RESEARCH ARTICLE

Agro-climatic profiles of summer mountain pastures in the French Alps: towards a monitoring tool to contribute to climate risk assessment

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Abstract

Summer mountain pastures (also called *alpages*) are a central element for many agro-pastoral livestock systems in the alpine region, by providing the feedstock for herds during the summer transhumance. However, vegetation phenology and productivity in mountain pastures are increasingly affected by climate hazards exacerbated by climate change, such as early snow removal, late frost events, or droughts. Difficulties can then arise to match animal demand with forage resource on *alpages* and, in the long term, threaten the sustainable management of these highly multifunctional socio-ecological systems. To help agro-pastoral actors adapt, an essential step is to quantify the risk of impacts on the forage resource, due to an increased occurrence or intensity of climate hazards.

Exposure to climate hazards on *alpages* is defined locally by topographic aspects in combination with the broader influence of the regional climate. Our work therefore aimed at providing a tailored assessment of potential climate risk for the forage resource at the individual scale of each *alpage* in the French Alps. To this end, we developed agro-climatic indicators based on atmospheric and snow cover data accounting for geographic and topographic conditions, and applied them to a database providing unique spatially explicit information at the *alpage* level.

For the first time, we introduce a description of agro-climatic conditions and provide a classification of agro-climatic profiles of *alpages* in the French Alps, ranging from low to high potential risk for the forage resource, mainly following a North-South gradient combined with altitude. We also bring insights on the evolutions of the climate risk with climate change and discuss management implications for agro-pastoral livestock systems using *alpages*. We finally present a web-based visualization tool that aim at communicating agro-climatic profiles and their evolution to practitioners and at assisting decision makers in understanding climate-related risks on the *alpages* of the French Alps.

Keywords Climate change · Climate hazard · Alpine pasture · Pastoralism · Livestock farming · Forage resource · Adaptation

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1 Introduction

Pastoralism is widespread in mountain regions around the globe and has a long tradition in the Alps (Dodgshon 2019). In France, summer mountain pastures, hereafter referred to as "*alpage*" (i.e., the French word, which has already been used in the international literature, McGraw-Hill 2003; Dodgshon 2019), cover one-third of the total area of French Alps, and represent a significant part of farmlands and forage resources for agro-pastoral livestock systems (Dobremez et al. 2016). *Alpages* are semi-natural pastures located along the montane and the low productive subalpine and alpine belts, exclusively managed through grazing during the

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summer months (Dorioz 1998; Dobremez et al. 2016; Herzog and Seidl 2018). They are essential for the functioning of agro-pastoral farms located in valleys and neighboring regions, by providing the feedstock for domestic herds during summer, due to a seasonal offset in the grass growth at high altitudes. They guarantee, at least in part, the livelihood of smallholder farmers, breeders, and herders through the commercialization of dairy and meat products (Dobremez et al. 2016; Mazzocchi and Sali 2019). In turn, the traditional exploitation of *alpages* provides positive externalities that benefit the local population and tourism activities, through the preservation of ecosystem services, biodiversity, and cultural landscapes (Dorioz 1998; Herzog and Seidl 2018; Mazzocchi and Sali 2019). Overall, due to a long history of co-evolution with pastoral activities, *alpages* host an extremely rich biodiversity (Bornard et al. 2007).

European mountain regions are among the most exposed to the ongoing and projected climate changes (Gobiet et al. 2014), with severe associated risks of impacts on different socio-economic sectors, including pastoralism (Beniston 2012; Hock et al. 2019). Mountain regions have already been subjected to a strong increase in temperature in the last decades, with, for example in the French Alps, an average increase of 2.25°C recorded in yearly temperatures over the period 1900–2020 (AGATE 2020). This trend is predicted to strengthen, with temperatures projected to continue increasing at an average rate of 0.3°C per decade (Hock et al. 2019). Projections for precipitations are more uncertain, but changes in seasonal precipitation patterns and increase in frequency or intensity of droughts are observed (Calanca 2007; Haslinger and Blöschl 2017; Hock et al. 2019). In mountain pastures of the Alps, the constantly earlier snow removal, the abnormally warm springs, and the dry periods induced by climate change are of major concern for pastoral activities. Indeed, these factors not only impact the snow melt-out date and plant phenology (Jonas et al. 2008; Arnold et al. 2014; Klein et al. 2016; Vuffray et al. 2016), but also, expose vegetation to late frost events (Inouye 2008; Wheeler et al. 2014) and alter biomass productivity (Calanca et al. 2016; Corona-Lozada et al. 2019; Grigulis and Lavorel 2020).

