. mountain grassland-specialised dairy cattle	DC-1	North	Excl. (EC, RE)	+++	++	Excl. (PH)	++	NA	NA	0	0	0	Planned	NA
	DC-2	North	Excl. (EC, RE)	+++	++	Excl. (PH/ WO)	++	+	0	0	0	0	0	0
	DC-3	North	Excl. (EC, RE)	+++	Excl. (PH)	Excl. (PH)	+	0	+	0	0	0	0	Planned
	DC-4	North	++	++	++	Excl. (WO)	+	++	+	0	++	0	0	Planned
	DC-5	North	Excl. (EC, RE)	Planned	++	Excl. (PH, WO)	+++	0	NA	0	++	0	0	NA
	DC-6	North	Excl. (EC, RE)	Excl. (LP, WO)	++	+	+	0	NA	0	++	0	0	NA
	DC-7	Central	Excl. (EC)	++	++	Excl. (PH)	++	0	NA	0	0	Excl. (EC)	0	NA
	DC-8	Central	Excl. (EC, RE)	Excl. (LP)	++	Excl. (PH)	++	0	+	0	Excl. (TF)	Excl. (EC)	++	Planned
	DC-9	Central	Excl. (EC, RE)	++	++	Excl. (PH)	++	+	NA	+	++	0	0	NA
	DC-10	West	Excl. (EC)	++	++	+	+	+	NA	0	0	0	+++	NA
2. mountain pastoral suckler	MP-1	North	Excl. (EC)	++	++	Excl. (PH)	++	+	0	+	0	Excl. (EC)	Excl. (EC)	Planned
	MP-2	North	Excl. (EC)	Excl. (LP)	++	+	+	+	0	Excl. (WP)	0	Excl. (EC)	0	++
	MP-3	Central	Excl. (EC)	Excl. (WO)	++	Excl. (PH)	+	++	NA	Excl. (WP)	0	+++	0	NA
3. middle-mountain pastoral suckler	MP-4	West	Excl. (EC)	Excl. (LP)	++	Excl. (PH)	+	+	++	0	0	Excl. (EC)	0	+++
	MMP-1	West	Excl. (EC)	+++	++	Excl. (PH)	++	++	0	0	0	0	0	+++
	MMP-2	South	Excl. (EC)	Excl. (WO)	++	Excl. (PH)	+	+	0	0	0	0	0	+++
	MMP-3	South	Excl. (EC)	Excl. (LP)	++	Excl. (PH)	+	+	0	0	0	0	0	+++
	MMP-4	South	Excl. (EC)	+	++	Excl. (PH)	+	+	0	0	0	0	0	0
	MMP-5	South	NA	+	NA	NA	+	++	0	0	0	0	0	++
MMP-6	South	Excl. (EC)	Planned	++	Excl. (PH)	+	++	NA	Excl. (SR)	0	0	Planned	NA	

this group). This group is composed of farms located on the plateau, mostly in the central and western sectors (plus two farms located in the north). They are either grassland-specialised dairy cattle or mountain pastoral suckler systems.

4. Discussion

Our results open the way to several points of discussion. In a first section, we summarise the nature and level of farms' exposure and sensitivity and the strategies farmers have implemented to persist and adapt to drought, in the light of geographical, biophysical and socio-technical contexts of farms. In a second section, we analyse the different combinations of these components and how they contribute to different patterns of drought risk across farms. In a third section, we highlight options for adapting to drought by discussing the main constraints to the implementation of coping and adaptive measures.

