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## To cite this version:

C. Deleglise, H. Dodier, Laurent Garde, H. François, Isabelle Arpin, et al.. A Method for Diagnosing Summer Mountain Pastures' Vulnerability to Climate Change, Developed in the French Alps. Mountain Research and Development, 2019, 39 (2), pp.D27-D41. 10.1659/mrd-journal-d-18-00077.1 . hal-02610271

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Source: Mountain Research and Development, 39(2)

Published By: International Mountain Society

URL: https://doi.org/10.1659/MRD-JOURNAL-D-18-00077.1

**Mountain Research and Development (MRD)**
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

**MountainDevelopment**
Transformation knowledge

# A Method for Diagnosing Summer Mountain Pastures' Vulnerability to Climate Change, Developed in the French Alps

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*Summer mountain pastures are complex coupled ecological and human systems. They provide vital forage for livestock during summer, and their traditional use is decisive for the maintenance of biodiversity, ecosystem services, and open landscapes, which benefit local populations and tourists. With climate change, the increased intensity and frequency of climatic hazards threaten the sustainable management of these systems. To foster climate adaptation in such complex systems, we developed a tool to assess their climate change–related vulnerability. The tool consists of a 3-step vulnerability analysis: first, of the inherent exposure of mountain pastures to climatic hazards based on their physical features; second, of vegetation sensitivity to climatic hazards and changes in practices; and third, of adaptive capacities that lie in the options for managing mountain pastures together with the farms using them. This work was carried out within the research and development network Sentinel Mountain Pastures, which addresses climate change adaptation issues on mountain pastures across the French Alps. We used a transdisciplinary approach that included participatory work with experts and interviews with stakeholders. We believe this diagnostic tool has high potential for practical application to support adaptation on summer mountain pastures, by allowing a shared integrative understanding of the complexity of mountain pasture systems by stakeholders. We hope this will provide new information for policymaking that enhances the resilience of summer mountain pasture systems.*

***Keywords:*** *Mountain pasture; climate change vulnerability; French Alps; climatic hazards; pastoralism; livestock farming adaptation.*

***Peer-reviewed:*** *January 2019* ***Accepted:*** *May 2019*

## Introduction

Summer mountain pastures are complex systems in which the human and ecological dimensions are closely linked. Composed of a mosaic of grazed ecosystems that forms a functional agricultural management entity, they are managed by human actors (eg herders, farmers, and park managers) within an environment made up of the geographical context, economic opportunities, and social networks (Darnhofer et al 2012; Nettier et al 2017). In Europe, they are best known for their provision of forage to domestic herbivores during the summer and therefore have important agricultural and economic roles (eg livestock breeding and production; Dobremez et al 2016). Their traditional agricultural use also contributes decisively to biodiversity and to the maintenance of landscapes of great cultural value (Bornard and Cozic 2000; MA 2005; Quétier et al 2010; Walsh et al 2014; Schermer et al 2016). They are also often multifunctional areas and support a variety of ecosystem services that benefit local populations and tourists (MA 2005; Lamarque et al 2011).

Climate change is expected to be especially strong in mountain regions (Auer et al 2007; Calanca 2007; Serquet et al 2013) and to affect summer mountain pastures through increased variability in temperatures, changes in rainfall patterns and water availability, and perturbations in ecosystems (Fellmann 2012). In the short term, climate variability, in particular extreme events, leads to high interannual variability in the forage supply for grazing livestock (eg Deléglise et al 2015; Calanca et al 2016). In the long term, climate change is expected to impact biodiversity and ecosystem services such as forage supply—both directly, for example through effects on vegetation composition (Garamvölgyi and Hufnagel 2013; Matteodo et al 2013), and indirectly, through changes in traditional pastoral practices (eg Gavazov et al 2013; Schirpke et al 2017).

https://doi.org/10.1659/MRD-JOURNAL-D-18-00077.1

Adaptation practices commonly implemented to ameliorate climate-induced changes to cropping or livestock systems often consist of efforts to control environmental conditions (eg irrigation and fertilization), possibilities for which are very limited on mountain pastures because of natural constraints, short season length, access difficulties, and barriers to mechanization. If adaptation practices are not applied, there is a risk that pasture ecosystems will degrade due to overgrazing or other inappropriate use, with potentially irreversible long-term ecological consequences that could cause difficulties for livestock farmers who rely on this summer resource (Dobremez et al 2014). Thus, the challenge of adapting to climate change and its increasing variability on summer mountain pastures is to guarantee both the sustainability of livestock farming and the long-term preservation of mountain pasture forage resources, biodiversity, and landscapes.

In the French Alps, the tools currently used to manage mountain pastures were not developed to deal with climate change and uncertainty. Standard descriptions of pasture vegetation types were established to quantify the forage resources available in an average year (Jouglet 1999; CERPAM and PNE 2006; Bornard et al 2007), and pasture management strategies were elaborated to meet zootechnical objectives in this context (eg Savini et al 1995, 2010). These tools do not make it possible to measure the extent of variation, from one year to the next, in plant communities' dynamics and properties — for example, how their palatability and resistance to grazing are affected in the face of climatic hazards (Deléglise et al 2015). Yet this knowledge is crucial for herders, for instance to adjust grazing routes or complementary feed sources during the pasturing season as well as between years.

Existing tools also ignore the links between summer mountain pastures and the livestock farms that use them. This leaves a significant gap in knowledge about adaptive capacity, because farm management choices affect the number and type of pasturing livestock and the length of the pasturing period (Rigolot et al 2014; Nettier et al 2015, 2017).

To meet the challenge of adaptation on summer mountain pastures, it has thus become essential to develop a new management tool that integrates these types of information and supports the development of adaptation strategies at the scale of the whole system, including the farms using mountain pastures. We therefore propose a diagnostic tool to assess climate change–related vulnerability.

Climatic vulnerability is the degree to which a system is likely to be negatively affected by the effects of climate change, including climate variability and extremes (IPCC 2001). This commonly accepted definition encompasses a variety of scientific approaches, from biophysical to socioeconomic, leading to different evaluation methods (Costa and Kropp 2013; González Tánago et al 2016). For our purposes, we defined vulnerability as the consequence of 3 interconnected components: exposure to risks, sensitivity to damage, and adaptive capacity (IPCC 2001, 2007). Under this definition, a system is vulnerable if it is exposed to and sensitive to the effects of climate change and has only limited capacity to adapt, and less vulnerable if it is less exposed or less sensitive or has a strong adaptive capacity (Adger 2006; Eakin and Luers 2006; Smit and Wandel 2006).

Vulnerability assessments are an essential element of efforts to influence policies and programs to reduce risks associated with climate change (Füssel and Klein 2006; Renaud and Jansky 2008; IPCC 2014; Muccione et al 2016). The vulnerability framework outlined here has been widely used for integrated natural resource management in the face of natural risks at regional and local scales (eg Hagmann and Chuma 2002; Luers et al 2003; Malone and Engle 2011), and has proven its relevance to climate change adaptation issues in agriculture (Fellmann 2012; Urruty et al 2016). It has also been used effectively on summer mountain pastures to support adaptation to another disturbance factor, wolf predation (CERPAM et al 2012).