Grazing management on an *alpage* aims to match animal demand with forage availability throughout the summer transhumance season and is based on the functional and temporal complementarity of resources within the *alpage*. This management is thus site-specific due to the variety of sizes, configurations and elevations, to the multiple uses and to the particular governance rules of these individual or collective areas (CERPAM and PNE 2006) (Fig. 1). Although *alpages* are being used in interaction with farms, their management is often delegated to a herder, who has a certain degree of autonomy. This is because of their remote location, which does not make it possible to bring livestock back to the farm every day. Farmers and herders have long been used to coping with a certain degree of climate uncertainty and forage resource variability on *alpages* (e.g., herders' know-how and knowledge of the *alpage*, Nettier et al. 2017). However, when climate conditions and shortage of forage threaten the viability of herd management, farmers, and herders are forced to implement short-term and reactive actions (Nettier et al. 2011). For example, in the early 2000s, when farmers and herders faced a series of severe droughts, reactive actions included advanced herds' descent dates, changes in stocking rates, changes in grazing calendars and overgrazing of certain areas (Nettier et al. 2011; Dobremez et al. 2014). Such reactive management may threaten the stock of forage in the long term and cause joint impacts on other resources and on biodiversity (Dobremez et al. 2014; Joyce and Marshall 2017). Thus, identifying long term and anticipatory strategies, accounting for the increased occurrence or intensity of climate hazards, appears critical for the sustainable management of these highly multifunctional socio-ecological systems (e.g., putting in place infrastructures to more easily use hardly accessible areas, using additional summering areas, etc., Nettier et al. 2017; Deléglise et al. 2019).

In order to support adaptation efforts of agro-pastoral actors who use *alpages*, an essential step is to provide information on the potential impacts of climate change on these unique pastoral systems. As defined by the IPCC fifth assessment report, the climate-related risks are the potentially negative consequences for humans and social-ecological systems that emerge from complex interactions between the occurrence of climate hazards, the exposure (presence and characteristics of elements in the systems), and the vulnerability of the system (propensity of the elements in the systems to be negatively affected) (IPCC 2014). Risk-based assessments have already been proven useful for climate change adaptation in rangeland-based livestock systems in different parts of the world (Joyce and Marshall 2017). However, they are lacking for the pastoralism sector in Europe (Hock et al. 2019). In order to better manage the risk of climate impacts on the uses of *alpages*, it is first of all necessary to characterize: (i) the occurrence and intensity of climatic factors that impact vegetation development and subsequent forage resource availability on *alpages*, and (ii) the evolution of these climatic factors compared to historical conditions. In a previous work combining scientific knowledge with the expertise of *alpages*' practitioners (Nettier 2016; Chaix et al. 2017), three climatic factors have been identified as most impactful on the forage quantity and quality on *alpages*: (i) temperatures at the start of the growing season following snow removal,

Fig. 1 In the alpine region, domestic herds ascend to *alpages* in late spring and stay there for several months. A dairy cattle herd in the northern French Alps (left) and a sheep herd in the central French Prealps (right). Photographs courtesy of Grégory Loucougaray.

which affect the rate of plant development, (ii) frost events after snow removal, and (iii) availability of water for plant growth (i.e., the balance between the level of precipitation and that of evapotranspiration). We propose to use these three climatic factors to characterize agro-climatic conditions and their evolution, and thus the potential climate risks on the *alpages*. Because it is essential to provide information at the level of the management unit, i.e., the level at which decisions are taken by practitioners, to contribute directly to the implementation of adaptation actions in the field (Joyce and Marshall 2017), we explicitly focus our approach on the *alpage* level. The agro-climatic approach we present here represents the first step to a holistic assessment of the effective risk due to climate change on the *alpages*, which additionally needs to account for the degree of ecosystems and human responsiveness (Deléglise et al. 2019).