4.1. Exposure, sensitivity and strategies implemented by livestock farmers to face drought

In the first step of our analysis, we showed that even within a small territory, livestock farms were unevenly exposed to drought. This uneven exposure aligns with results from other studies in mountain settings (e.g. Deléglise et al., 2022), where the degree of exposure of a system to climate variability and change can be associated to a geographical determinism. A striking point here is that, while we expected farms on the plateau to be the least exposed to drought, i.e. benefiting from more mountain and/or oceanic climatic influences and attenuated manifestations of drought with altitude than farms in the middle-altitude sectors often located further south and subjected to more pronounced Mediterranean influences, this was only evident for farms in the northernmost part of the plateau. Although the climate at this altitude was once considered humid in our case study, farms located in the central and/or western parts of

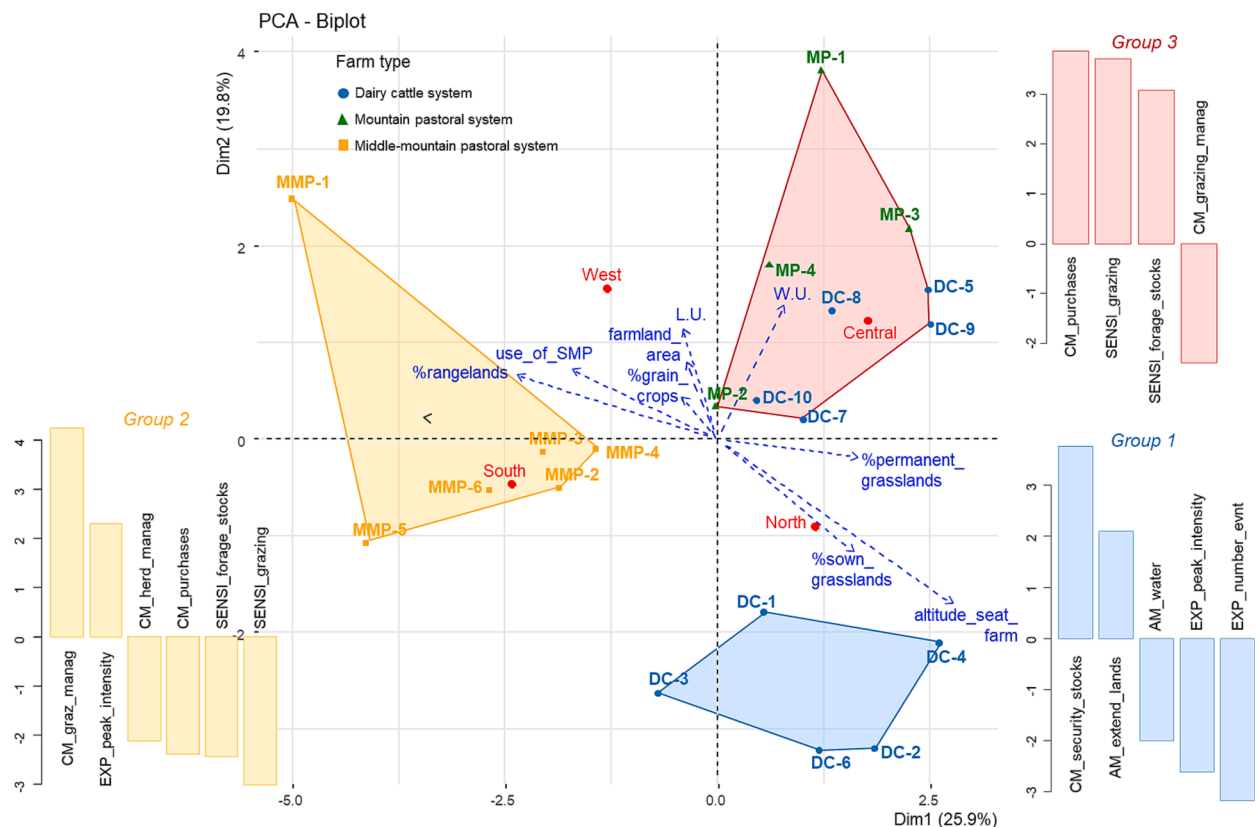


Fig. 3. Principal component analysis of 20 farms (individuals) according to components of exposure and vulnerability (variables). To provide a simplified visualization, only individuals and illustrative supplementary variables (not contributing to the axes) are shown (blue dotted lines = continuous variables, red points = qualitative variables). Groups (i.e. coloured shapes) are derived from a hierarchical classification on principal components (see Section 2.5 for details). Barplots next to the groups display the *v.test* value of the exposure and vulnerability variables that have a significant contribution to the formation of groups. Meaning of variables in the barplots: *EXP_number*: number of total drought events during the 2017–2020 period; *EXP_peak_intensity*: peak intensity of drought events averaged over 2017–2020; *SENS_forage_stocks*: impact level on forage resources for stocks; *SENS_grazing*: impact level on grazing resources; *CM_purchases*: importance of extraordinary feed purchases; *CM_security_stocks*: importance of the use of security stocks; *CM_graz_manag*: importance of coping measures implemented concerning grazed surfaces and grazing routine; *CM_herd_manag*: importance of coping measures implemented concerning herd management; *AM_water*: importance of adaptive measures concerning the water resource; *AM_extend_land*: importance of extension in farmland area in the past recent years. See Table 1 for the meaning of illustrative supplementary variables.

the plateau have been particularly exposed to drought in recent years, probably due to the northward and upward shift in Mediterranean climatic influences with climate change (Hertig and Tramblay, 2017).

In a second step, our analysis confirmed that the sensitivity of farms to drought stands rather independent of exposure, i.e. that farms exposed to similar meteorological drought patterns can be differently impacted. This result can be explained by the fact that topographical aspects, soil types and vegetation characteristics mainly determine the sensitivity to drought of forage or water resources, whereas the duration or intensity of drought may play a secondary role, as found in other contexts (Knapp et al., 2015). For