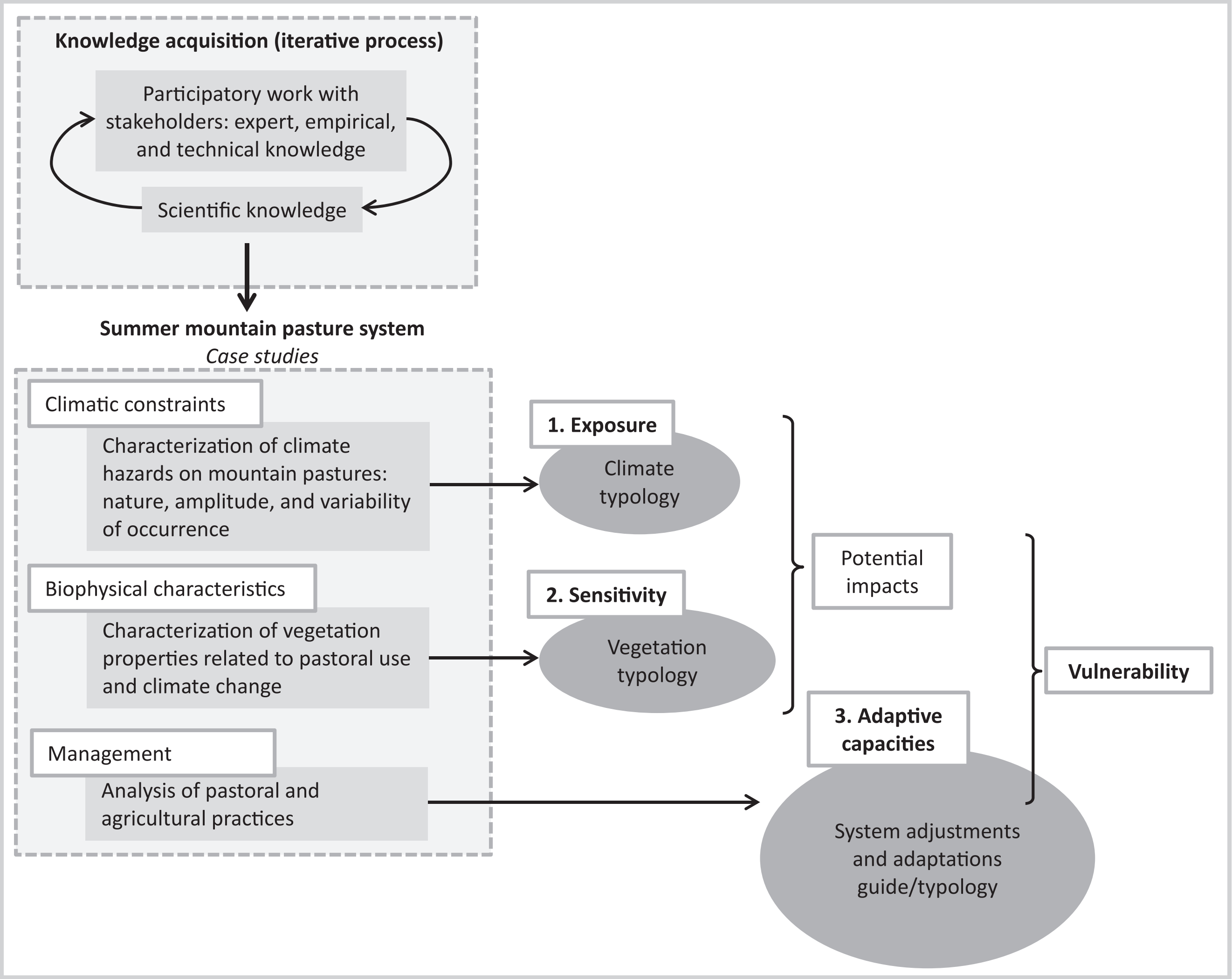
The work we present here was carried out within the Sentinel Mountain Pasture research and development program (Dobremez et al 2014), which was launched after several drought years in the 2000s had raised concerns over the impact of climate change and variability on summer mountain pastures in Ecrins National Park in France. The program has now extended to the French Alps, covering 7 national and regional parks. It includes the long-term monitoring of a diversified network of summer mountain pasture systems and is the basis for a collaborative learning process between researchers from various disciplines (agronomy, ecology, climatology, and sociology), agricultural and pastoral experts, protected area managers, and farmers and herders (Darnhofer et al 2017; Arpin and Cosson 2018). We analyzed the aforementioned 3 factors contributing to climate change-related vulnerability of mountain pastures—exposure, sensitivity, and adaptive capacities—to develop a diagnostic tool that can be used to promote adaptation efforts as part of the sustainable management of summer mountain pasture systems.

## Material and methods

### General methodology

To diagnose the vulnerability to climate change of summer mountain pasture systems, we adapted the 3-step framework described above (IPCC 2001, 2007) to these systems: (1) characterization of their inherent exposure as determined by their physical features, (2) characterization of their sensitivity through analysis of the sensitivity of their vegetation, and (3) analysis of the adaptive capacities

**FIGURE 1** Methodology for the construction of a diagnostic tool to assess the vulnerability of summer mountain pasture systems.



through analysis of options for managing pastures and of the interaction between the pastures and the farms using them (Figure 1). The work was carried out at the scale of the French Alps within the Sentinel Mountain Pasture program (Dobremez et al 2014).

Knowledge acquisition relies on a multiple evidence-based approach, which relies on the development of synergies across different knowledge systems (Tengö et al 2014; Klenk and Meehan 2015): scientific knowledge (from various disciplines, notably ecology), expert knowledge (knowledge of advisors on nature conservation, pastoralism, and agriculture), and local knowledge from herders and farmers. These different knowledge systems were brought together through participatory exercises conducted by researchers prior to this study with many stakeholders involved in mountain pasture management (see Nettier 2016).

### Exposure characterization

Exposure is the duration, amplitude, and frequency of changes in the climate of the system (IPCC 2001). We defined it as the set of climatic hazards to which mountain pastures have a certain probability of exposure, because of their geographical location and topography.

First, we identified the climatic hazards that impact the ability of mountain pasture ecosystems to provide forage to herds, through participatory modeling exercises with experts conducted by researchers between 2013 and 2015 (for details see Nettier 2016).

Second, we developed agro-climatic indicators reflecting these hazards at the scale of mountain pastures. The challenge was to estimate the snowmelt date, which conditions the start of grass growth in mountain environments, and to take into account the spatial variability of the climate within a pasture, which can be very strong and can influence pasture use throughout the pasturing season (eg snowmelt can occur several months apart in different parts of the pasture). For this, we used long-term climatic datasets from the SAFRAN model provided by Meteo-France, which offers atmospheric data (precipitation, temperature, wind speed, relative humidity, incident radiation) for 23 mountain ranges in the French Alps; the data are provided by elevation (300 m intervals), slope, and orientation (Durand, Giraud, et al 2009; Durand, Laternser, et al 2009). At the mountain pasture scale, this makes it possible to take into account the characteristics of the regional climate and the topography (orientation, slope, and elevation). Then, the combination of the SAFRAN model with the detailed snowpack model Crocus (Vionnet et al 2012; François et al 2014) allowed us to develop an original methodology to estimate the snowmelt date for mountain pastures, based on periods of snow presence and absence and time between these periods. We calculated average values and standard deviations for 1984–2014 of agro-climatic indicators for each of the 2780 mountain pastures referenced in the French Alps pasture survey (Dobremez et al 2016) for which climatic data and a digital terrain model were available. Analyses were carried out using PostgreSQL/PostGis and Python 2.7.

We then used principal component analysis, followed by an ascending hierarchical classification, with the average and standard deviation of computed indicators taken as variables and the 2780 mountain pastures taken as objects, to develop a typology of mountain pasture exposure for the whole French Alps. Analyses were carried out using R 3.4.2 statistical software (R Development Core Team 2017).

### Sensitivity characterization

Sensitivity is the degree to which a system is positively or negatively affected by changes in the climate factors to which it is exposed (IPCC 2001). We characterized the sensitivity of mountain pastures through the response of pasture vegetation to climatic hazards. During consultations, members of the Sentinel Mountain Pasture program indicated that vegetation is the primary concern related to climate change. The sensitivities of water resources, animals (eg to heat or emerging diseases), and workers were therefore not directly taken into account.

In mountain pastures during the summer grazing season, different vegetation types are combined, at different locations and times, through different pastoral practices, to meet the feeding requirements of livestock and to ensure the long-term sustainability of the resource. Inspired by the methodology developed for Mediterranean rangeland-based feeding systems to cope with strong climate variability (Bellon et al 1999; Moulin et al 2001; Farrié et al 2015), we documented the functions the mountain vegetation types can fulfill for the feeding of herds according to (1) their *agronomic properties*—seasonal biomass production, flexibility (in time and type of use), and nutritional quality; (2) their *sensitivity to climatic hazards and pastoral practices*, which modulates their main feeding function and sometimes allows for adjustment functions; and (3) the *precautions needed to preserve these properties* in the long term. We then classified these vegetation types within a list that was sufficiently generic to be valid across the French Alps and to enable us to maintain correspondence with earlier classification systems (Jouglet 1999; CERPAM and PNE 2006; Bornard et al 2007).

### Analysis of adaptive capacity

Adaptive capacity is a system's ability to prepare for and adjust to stress, to minimize potential damage, take advantage of opportunities, and cope with the consequences in order to be less vulnerable (IPCC 2001; Adger 2006). In the context of this study, it is the ability of the managers of mountain pasture systems to find solutions to potential shortages of resources for herds, while keeping in mind other issues in mountain pastures (eg environmental concerns) and on farms (eg technical constraints).