In this study, we introduce a specific set of agro-climatic indicators designed to be meaningful regarding the impact of the three climatic factors listed above (i.e., water availability, temperature accumulation, and frost events after snow melt-out) on the forage resource and pastoral management in the *alpages*. Their computation at the *alpage*-level accounts for the influence of both the regional climate and local topographic conditions, by using atmospheric and snow data covering the entire French Alps with respect to elevation, slope, and orientation, in combination with a database providing unique geographical and topographic information for a total of 2779 *alpages* referenced in the French Alps. Our main objectives were to:

1. Provide agro-climatic indicators able to shape agro-climatic profiles of *alpages*;
2. Analyze the spatial distribution of agro-climatic conditions on *alpages* at the French Alps scale, and their evolution over the last 60 years;
3. Offer a web-based visualization tool of agro-climatic profiles of *alpages* and their evolution, which will facilitate the communication with practitioners.

2 Materials and methods

2.1 General methodology

The methodology for the construction of agro-climatic indicators built up on a previous work (Nettier 2016) carried out within the "*Alpages Sentinelles*" research and development program which addresses climate change adaptation issues on summer mountain pastures across the French Alps (Dobremez et al. 2014, https://www.alpages-sentinelles.fr/). First, a participative approach was implemented with the collaboration of researchers from various disciplines (agronomy, ecology, climatology), agricultural and pastoral extension officers, and protected areas managers, to determine the major climatic constraints for the use of *alpages* (Nettier 2016; Chaix et al. 2017). This led to the choice and definition of meaningful indicators, adapted to stakeholders' representations of the phenomena and consistent with the current scientific literature. Second, a pilot test study was carried out by computing the indicators for the 25 pastures of the "*Alpages Sentinelles*" network, in order to elaborate a preliminary analysis of agro-climatic profiles of *alpages* and to validate the method (Nettier 2016). The study we present here is the consolidation and expansion of this preliminary work to the entire French Alps, using adapted data sources and indicators to meet the need for a wider spatial and temporal coverage.
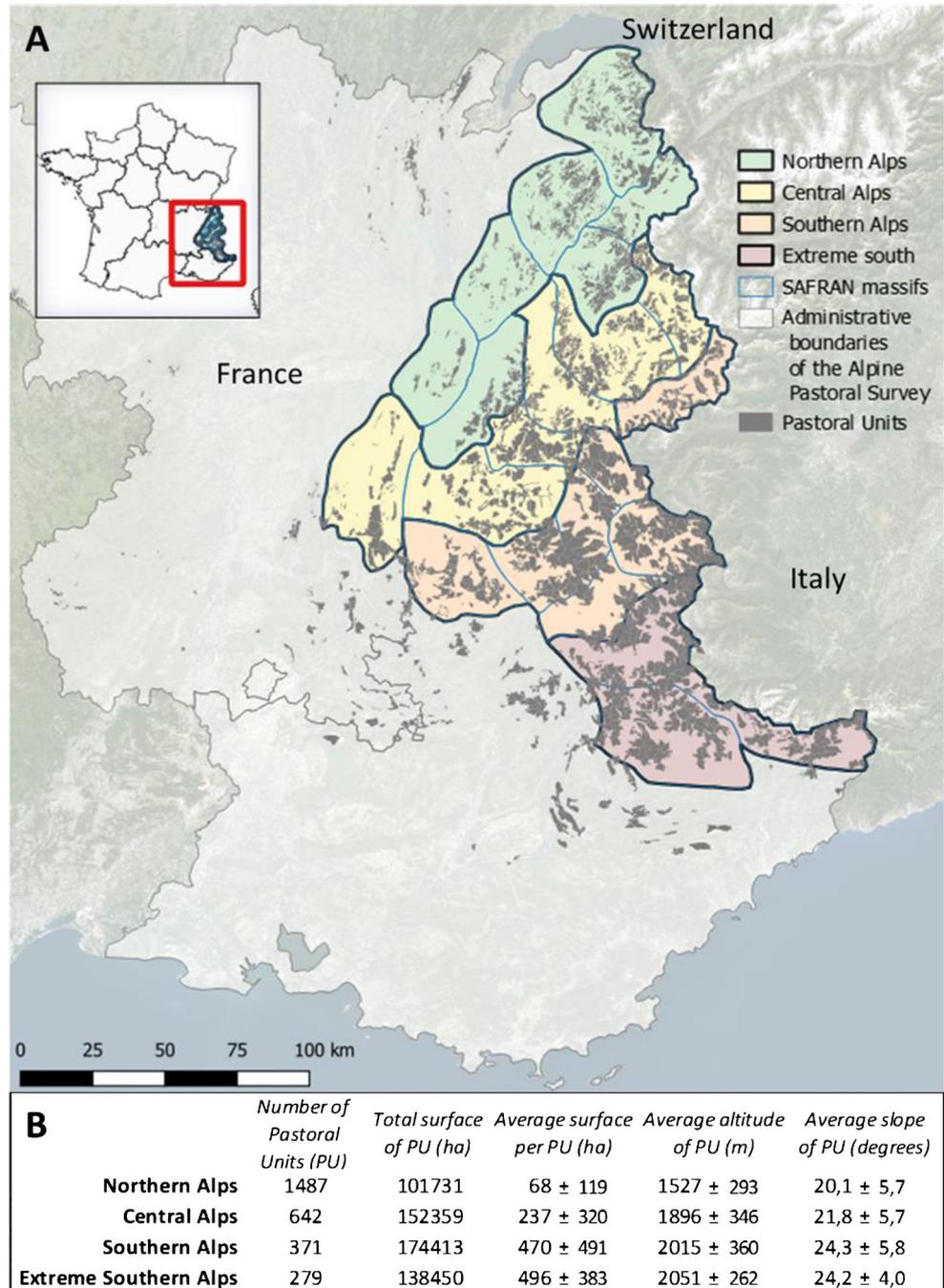
2.2 Study area and objects