instance, low productive pastures, typical of the poor soil conditions in the middle-altitude sectors of the study area, are less sensitive to water stress than productive grasslands on the plateau, due to the presence of shrubs and herbaceous species with a conservative growth strategy (Dodier et al., 2023). But, more importantly, the long-term co-evolution between climate, vegetation and practices may have influenced individual perceptions of impact severity. In particular, we hypothesise that farmers in the southern and middle-altitude sectors of the VRP perceived the impacts of drought to be relatively low, despite exposure to severe droughts, due to their longer habituation to a dry summer climate and because their system is intrinsically configured to withstand climatic variability (e.g. livestock mobility, extensive herd management), like in more Mediterranean systems (Jouven et al., 2010; Aguilera et al., 2020).

In a third step, our analysis showed that strategies to face drought varied across farms in the type and importance of coping and adaptive measures activated, in particular between grassland-specialised dairy farms and pastoral suckler systems. Grassland-specialised dairy farms coped with droughts by building up security stocks or extending grazing surfaces at the expense of stockpiling, and, if necessary, compensating with purchases thanks to sufficient cash flow. Pastoral farms reacted through increasing grazing in buffer areas, flexibility in grazing routines, the education of animals to consume rough vegetation and the capacity of herds to withstand low-feed intake periods. In the long-term, grassland-specialised dairy systems have generally focused on increasing the surface area and/or the productivity of mown grasslands to oversize security stocks, while middle-mountain pastoral systems have tended to increase grazing resources through reopening of pastoral areas, new agreements with forest managers or neighbouring farms, better management and equipment of summer mountain pastures, etc. Mountain pastoral systems hold an intermediate strategy as they share attributes of both other types. Apart from these distinctions across farms, a striking point we highlight here is that all farmers avoided major structural changes in the organisation and functions of their systems. In other words, so far they did not transform (Darnhofer et al., 2010; Fedele et al., 2019), through e.g. a major diversification of livestock species or a change in production orientation (Bertolozzi-Caredio et al., 2021). We hypothesize that their current management of drought risk is anchored in the experience of intermittent droughts, which most systems could absorb or adjust to so far (Darnhofer et al., 2010; Nettier et al., 2010; Salmoral et al., 2020; Beitnes et al., 2022). Lack of transformative measures implemented may otherwise reflect strong external drivers such as path dependence and broader economic, social, institutional or politic constraints (Bertolozzi-Caredio et al., 2021; Beitnes et al., 2022). In the context of future climate change that predicts recurring multi-year droughts, it remains hard to assess the extent to which deeper changes would be implemented by farmers and would then question the core identity and main functions of their system.