We analyzed semistructured interviews that were conducted each year from 2009 to 2017 with herders and farmers in a network of 31 summer mountain pastures and 37 farms using the pastures in various geographical, ecological, and socioeconomic contexts across the French Alps (see Nettier 2016 for more details). The interviews were conducted with herders on mountain pastures at the end of the summer season, and with farmers on farms at the end of the year, by an agronomy researcher accompanied by a pastoralist or an agricultural expert. They followed a general guide to understand and then classify pastoral and agricultural practices (Landais and Balent 1995; Girard 2006). Each year, interviews emphasized the specificities of climatic conditions in order to identify strategies implemented (or intended) to cope with climatic hazards. From these interviews, we compiled a list of strategies to adapt to climatic hazards, which we considered manifestations of adaptive capacities (Smit and Wandel 2006).

## Results

### Exposure

Three main climatic hazards that impact the pasture ecosystem's ability to provide forage to herds were identified: (1) drought, which affects the quantity and quality of biomass; (2) temperatures during the spring season (after snowmelt), which affect the time frame during which the forage resource will be available to herds in a given phenological stage; and (3) frost after snowmelt, which affects the quality and quantity of biomass.

Then 10 agro-climatic indicators were calculated to express the amplitude and variability of occurrence of

**TABLE 1** Agro-climatic indicators used to characterize exposure of mountain pastures in the French Alps to climatic hazards, 1984–2014.

| Agro-climatic indicator | Unit | Definition |
|---|---|---|
| **Average water balance, July (WB_july_mean)** | mm (average) | Theoretical water balance computed as precipitation minus potential evapotranspiration during July at the scale of the mountain pasture. It represents the water theoretically available for plants during the first grass growth—about from the arrival of herds on the lowest part of the pasture until their ascension to the higher parts. |
| **Variability of water balance, July (WB_july_sd)** | mm (SD) | Interannual variation in the above indicator. |
| **Average water balance, September (WB_sept_mean)** | mm (average) | Theoretical water balance computed as precipitation minus potential evapotranspiration during September at the scale of the mountain pasture. It represents the water theoretically available for plants during the autumn grass regrowth, generally grazed by herds on the lowest part of the pasture after they have come down from the higher parts. |
| **Variability of water balance, September (WB_sept_sd)** | mm (SD) | Interannual variation in the above indicator. |
| **Average spring advancement (spring_adv_mean)** | Day of the year (average) | Date of reaching 600 degree-days[a)] after snowmelt on at least 25% of the mountain pasture surface area, theoretically indicating the presence of enough resource (surface and vegetation phenological stage) to allow the start of grazing in the pasture. |
| **Variability of spring advancement (spring_adv_sd)** | Number of days (SD) | Interannual variation in the above indicator. |
| **Average spring spread (spring_spread_mean)** | Number of days (average) | Number of days between the time the first pixel[b)] of the pasture reaches 600 degree-days[a] after snowmelt and the time the last pixel reaches 600 degree-days (excluding the 10% of the pixels for which snowmelt is the latest). This roughly estimates the period during which there is available vegetation in a first-growth stage in the pasture. |
| **Variability of spring spread (spring_spread_sd)** | Number of days (SD) | Interannual variation in the above indicator. |
| **Average frequency of spring frost events (nd_frost_mean)** | Number of days (average) | Number of days with minimum temperatures below −5°C between snowmelt date and date of reaching 600 degree-days[a] at the scale of the mountain pasture. |
| **Variability of the frequency of spring frost events (nd_frost_sd)** | Number of days (SD) | Interannual variation in the above indicator. |

SD = standard deviation

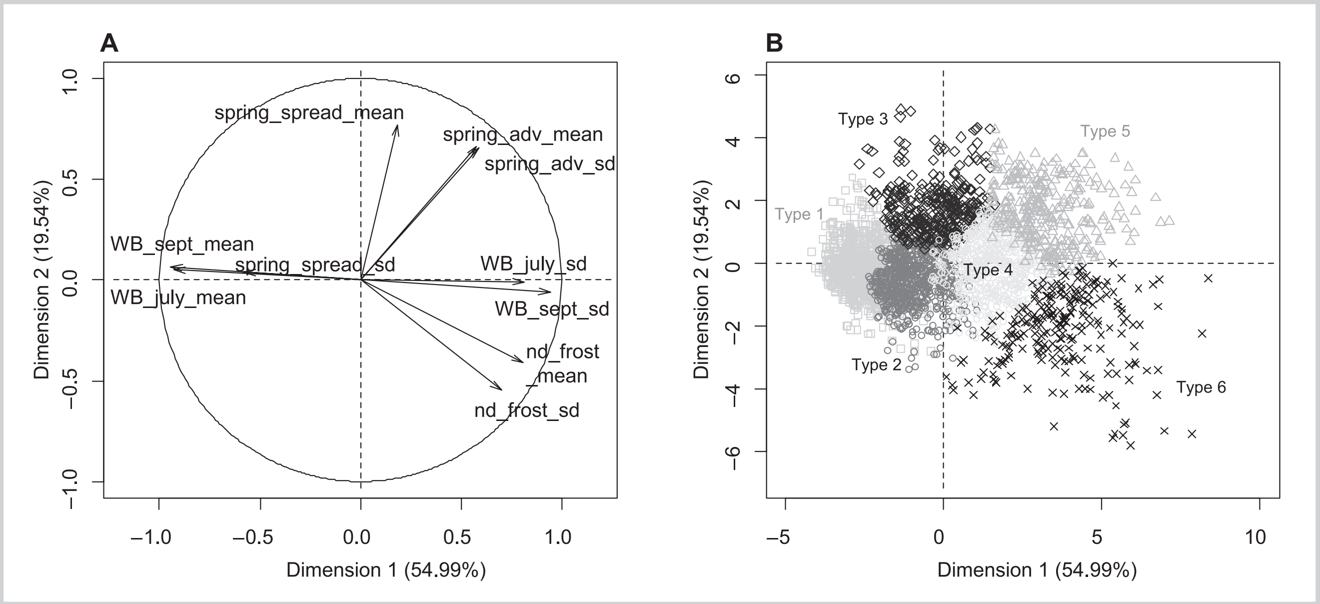
[a)] The threshold of 600 degree-days was chosen because (1) it is reached on the lowest parts of sentinel mountain pastures (average over the 31 sentinel mountain pastures during 1984–2014) at a date (end of June to mid-July) very close to the average date of the herds' arrival in these pastures (Nettier 2016); and (2) it is referenced in the literature as the temperature sum necessary for the reproductive apex of many grass species to reach 10 cm in height (Ansquer et al 2004), which is the phenological stage at which grasses provide maximum nutritional status without grazing compromising their regrowth.

[b)] Pixel refers to the pixels of the digital terrain model of mountain pastures, with a resolution of 25 × 25 m.

these 3 climatic hazards at the scale of mountain pastures and for the whole pasturing season—from spring to late summer (Table 1). The statistical classification of mountain pastures based on these 10 indicators (Figure 2) made it possible to construct a typology of mountain pasture climatic exposure at the French Alps scale. This typology contains 6 types, from very well watered to very drought prone (Figure 2B; Table 2). The average water balances in July and September (as well as their interannual variability) are very differentiating factors of the exposure of mountain pastures to climate hazards (correlations of –0.94 and –0.93 on axis 1 in Figure 2A) followed by the average frequency of frost events (correlation of 0.81 on axis 1).

The average spring "spread" (roughly, the time it takes for the entire pasture to reach a certain accumulation of temperature) and spring "advancement" (the date the earliest quarter of the pasture reaches a given temperature accumulation to allow grazing—see Table 1 for details on both these terms) are other differentiating

**FIGURE 2** Climatic exposure typology revealed through statistical classification of 2780 mountain pastures according to the value of 10 agro-climatic indicators: (A) principal component analysis; (B) ascending hierarchical classification. Positive water balance values were capped at 50 mm to give more weight to water deficit patterns in the statistical classification.



factors (correlations of 0.77 and 0.67, respectively, on axis 2 in Figure 2A). The typology (type description and indicator values) is available for nearly all French Alps mountain pastures, allowing a rapid assessment of the exposure of a given pasture.