The study area is the French Alps massif, extending between Lake Geneva in the north and the Mediterranean Sea in the south. The 2779 *alpages* considered in this study are pastoral units that follow the definition of the French alpine pastoral inventory (Dobremez et al. 2016): they are semi-natural pastures, generally located within the montane and subalpine altitudinal belts, exclusively used by extensive grazing and have a dedicated summering function, i.e., they are grazed from about June to

October. They correspond to the georeferenced pastoral units in the French alpine pastoral survey whose spatial location is covered by the meteorological data we used (Fig. 2); they represent 88% of the 3145 georeferenced pastoral units in total. Following the bioclimatic zonation of the French Alps (mainly latitudinal and longitudinal gradients, Durand et al. 2009a), we considered four main subareas in our analysis: Northern Alps, Central Alps, Southern Alps, and Extreme Southern Alps (Fig. 2).

2.3 Meteorological data

We used *S2M* meteorological and snow cover reanalysis (Vernay et al. 2020) which combines two models, namely SAFRAN atmospheric reanalysis (Durand et al. 2009a, 2009b) and *Crocus* snow cover model. SAFRAN provides daily data of weather conditions, from 1959 to 2018, over 23 sub-massifs of the French Alps (called SAFRAN massifs) (Fig. 2), defined by their climatological homogeneity (Durand