Finally we would like to stress that, while exposure could be directly linked to geographical determinants, it is difficult to fully distinguish between the components of vulnerability, namely sensitivity (biophysical factors of vulnerability) and coping or adaptive capacity (human factors of vulnerability), as pinpointed by Smit and Wandel (2006). As was found in other agricultural contexts, differences in climatic or biotechnical contexts of farms shape the farmers' perceptions of climate variability, and, accordingly, their different sensitivity and adaptive capacity (Singh et al., 2020).

4.2. Differential patterns of drought risk

Analysis of the combinations of exposure and sensitivity levels with the different strategies farmers have implemented to persist and adapt to drought revealed three main groups of farms with different underlying drivers of final risk of impacts.

The first two groups of farms, despite contrasting in terms of drought exposure and strategies implemented, shared a relatively low sensitivity to drought. So far, these two groups appear to be less at risk than the third group, which is characterised by high sensitivity to drought and, comparatively, low coping and adaptive capacity. The first two groups are each composed of farms belonging to a single type of livestock system and a single sector (i.e. grassland-specialised dairy system located in the north on the one hand, and middle-mountain pastoral systems located in the south on the other), confirming our hypothesis that the geographical and/or biotechnical contexts of farms largely determine the risk they face in the event of drought. Probably benefiting of the most favourable geographical and/or biophysical conditions in our case study, combined with different measures that allowed extending the farmland and over-sizing the security stocks in relation to the needs of the herd, the first group is relatively at low drought risk. A previous study showed that ecological intensification was achieved in the grassland-specialised dairy cattle farms of this group thanks to a strong complementarity between cultivated and semi-natural grasslands (Loucougaray et al., 2015), thus reinforcing their buffer capacity (Darnhofer et al., 2010). The second group of farms (i.e. middle-mountain pastoral farms) compensated for more adverse geographical and biophysical conditions with strong coping capacity notably regarding the management of the grazing system, typical of extensive pastoral systems in marginal production areas (Aguilera et al., 2020). These farms rely more than others on a diversity of practices and resources used, at different levels, in biological, technical or organisational components, which is an important condition for improved buffer and adaptive capacity (Martin and Magne, 2015; Nettier et al., 2017; Dumont et al., 2022). In particular, the variation in altitude of parcels (e.g. transhumance to a summer pasture), the diversity of functions (e.g. in terms of period and modality of use) and types (e.g. wooded pastures, orchards) of pastoral resources used, and the wealth of know-how of breeders and herders are important factors to buffer climate variability in these systems (Nettier et al., 2017).

Interestingly, the cluster analysis revealed a third group, consisting of farms of two different livestock system types, whose drought risk appears to be essentially driven by high sensitivity, as perceived by farmers. In the case of these farms, it is typically difficult to

dissociate high sensitivity to drought from a lack of coping or adaptive capacity, i.e. the biophysical and social components of vulnerability (Smit and Wandel, 2006). There is a kind of self-reinforcement of drought risk due to insufficient coping and adaptive capacity in the face of high impacts, probably correlated with the recent rise in drought exposure. For example, the lack of security fodder stocks to supplement herds during the drought period has resulted in some farms overgrazed certain areas, dramatically altering their productivity for several years and having a negative cascading effect on their ability to rebuild security stocks. The subsequent recurring need to purchase external feed then permanently reduced the financial capacity of these farms to invest, for example, in new grassland leases. In addition, it is to notice that pastoral farms of this group often relied on less diversified resources and practices than those in the middle-mountain sectors, which is another factor increasing their vulnerability. Indeed, the diversity of buffer areas and pastoral resources is lower on the plateau, dominated by productive grasslands on the one hand, and remote and steep pastures with poor soil conditions neglected by dairy farms on the other, than in the piedmonts and neighbouring valleys with a more mixed crop-grassland-forest landscape. They also combine a lesser diversity of cultural practices, such as the growing of drought-resistant but cold temperature sensitive species (e.g. lucerne, sorghum), which are much widespread in the middle-altitude sectors. Finally, the lack of awareness of extreme climatic hazards or the lack of past experiences may be an additional factor explaining low adaptive capacity and increased vulnerability in these farms, as evidenced in the Nordic agriculture (Käyhkö, 2019).