## Sensitivity

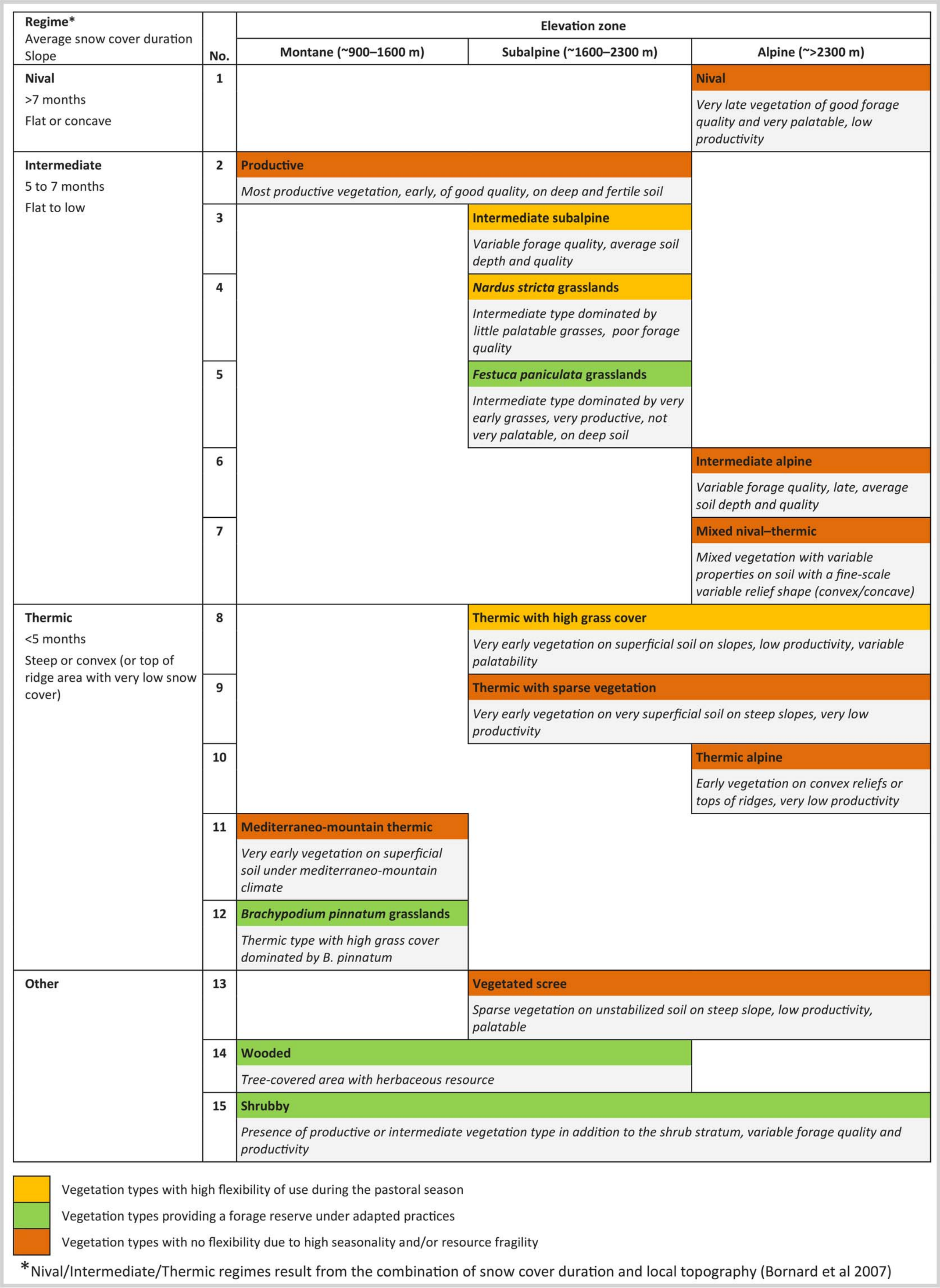
Our classification of mountain pasture vegetation contains 12 main vegetation types (Figure 3), which belong to 3 “regimes.” “Regimes” are a combination of physical factors (snow cover duration and geomorphology) that—together with elevation— determine soil conditions and vegetation characteristics. In addition, our classification contains 3 other vegetation types that are not related to a specific regime. These types often cover smaller areas but are important pasture vegetation, in particular because of their potential buffer role in case of forage shortage. They include vegetated screes and shrubby and wooded areas.

**TABLE 2** Climatic exposure typology for summer mountain pastures.

| Type | Definition |
|---|---|
| **1. Very well watered, early** | Pastures with the most water and least drought exposure. Spring advancement is earlier than average, but with very low exposure to frost events after snowmelt. Spring spread is relatively short with low interannual variability. |
| **2. Well watered, early** | Relatively well-watered pastures that can be exposed to drought in some years. Spring advancement is earlier than average, but with low exposure to frost events after snowmelt. Spring spread is short with low interannual variability. |
| **3. Well watered, late** | Relatively well-watered pastures that can be exposed to drought in some years. Spring advancement is late, which prevents exposure to frost events after snowmelt. Spring spread is long with high interannual variability. |
| **4. Dry, average** | Pastures that are exposed to drought. Spring advancement and spread are average, as is exposure to frost events after snowmelt. |
| **5. Dry, late** | Pastures that are very exposed to drought. Spring advancement is late, but exposure to frost events after snowmelt is higher than average. Spring spread is longest on this type, with great interannual variability. |
| **6. Very dry, early, frost** | Pastures with the greatest exposure to drought. Spring advancement is earliest, exposure to frost events after snowmelt is highest, and interannual variability of exposure to frost events is high. Spring spread is average. |

https://doi.org/10.1659/MRD-JOURNAL-D-18-00077.1

**FIGURE 3** Classification of mountain pasture vegetation.



<table>
<tr><th rowspan="2">Regime*<br>Average snow cover duration<br>Slope</th><th rowspan="2">No.</th><th colspan="3">Elevation zone</th></tr>
<tr><th>Montane (~900–1600 m)</th><th>Subalpine (~1600–2300 m)</th><th>Alpine (~>2300 m)</th></tr>
<tr><td><b>Nival</b><br>>7 months<br>Flat or concave</td><td>1</td><td colspan="2"></td><td>🟧 <b>Nival</b><br><i>Very late vegetation of good forage quality and very palatable, low productivity</i></td></tr>
<tr><td rowspan="6"><b>Intermediate</b><br>5 to 7 months<br>Flat to low</td><td>2</td><td colspan="2">🟧 <b>Productive</b><br><i>Most productive vegetation, early, of good quality, on deep and fertile soil</i></td><td></td></tr>
<tr><td>3</td><td></td><td>🟨 <b>Intermediate subalpine</b><br><i>Variable forage quality, average soil depth and quality</i></td><td></td></tr>
<tr><td>4</td><td></td><td>🟨 <b><i>Nardus stricta</i> grasslands</b><br><i>Intermediate type dominated by little palatable grasses, poor forage quality</i></td><td></td></tr>
<tr><td>5</td><td></td><td>🟩 <b><i>Festuca paniculata</i> grasslands</b><br><i>Intermediate type dominated by very early grasses, very productive, not very palatable, on deep soil</i></td><td></td></tr>
<tr><td>6</td><td colspan="2"></td><td>🟧 <b>Intermediate alpine</b><br><i>Variable forage quality, late, average soil depth and quality</i></td></tr>
<tr><td>7</td><td colspan="2"></td><td>🟧 <b>Mixed nival–thermic</b><br><i>Mixed vegetation with variable properties on soil with a fine-scale variable relief shape (convex/concave)</i></td></tr>
<tr><td rowspan="5"><b>Thermic</b><br><5 months<br>Steep or convex (or top of ridge area with very low snow cover)</td><td>8</td><td></td><td colspan="2">🟨 <b>Thermic with high grass cover</b><br><i>Very early vegetation on superficial soil on slopes, low productivity, variable palatability</i></td></tr>
<tr><td>9</td><td></td><td colspan="2">🟧 <b>Thermic with sparse vegetation</b><br><i>Very early vegetation on very superficial soil on steep slopes, very low productivity</i></td></tr>
<tr><td>10</td><td colspan="2"></td><td>🟧 <b>Thermic alpine</b><br><i>Early vegetation on convex reliefs or tops of ridges, very low productivity</i></td></tr>
<tr><td>11</td><td>🟧 <b>Mediterraneo-mountain thermic</b><br><i>Very early vegetation on superficial soil under mediterraneo-mountain climate</i></td><td colspan="2"></td></tr>
<tr><td>12</td><td>🟩 <b><i>Brachypodium pinnatum</i> grasslands</b><br><i>Thermic type with high grass cover dominated by B. pinnatum</i></td><td colspan="2"></td></tr>
<tr><td rowspan="3"><b>Other</b></td><td>13</td><td></td><td colspan="2">🟧 <b>Vegetated scree</b><br><i>Sparse vegetation on unstabilized soil on steep slope, low productivity, palatable</i></td></tr>
<tr><td>14</td><td colspan="2">🟩 <b>Wooded</b><br><i>Tree-covered area with herbaceous resource</i></td><td></td></tr>
<tr><td>15</td><td colspan="3">🟩 <b>Shrubby</b><br><i>Presence of productive or intermediate vegetation type in addition to the shrub stratum, variable forage quality and productivity</i></td></tr>
</table>