Fig. 2 A Study area, with the distribution of the 2779 pastoral units (*alpages*) within the 23 SAFRAN massifs, here grouped into 4 main subareas : Northern Alps (including massifs *Chablais*, *Aravis*, *Mont-Blanc*, *Beaufortain*, *Bauges*, *Chartreuse*, *Belledonne*), Central Alps (including massifs *Haute-Tarentaise*, *Vanoise*, *Maurienne*, *Grandes Rousses*, *Oisans*, *Vercors*), Southern Alps (including massifs *Haute-Maurienne*, *Thabor*, *Pelvoux*, *Champsaur*, *Devoluy*, *Queyras*, *Embrunnais-Parpaillon*) and Extreme Southern Alps (including massifs *Ubaye*, *Haut-Var – Haut-Verdon*, *Mercantour*). The shaded relief background indicates the administrative extent of the alpine pastoral inventory (including in total 3145 pastoral units) part of which is not covered by the SAFRAN massifs. **B** Average physical features of pastoral units per main geographic area.

B	Number of Pastoral Units (PU)	Total surface of PU (ha)	Average surface per PU (ha)	Average altitude of PU (m)	Average slope of PU (degrees)
Northern Alps	1487	101731	68 ± 119	1527 ± 293	20,1 ± 5,7
Central Alps	642	152359	237 ± 320	1896 ± 346	21,8 ± 5,7
Southern Alps	371	174413	470 ± 491	2015 ± 360	24,3 ± 5,8
Extreme Southern Alps	279	138450	496 ± 383	2051 ± 262	24,2 ± 4,0

et al. 2009a). This daily data is refined according to topographic criteria: altitude, slope, and orientation. Atmospheric data include minimum and maximum air temperatures, precipitations, wind speed, relative humidity, and incident longwave and shortwave radiations. Besides, atmospheric data is used as input to the *Crocus* snow cover model, which simulates snow cover dynamics and the timing of snow melt-out, a crucial issue for vegetation dynamics in mountain pastures. The estimation of the snow melt-out date in the S2M reanalysis has recently been satisfactorily evaluated against in situ snow depth observations (Vernay et al. 2022). Finally, all the variables we used are categorized within 23 massifs, 300 m altitudinal bands, 5 slopes categories, and 8 orientation categories. In practice, this means that two locations sharing the same categorical combination, i.e., at the same altitude, with same slope and orientation, within the same SAFRAN massif, are assumed to encounter the same meteorological and snow cover conditions.

2.4 Computation of preliminary metrics

For each unique combination of these categorical variables (i.e., in one SAFRAN massif, at a given altitude, for a given slope category, at a given orientation), we computed the following preliminary metrics:

-The snow melt-out date was estimated as the last day of the longest continuous period with at least 5 cm of modeled snow on the ground between August 2nd of year n-1 and August 1st of year n. This date was then used as a proxy for the onset of the vegetation growing season. In case of absence of snow, which concerned only a few *alpages* and only some years, this proxy was estimated as the day at which the daily mean temperature was higher than 5°C for at least 6 consecutive days, from January 1st of year n.

-The cumulated growing degree-days (GDD) was computed as the sum of daily mean temperature above the base temperature (0°C) from the snow melt-out date. It is a measure of heat accumulation for plant growth that is largely used to predict the phenological development of grassland species (e.g., Grigulis and Lavorel 2020).

-The date of reaching 600 growing degree-days was chosen as a proxy for the reaching of the heading stage of forage grasses in mountain pastures (i.e., the end of the elongation stage in Moore et al. 1991). This heading-flowering stage is the phenological stage targeted by herders for the start of grazing in an *alpage* (Nettier 2016). For grass species of plant functional type C (i.e., species that dominantly constitute the forage resource in mountain pastures, Bornard et al. 2007), this stage is reached between 600 and 900 degree-days in mid-mountain ranges (Launay et al. 2011), but can be assumed to be reached around 600 degree-days in higher altitude pastures due to a slightly faster development (Rossignol et al. 2014; Vuffray et al. 2016).