4.3. Adaptation options to reduce the drought risk in the VRP livestock farms

Because farmers adapt to changing climate conditions while being part of a complex and broader social-ecological system, different factors, either biophysical or social, internal or external to farms, can constraint farms' coping and adaptive capacity against climate stressors (Le Dang et al., 2019). Four points appeared particularly striking in the possibility for farmers in the VRP to implement adaptation measures: biophysical limits, land pressure, wolf predation and level of farm's income.

Our in-depth content analysis of interviews highlighted first the importance of biophysical factors in reducing farmers' implementation of adaptation measures in the VRP. The absence of surface water, shallow soils, steep slopes or long snow-covered periods restrict the range of possible agronomic levers to persist or adapt to drought (irrigation, mechanisation, diversification of crops and rotations, etc.). Farmers all mentioned the need for networking among themselves as well as with technical advisors to share new technical knowledge, experiences and know-how adapted to their local context (e.g. test of new grass-legume mixes and forage crops, planting of fodder trees, better knowledge of permanent grasslands properties, etc.). This aligns with ways already reported to improve farmers' adaptive capacity to cope with disturbances, based on the establishment of social networks and collective action (e.g. Urruty et al., 2016; Nettier et al., 2017). Initiatives to establish or reinforce knowledge exchange about tailored technical adaptations could hence be encouraged with the help of local agricultural extension advisers or park officers in the VRP.

Second, an important constraint restricting the implementation of adaptation measures is the low agricultural land availability, as repeatedly mentioned in the interviews and echoing a well-known weakness of mountain livestock agriculture (e.g. Ripoll-Bosch et al., 2012). Conflicts for land access are important on the entire plateau and foothills of the VRP due to pressure from other uses (e.g. increasing rates of peri-urbanization) and pressure between farms themselves (e.g. rental of lands by farms coming from surrounding plains). This obviously limits the possibility for farmers to extensify and to increase their buffer capacity. Some farmers also cited precariousness of land leases as an obstacle to the implementation of long-term measures that require several years to get established or significant financial investments such as planting of fodder trees, or setting up of water infrastructures. To foster farmers' adaptation to drought, considering the issue of land availability and attribution seems unavoidable. This would require consultation procedures between a large set of actors involved in the use of land resources (landowners, farmers, local or regional authorities, etc.) and probably a wider deployment of regulatory and financial tools directly protecting agricultural use.

Third, the level of farmer's income is also an obvious constraint to the activation of some adaptation measures to drought, such as the possibility to make investments (e.g. building infrastructures for water storage) or to rent or purchase supplementary lands. Often, this lack of economic margin does not allow reducing the herd size, which would equate lowering productivity. This economic constraint is particularly strong in small pastoral suckler farms due to very low prices of animal outputs and low CAP subsidies (O'Rourke et al., 2016). Dairy farms might face this economic barrier at a lesser extent as they capture greater benefit for their production, e.g. by processing part of their production directly on farm and/or thank to high local and regional PDO recognition of cheese production (Alavoine-Mornas and Madelrieux, 2015), but so far have not considered viable the option of reduction of the herd size in the future. To raise some of the financial barriers, collective organization of farmers have proven to be successful (Urruty et al., 2016). For instance, collective funding has allowed the building of an innovative water storage on the top of a collective summer mountain pasture while, individually, farmers could not support such investment on their pastures. Also, farmers involved in PDO or PGI productions could take advantage of local governance and partly self-organised cooperatives (Alavoine-Mornas and Madelrieux, 2015; Pachoud et al., 2020) to address the issue of increased production costs with climate change. Finally, at a political level, the redefinition of CAP subsidies (i.e. allocated to extensive livestock farming for its positive externalities; Bernués et al., 2014; O'Rourke et al., 2016) might consider that climate-resilient transition increases production costs (e.g. decrease in productivity, investment costs for diversification) and explicitly support it in a near future.