🟨 Vegetation types with high flexibility of use during the pastoral season

🟩 Vegetation types providing a forage reserve under adapted practices

🟧 Vegetation types with no flexibility due to high seasonality and/or resource fragility

*Nival/Intermediate/Thermic regimes result from the combination of snow cover duration and local topography (Bornard et al 2007)

We further categorized each vegetation type according to its agroecological properties (productivity, nutritional content, palatability, growing period, and resistance to water stress) and its current pastoral use. This classification describes the plant's (1) main function for the feeding of herds, (2) adjustment functions (flexibility) in case of forage shortage following climatic hazards, and (3) sensitivity to different climatic hazards and pastoral practices (Figure 4). This classification aims to serve as a basis for characterizing the sensitivity of a given mountain pasture through the analysis of the diversity and complementarity of the vegetation types it hosts (see Figure 5 for an application example). However, the vegetation's potential functions must be considered in a nuanced way according to each summer pasture's configuration and the constraints that affect the possibility of using the vegetation in an optimal manner.

### Adaptive capacity

During the study period (2009–2017), a diversity of climatic hazards occurred, some of which markedly affected forage availability (in duration and/or quantity), which allowed us to analyze the response of herders and farmers to climate variability. On this basis, we identified a set of short-term adjustments and long-term adaptation strategies that we summarized in a grid intended to serve as a basis for thinking about adaptive management of mountain pasture systems (Table 3).

First, we identified adaptive capacities based on short-term adjustments in the mountain pasture during the pasturing season, closely linked to biophysical assets and constraints (including the diversity of vegetation types present in the pasture, spatial configuration or physical constraints that reduce access, and predation risk) and to the herder's technical skills and experience. Second, we identified adaptive capacities that involve long-term structural adaptation in the mountain pasture, involving cooperation between stakeholders to set up new infrastructure or change management rules. Third, we identified both short- and long-term adaptations in the interaction between the mountain pasture and the farm(s) using it, with repercussions for the functioning of farms and involvement of a broader and more complex set of factors (eg economic context, farm work organization, and technical feasibility). These adaptations varied widely according to the agricultural sector, the type of livestock farming system (cattle/sheep, dairy/suckling, local/transhumant), the social network (eg collective organization of farmers), and the geographical context of the farm (see Figure 5 for an example).

## Discussion and conclusions

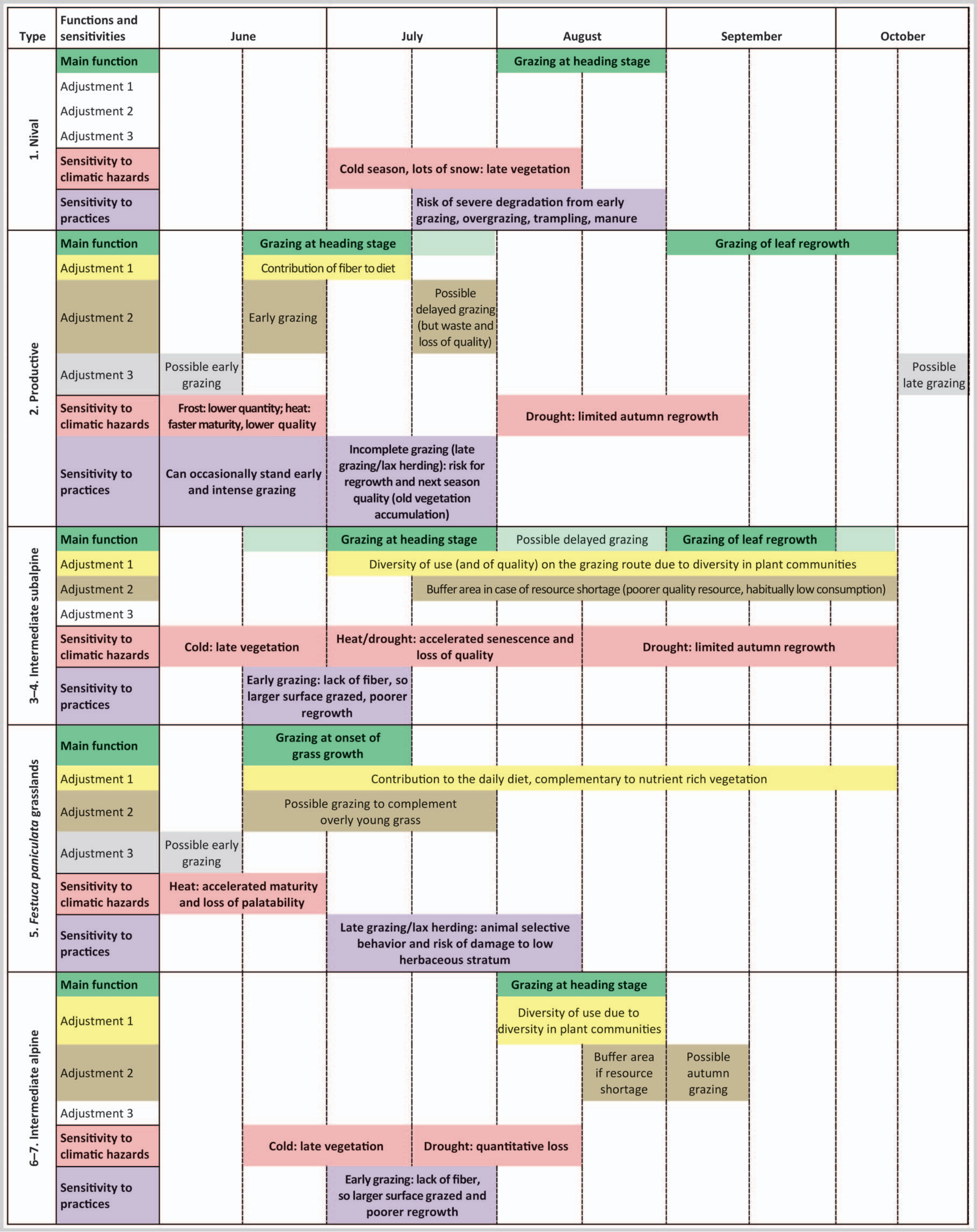
Climate change—in particular, the current and projected increased variability in temperature and water availability—is of major concern in providing forage for summering livestock as well as for the sustainable management of summer mountain pastures. While previous research on climate change in mountain pastures has long studied the physical, ecological, and human (management and social) dimensions separately (eg Jung et al 2014; Rigolot et al 2014), we addressed these dimensions together within a vulnerability analysis framework. On this basis we have developed a diagnostic tool that can be used directly by practitioners for climate change adaptation, and we hope that the new integrative information it will bring will provide useful input to policy discussions at the regional scale. The tool has 3 steps, each allowing the diagnosis of a separate component of the climate change–related vulnerability of summer mountain pastures.

The first step identifies exposure to the climatic hazards that are of primary concern in pasture management. To this end, we developed agro-climatic indicators specific to complex mountain environments (ie taking into account snowmelt dynamic and high spatial variability within management units), which is innovative compared to previous assessment of climate change exposure in grassland-based livestock systems (eg Ruget et al 2010; Sautier et al 2013; Lardy et al 2015). For practical implementation of this step, we developed a typology of exposure to climatic hazards. The information this typology contains for 2780 summer mountain pastures is available to partners of the Sentinel Mountain Pasture program on the website hosting the French Alps pastoral survey (http://enquete-pastorale.irstea.fr/). A limitation of this typology is that it does not take into account highly local phenomena—not uncommon in complex mountain environments—that may affect local vegetation dynamics.

The second step evaluates the sensitivity of summer mountain pastures to climatic hazards by evaluating the ability of their vegetation to meet feeding functions for herds (Bellon et al 1999) while coping with different climatic hazards and changes in pastoral practices. For practical implementation, we developed a new classification of mountain pasture vegetation. Among the existing classifications (eg Bornard et al 2007; Duru et al 2010; Carrère et al 2012), it is the only one to address the sensitivity of vegetation not only in terms of biomass loss—the element most frequently simulated in many current models (eg Calanca et al 2016)—but also in terms of how other properties (eg timing of use) are affected by climatic hazards. A limitation of this classification is its relative complexity of use, as it requires both botanical skills (to identify different vegetation types) and expertise in pasture management (to analyze the potential consequences of each climatic hazard for the successful conduct of herds throughout the growing season).

After exposure and sensitivity are assessed, the third and final step analyzes the system's adaptive capacities to identify the best options for reducing the potential impacts of climate change (Adger 2006; IPCC 2007). For this, we constructed a guide that highlights the different spatiotemporal levels at which realistic adaptations can be implemented in a given context. Beyond adaptive capacities inherent in mountain pastures, it is essential to consider the complex interactions that occur in related contexts, especially at the level of the farm or even the local farmers' organization (Nettier 2016; Nettier et al

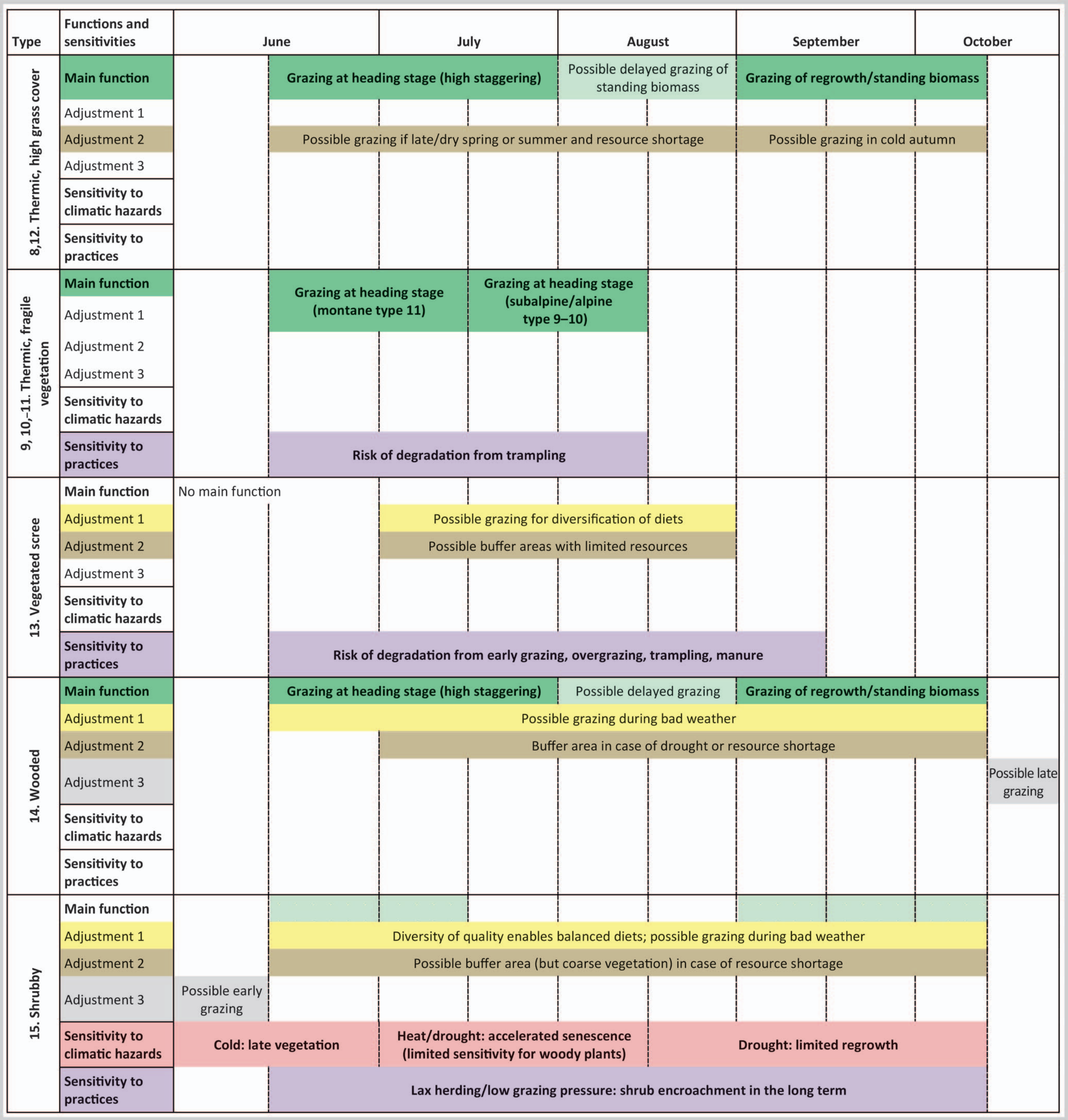
**FIGURE 4** Functions of mountain pasture vegetation types and their sensitivity to climatic hazards and to pasture management practices: (A) types 1–7; (B) types 8–15, see next page. The main function indicates the main periods of use for optimal pasture management (green) as well as case-specific periods of use (light green) in absence of climatic hazards. Adjustment function 1 (yellow) indicates adjustments at the scale of a single day for everyday hazards (such as bad weather or excessive heat); adjustment function 2 (light brown) indicates adjustments at the scale of a long feeding sequence (several weeks to a month); adjustment function 3 (gray) indicates adjustments in the interaction between farm and pasture. Sensitivity to climatic hazards (light red) and pasture management practices (purple) is also indicated. (Figure 4 continued on next page.)



<table>
<tr><th>Type</th><th>Functions and sensitivities</th><th colspan="2">June</th><th colspan="2">July</th><th colspan="2">August</th><th colspan="2">September</th><th colspan="2">October</th></tr>
<tr><td rowspan="6">1. Nival</td><td>Main function</td><td></td><td></td><td></td><td></td><td colspan="2">Grazing at heading stage</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to climatic hazards</td><td></td><td></td><td colspan="3">Cold season, lots of snow: late vegetation</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to practices</td><td></td><td></td><td></td><td colspan="3">Risk of severe degradation from early grazing, overgrazing, trampling, manure</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="6">2. Productive</td><td>Main function</td><td></td><td colspan="2">Grazing at heading stage</td><td>🟩</td><td></td><td></td><td colspan="3">Grazing of leaf regrowth</td><td></td></tr>
<tr><td>Adjustment 1</td><td></td><td colspan="2">Contribution of fiber to diet</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 2</td><td></td><td>Early grazing</td><td></td><td>Possible delayed grazing (but waste and loss of quality)</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 3</td><td>Possible early grazing</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Possible late grazing</td></tr>
<tr><td>Sensitivity to climatic hazards</td><td colspan="2">Frost: lower quantity; heat: faster maturity, lower quality</td><td></td><td></td><td colspan="3">Drought: limited autumn regrowth</td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to practices</td><td colspan="2">Can occasionally stand early and intense grazing</td><td colspan="2">Incomplete grazing (late grazing/lax herding): risk for regrowth and next season quality (old vegetation accumulation)</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="6">3–4. Intermediate subalpine</td><td>Main function</td><td></td><td>🟩</td><td colspan="2">Grazing at heading stage</td><td colspan="2">Possible delayed grazing</td><td colspan="2">Grazing of leaf regrowth</td><td>🟩</td><td></td></tr>
<tr><td>Adjustment 1</td><td></td><td></td><td colspan="7">Diversity of use (and of quality) on the grazing route due to diversity in plant communities</td><td></td></tr>
<tr><td>Adjustment 2</td><td></td><td></td><td></td><td colspan="6">Buffer area in case of resource shortage (poorer quality resource, habitually low consumption)</td><td></td></tr>
<tr><td>Adjustment 3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to climatic hazards</td><td colspan="2">Cold: late vegetation</td><td colspan="3">Heat/drought: accelerated senescence and loss of quality</td><td colspan="4">Drought: limited autumn regrowth</td><td></td></tr>
<tr><td>Sensitivity to practices</td><td></td><td colspan="2">Early grazing: lack of fiber, so larger surface grazed, poorer regrowth</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="6">5. <i>Festuca paniculata</i> grasslands</td><td>Main function</td><td></td><td colspan="2">Grazing at onset of grass growth</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 1</td><td></td><td colspan="8">Contribution to the daily diet, complementary to nutrient rich vegetation</td><td></td></tr>
<tr><td>Adjustment 2</td><td></td><td colspan="3">Possible grazing to complement overly young grass</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 3</td><td>Possible early grazing</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to climatic hazards</td><td colspan="2">Heat: accelerated maturity and loss of palatability</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to practices</td><td></td><td></td><td colspan="3">Late grazing/lax herding: animal selective behavior and risk of damage to low herbaceous stratum</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="6">6–7. Intermediate alpine</td><td>Main function</td><td></td><td></td><td></td><td></td><td colspan="2">Grazing at heading stage</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 1</td><td></td><td></td><td></td><td></td><td colspan="2">Diversity of use due to diversity in plant communities</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 2</td><td></td><td></td><td></td><td></td><td></td><td>Buffer area if resource shortage</td><td>Possible autumn grazing</td><td></td><td></td><td></td></tr>
<tr><td>Adjustment 3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to climatic hazards</td><td></td><td colspan="2">Cold: late vegetation</td><td colspan="2">Drought: quantitative loss</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sensitivity to practices</td><td></td><td></td><td colspan="2">Early grazing: lack of fiber, so larger surface grazed and poorer regrowth</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

2017). A limitation of this step is that it is difficult to differentiate, during analysis, between adaptive capacity and sensitivity (Engle 2011). Adaptive measures in a given mountain pasture rely first of all on the herder's technical skills and experience to adjust management (herder capacity), but are also heavily dependent on the specific vegetation types and functions in that pasture (vegetation sensitivity).