Finally, we found that the risk of predation by wolves is a major and immediate concern for all pastoral farms interviewed, echoing a widespread situation in Europe (Meuret et al., 2021). Accounting for this risk restricts farmers' scope for managing grazing (e.g. stop of nocturnal grazing, limitation of grazing in sylvo-pastoral areas or in remote sectors of summer mountain pastures) or herd (e.g. shifting lambing periods so that they take place indoors in winter, stop ascending lambs to mountain pastures) in the face of droughts. It indirectly exacerbates the need for external feed and forage and reduces farmers' buffer capacity. The coordination of measures related to wolf predation protection with those promoting adaptation to climate change remains complex at this stage, and, experts

such as [Meuret et al. \(2021\)](#) posit that this integration of constraints cannot be achieved without more flexible national and European wolf regulation frameworks.

5. Conclusions

Our study provides insights into the construction of the drought risk for extensive livestock farms in a traditional breeding region in the French Pre-Alps at the forefront of climate change impacts. We found that even in a quite small mountainous region, farms displayed varying combinations of exposure and vulnerability levels and that these different components of the drought risk could be interlinked with feedback effects. Although we found a strong determinism of geographical, biophysical and socio-technical factors in the formation of the three main risk patterns revealed by our analysis, these patterns transcended the three main farm types in the initial typology. This highlights the importance of a farm-level approach and of distinguishing between the different facets of drought risk, as measures relevant to supporting adaptation need to be tailored to each specific combination.

The originality of our approach stems from the combination of quantitative climatic data and the content analysis of qualitative interview data, synthesized by means of a multivariate analysis to inform about the combinations between the different facets of drought risk. Despite a limited sample size, extensive discussion with farmers and in-depth content analysis permitted a detailed understanding of the characteristics of the farms and of their links to farmers' perceptions of drought impacts and strategies to cope with or adapt to them ([Bertolozzi-Caredio et al., 2021](#); [Beitnes et al., 2022](#)). Also, by capturing decision-making at farm level, we have added an integrated dimension to the approach, with the possibility of transferring our work directly to local stakeholders ([Käyhkö, 2019](#)).

Furthermore, by providing an early experience of a significant, albeit heterogeneous, increase in drought exposure with climate change, our case study could serve as a precursor for other traditional mountain breeding regions that will face similar challenges in the near future. Our results contribute to the current discussion on adaptation of extensive livestock production systems to the risk of drought, as in the case of highly nomadic pastoral systems in Asia and Africa ([Tugjamba et al., 2023](#)), which like in the Vercors, are deeply anchored in their socio-ecological surroundings. In particular, our study provides an opportunity to step back from most of the promising drought adaptation measures (e.g. sowing of drought-resistant crops, improved or secured irrigation practices, [Rojas-Downing et al., 2017](#); [Salmoral et al., 2020](#); [Stephan et al., 2023](#)) identified in production systems that are not subject to the same severe natural constraints as mountain livestock systems and that probably have more economic latitude. In addition, some of the adaptation measures promoted for the agro-ecological transition of livestock production (e.g. reduced dependence on external inputs, forage self-sufficiency, [Martin and Magne, 2015](#)) appear marginal here as they are already implemented as core functioning of agro-pastoral farms.

It turns out that the farms studied in the VRP have been so far focused on strengthening their buffer capacity as a major current option to reduce their vulnerability to intermittent drought. To further support farms in this current option, different strategies need be reinforced or unlocked beyond the farm level. For instance, actions and frameworks that support farmers' collective organisation could promote the dissemination and exchange of knowledge or overcome financial problems. In addition, local and national institutional or policy instruments could help address issues of access to land or wildlife-livestock interactions. However, a higher frequency of extreme droughts in the future, combined with other facets of climate change and socio-economic changes, may require deeper transformative change for farms to achieve long-term sustainability ([Darnhofer et al., 2010](#); [Beitnes et al., 2022](#)). In this endeavour, political and economic supports appear essential to extensive livestock farming ([Fedele et al., 2019](#)). Hence the challenge ahead is to promote the transformation of mountain livestock farms towards more climate-resilient systems in a way that also preserves their agro-ecological functioning and related bio-cultural diversity, vital goods and services.

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Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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