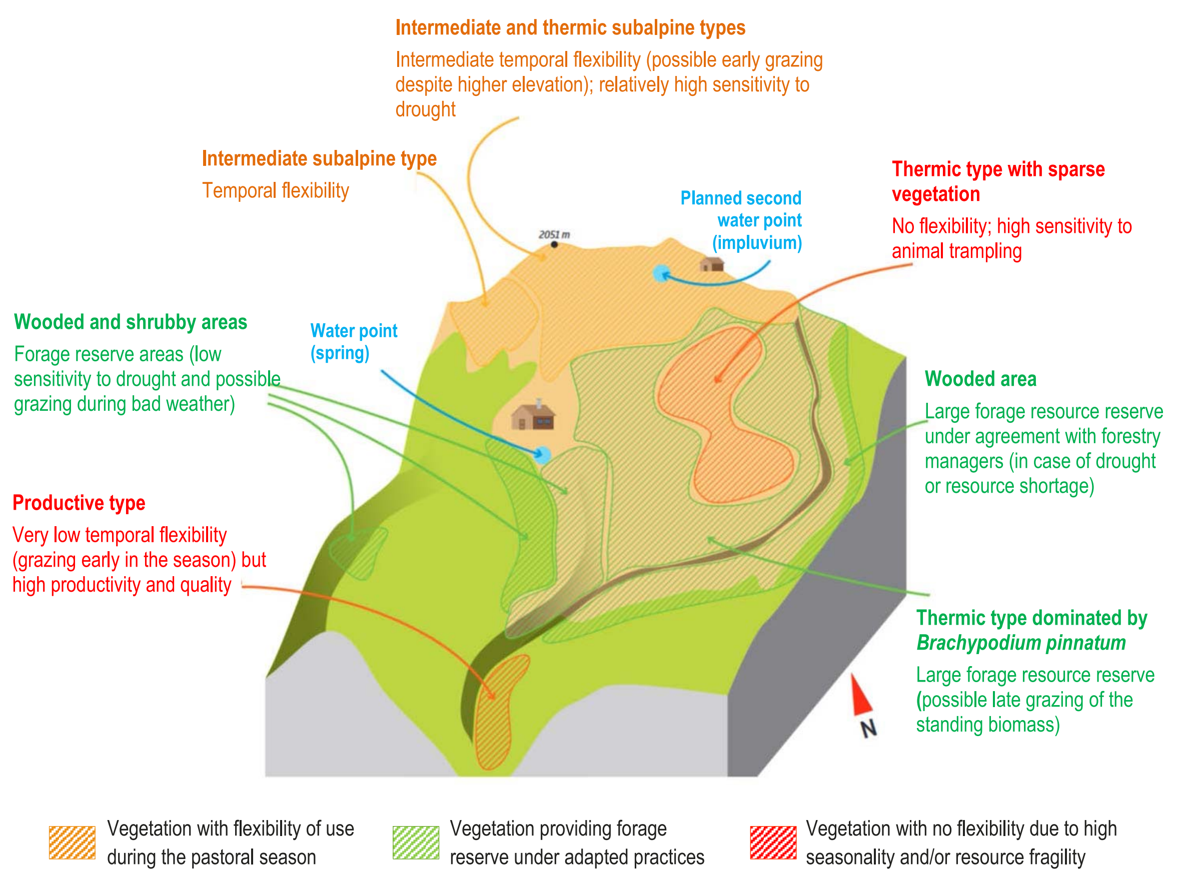
**FIGURE 4** Continued.



| Type | Functions and sensitivities | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 8,12. Thermic, high grass cover | **Main function** | **Grazing at heading stage (high staggering)** | | Possible delayed grazing of standing biomass | **Grazing of regrowth/standing biomass** | |
| | Adjustment 1 | | | | | |
| | Adjustment 2 | Possible grazing if late/dry spring or summer and resource shortage | | | Possible grazing in cold autumn | |
| | Adjustment 3 | | | | | |
| | **Sensitivity to climatic hazards** | | | | | |
| | **Sensitivity to practices** | | | | | |
| 9, 10,-11. Thermic, fragile vegetation | **Main function** | **Grazing at heading stage (montane type 11)** | **Grazing at heading stage (subalpine/alpine type 9–10)** | | | |
| | Adjustment 1 | | | | | |
| | Adjustment 2 | | | | | |
| | Adjustment 3 | | | | | |
| | **Sensitivity to climatic hazards** | | | | | |
| | **Sensitivity to practices** | **Risk of degradation from trampling** | | | | |
| 13. Vegetated scree | **Main function** | No main function | | | | |
| | Adjustment 1 | | Possible grazing for diversification of diets | | | |
| | Adjustment 2 | | Possible buffer areas with limited resources | | | |
| | Adjustment 3 | | | | | |
| | **Sensitivity to climatic hazards** | | | | | |
| | **Sensitivity to practices** | **Risk of degradation from early grazing, overgrazing, trampling, manure** | | | | |
| 14. Wooded | **Main function** | **Grazing at heading stage (high staggering)** | | Possible delayed grazing | **Grazing of regrowth/standing biomass** | |
| | Adjustment 1 | Possible grazing during bad weather | | | | |
| | Adjustment 2 | | Buffer area in case of drought or resource shortage | | | |
| | Adjustment 3 | | | | | Possible late grazing |
| | **Sensitivity to climatic hazards** | | | | | |
| | **Sensitivity to practices** | | | | | |
| 15. Shrubby | **Main function** | | | | | |
| | Adjustment 1 | Diversity of quality enables balanced diets; possible grazing during bad weather | | | | |
| | Adjustment 2 | Possible buffer area (but coarse vegetation) in case of resource shortage | | | | |
| | Adjustment 3 | Possible early grazing | | | | |
| | **Sensitivity to climatic hazards** | **Cold: late vegetation** | **Heat/drought: accelerated senescence (limited sensitivity for woody plants)** | **Drought: limited regrowth** | | |
| | **Sensitivity to practices** | **Lax herding/low grazing pressure: shrub encroachment in the long term** | | | | |

This diagnostic tool is intended to be used in a participatory fashion, under the supervision of experts in pastoralism in the presence of stakeholders (eg herders, farmers, landowners, and natural resources managers), by following a methodological guide recently published on the website of the Sentinel Mountain Pasture program (https://www.irstea.fr/fr/irstea/nos-centres/grenoble/sites-experimentaux-et-equipements-de-laboratoire/alpages-sentinelles). The objective is to create synergies between experts' insights on exposure and sensitivity, herders' observations on vegetation and climate patterns, farmers' observations on (for instance) work organization and economic constraints, and landowners' and natural resources managers' observations on other constraints.

**FIGURE 5** Application of the vulnerability diagnostic tool to a summer mountain pasture in the Sentinel Mountain Pastures network.



| Exposure | Sensitivity | Adaptive capacity |
|---|---|---|
| Summer mountain pasture of low elevation (but high elevational gradient: 900–2000 m), with steep slopes mainly facing west, located in the calcareous Prealps range, under climate with Mediterranean influence, classified as climatic exposure type 4. | The productive type can provide a good forage resource at the beginning of the summer pasturing season (thanks to early and rapid development of its grass species) but is sensitive to drought and to rapid temperature accumulation in spring (rapid drop in digestibility and palatability). In this case, the thermic types at the top of the pasture can also be used for early grazing. The forage reserve areas (wooded and shrubby types) as well as the *B. pinnatum* type can secure forage supply in the event of drought and limit the pressure on sensitive vegetation types. The diversity of types and the elevational gradient allow a relatively high spreading of vegetation maturity times, which can secure a supply of forage throughout the pasturing season. | • High short-term adjustment potential due to the nature and diversity of vegetation types strengthened by a steep elevational gradient<br>• Possibility of structural modifications, including setting up a new drinking water point to make better use of the highest parts of the pasture, and adding access to large wooded areas under administrative agreement with forestry managers<br>• Adjustment possibilities in the interaction with associated farms:<br>– Local sheep farmers with flexible arrival dates<br>– Suckling systems with ability of animals to cope with variable feed-intake periods<br>– Diversified grazing options on farmland and outside on the plain<br>– Differentiation in assets and constraints between local and transhumant farms |

The participatory process will make it possible to take into account complex natural and human interactions at the scale of the whole summer mountain pasture system and therefore provide a deeper integrative understanding of all actors, which is key to the practical reality of the climate adaptation process (van Kerkhoff and Lebel 2006; Tscharkert and Dietrich 2010; Duru et al 2012; Farrié et al 2015). Also, such a process has the potential to modify

TABLE 3 Mountain pasture systems' adjustments and adaptations to climate-induced resource shortages.

| On the summer mountain pasture | | Interaction between pasture and farms |
|---|---|---|
| **Short-term adjustment** | **Long-term adaptation** | **Short- to long-term adjustment/adaptation** |
| Changes to herd management and pasturing practices<br>**Actors:**<br>Herders' technical skills and knowledge of the pasture (within the limits of vegetation sensitivity and animal copping capacity) | Structural modification of the pasture to increase the resources available for herds<br>**Actors:**<br>Dialogue between farmers and landowners (eg with municipality, forestry agency, or managers of protected areas) | Adjustment of farming practices to reduce pressure on the pasture<br>**Actors:**<br>Farmers and farmers' collective organizations |
| **Examples:**<br>• Change the grazing route thanks to the diversity and complementary functions of vegetation types present in the pasture<br>• Increase the level of removal/consumption of vegetation types that can tolerate it<br>• Explore sections of the pasture that are rarely used because they are remote or difficult to access<br>• Reduce zootechnical objectives when tolerated by the animal species or breed and by the production system (suckling/dairy) | **Examples:**<br>• Add new surfaces to the pasture unit, such as wooded areas often present at low altitudes<br>• Invest in new equipment to enable the use of remote areas (eg herder's hut, access route, fences, or water access) | **Examples:**<br>• Advance/delay arrival/departure dates<br>• Reduce the number of pasturing animals<br>• Reduce the pasturing of animals with high needs (dairy animals, growing animals) |

TABLE 3 Extended.

| On the farms | |
|---|---|
| **Short-term implications** | **Long-term implications** |
| Adjustment of farming practices to compensate for the shortage of resources on the pasture<br>**Actors:**<br>Farmers | Adaptation of farming systems to compensate for long-term decrease (or increased variability) in pasture resources<br>**Actors:**<br>Farmers |
| **Examples:**<br>• Buy forage<br>• Change grazing management on the farm thanks to the diversity of resources and the use of standing biomass<br>• Use a supplementary summering area<br>• Make arrangements with other farmers or landowners (eg pasture outside the farm land) | **Examples:**<br>• Buy supplementary land<br>• Intensify cultivated forage areas (eg add irrigation, fertilization, increase the number of cuts)<br>• Change the forage system<br>• Change the breeding system (eg dates of parturition)<br>• Change the production system and work organization (compensate for decrease in animal numbers by value-added production, direct selling) |

practitioners' perceptions of climate uncertainties and risks, which is essential to adaptation action (Abid et al 2016). Lastly, the process of constructing the diagnostic tool itself, by acknowledging the values and specificities of the different knowledge systems (ie scientific, expert, local; Tengö et al 2014), is in itself meaningful to the actors involved, offering high potential for local acceptance and use of the tool (Darnhofer et al 2017).

We therefore believe that the future application of the tool, in particular an upcoming test on mountain pastures beyond the Sentinel Mountain Pasture network (to verify the effectiveness of the approach), will support anticipatory adaptations (eg set up new equipment) and provide concrete elements (eg the degree of exposure to climatic hazards in a given pasture) to orient supportive programs carried out by institutions such as national parks. This is a first step toward influencing programs and policies at larger scales (IPCC 2014; Aleksandrova et al 2016; González Tánago et al 2016; Muccione et al 2016).

Although this tool was based on an earlier vulnerability assessment framework produced by the IPCC (2001, 2007), it is nevertheless in line with the new risk assessment framework highlighted in the IPCC's fifth assessment report, in which risk represents the probability of occurrence of climatic hazards or changes multiplied by the magnitude of the consequences if they occur (IPCC 2014). The tool makes it possible to evaluate both the probability of occurrence of hazards (through the typology of pasture exposure to climatic hazards) and the severity of consequences if these hazards occur (through the analysis of sensitivity and adaptive capacities).

In addition, the elaboration of the method offers opportunities to generate new scientific knowledge with diverse promising applications to further support climate adaptation. For instance, it is envisaged to use regional climate scenarios for the future (Verfaille et al 2017) to predict the evolution of exposure to climatic hazards in mountain pastures—which could in turn inform simulations of mountain vegetation and biodiversity dynamics (eg Gavazov et al 2013). By integrating these simulations, the development of participatory scenarios with stakeholders to study diverse adaptation options (eg Lamarque et al 2013) could provide crucial knowledge on factors contributing to climate change–related vulnerability in the future. Such studies—by assessing impacts, damages, and potential shifts in systems—may also complement resilience research (Lindoso 2017).

The tool, which is based on an operational assessment of vulnerability, considers the system as stable in all factors except the climate. We believe it is fully adapted for local action to adapt to changes and uncertainties that currently affect summer mountain pastures, but can also benefit from a more theoretical socio-ecological resilience approach (Miller et al 2010; Lindoso 2017) that takes into account the dynamic aspect of systems, notably the coevolutions of climate, vegetation, and livestock systems (Nettier et al 2017).

Two other points merit further analysis for improvement of the tool: the impact of climate change on water resources for herds, which is becoming critical for pasture management in many mountain pastures of low or middle elevation (Piazza-Morel et al 2018), and the constraints imposed by the wolf predation risk (eg resource areas that are unusable if not protected against predation; CERPAM et al 2012; Garde 2015).

To conclude, we believe that the practical implementation of this tool across the French Alps will foster local adaptation efforts, by enhancing dialogue and synergies between a broad range of stakeholders and allowing a shared, integrative understanding of the complexity of mountain pasture systems. It also has the potential to bring to the fore the needs of the agro-pastoral sector to adapt to climate change, which is essential to designing relevant agricultural and development policies for uplands areas in a context of climate change. Although it was designed for mountain grazing systems, our approach offers a methodology and perspective that can be applied in other regions of the world concerned with the management of natural resources within complex social–ecological systems.

## ACKNOWLEDGMENTS

We thank all of the experts from CERPAM (Centre d'Etudes et de Réalisations Pastorales Alpes-Méditerranée), FAI (Fédération des Alpages de l'Isère), ADEM (Association Départementale d'Economie Montagnarde), Ecrins National Park, Vanoise National Park, LESSEM (Laboratoire des EcoSystèmes et Sociétés En Montagne), and LECA (Laboratoire d'Ecologie Alpine) who participated in participatory modeling during the PhD work of Baptiste Nettier. We thank Samuel Morin (Météo-France–CNRS [Centre National de la Recherche Scientifique]–CEN [Centre d'Etude de la Neige]) for providing the SAFRAN–Crocus climate data used in this study, and Frédéric Bray (Irstea Grenoble) for use of the French Alps mountain pasture survey database. This work has been supported by the LABEX ITEM (ANR-10-LABX-50-01), within the program Investissements d'Avenir, operated jointly by the French National Research Agency and the French Agency for Biodiversity. It was conducted in the Zone Atelier Alpes, a member of the ILTER (International Long Term Ecological Research) Europe network. Through its link to the Sentinel Mountain Pasture program, this work was also supported by the funders of this program: the French General Commission for Territorial Equity, the French Ministry of Ecology/Water and Biodiversity, the European Union (FEDER-POIA massif alpin), and the Auvergne-Rhône-Alpes and Provence-Alpes-Côte d'Azur regions.

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