-The number of days with daily minimum temperature below 0°C after snow melt-out and until the date of reaching 600 growing degree-days was computed to depict the risk of frost damage to plants during the vegetative stage of the first growth cycle (choosing the threshold of 300 growing degree-days after snow melt-out did not change the results).

-Atmospheric water balance was computed as cumulated precipitations minus cumulated reference evapotranspiration (ET_0) over three different periods to estimate the water limitation potentially encountered by plants in (i) the first vegetation growth period (snow-melt out to 600 degree-days), (ii) the summer growth period (August), and (iii) the fall regrowth period (September). ET_0 was computed according to the Penman-Monteith equation, which is considered as standard and recommended by the FAO (Calanca et al. 2011). The atmospheric water balance is a simple relation that has proven to be a very good proxy for the productivity in standard and irrigated grasslands (i.e., only limited by too cold or too hot temperature) (Calanca et al. 2011). In mountain pastures, this indicator depicts the potential for a limitation of plant growth due to water deficit, whereas the effective limitation of plant growth depends on properties of vegetation and soils.

2.5 The French alpine pastoral inventory data base

The pastoral inventory data base provides geographical, agronomic, and socio-economic information at the *alpage* level (i.e., pastoral unit) for a total of 3145 *alpages*, which together cover 680,000 ha in the French Alps (Dobremez et al. 2016; https://enquete-pastorale.inrae.fr/) (Fig. 2). For the computation of agro-climatic indicators, we used rasters of pastoral units combined with digital elevation models with a 25 × 25 m resolution available from the French National Institute of Geographic and Forest Information (IGN): (https://geoservices.ign.fr/documentation/diffusion/telechargement-donnees-libres.html#bd-alti-25-m). Besides, to generate explicative cofactors used in the multivariate analysis (see section 2.7), we calculated average physical variables at the pastoral unit level: average latitude and longitude, surface of pastoral unit, average altitude, elevation gradient, maximum, minimum and average slope, and surface proportion of North, South, East, and West orientations.

2.6 Computation of agro-climatic indicators

The preliminary metrics computed by categorical combination (see section 2.4) were spatially interpolated to each pixel of the pastoral unit rasters, according to the geographical location (i.e., the SAFRAN massif) and the

topographic characteristics (i.e., altitude, slope, orientation) of pixels. A rule was applied to match the "categories": (i.e., provided by the SAFRAN-Crocus output) with pixels provided by the digital elevation model at a 25 × 25 m resolution: each "category" was considered as the center of a value range from minus to plus half the step between two categories (i.e., +/−150 m for the altitude values, +/−5° for the slopes, and +/−22.5° for orientation). Thus, the corresponding preliminary metric value could be assigned to each pixel within the pastoral units. Then, these values were aggregated at the pastoral unit level following specific rules (see Table 1) to obtain 6 agro-climatic indicators for each of the 2779 pastoral units, every year (Table 1). Four indicators represent average conditions at the *alpage*-level (i.e., Frost-600; WB-600, WB-July and WB-September), one indicator indicates temperature conditions after snow melt-out on the low or "early" part of the *alpage* (i.e., GDD-600), and one indicator represents the intra-*alpage* heterogeneity of temperature conditions (i.e., Spread-600) (see Table 1). Indeed, based on a previous work with stakeholders (see section 2.1), it was pointed out that it was relevant to take into account the intra-*alpage* spatial heterogeneity of agro-climatic conditions for informing management. This relies on the assumption that *alpages* presenting inner spatial heterogeneity in snow removal and temperature accumulation allow for more flexibility in management in the face of climatic hazards, than physically homogeneous *alpages*. However, for precipitation-based indicators, we did not consider the intra-*alpage* spatial heterogeneity because of (i) the risk of over-interpreting the underlying climatic model for phenomena not or poorly integrated (e.g., localized rain showers) and (ii) the lack of relevance for management (e.g., possible intra-*alpage* spatial heterogeneity of water balance indicators favoring grass regrowth at high altitudes will be challenged by the risk of early snow and therefore might not be exploitable for grazing).

Data was processed using PgAdmin 4.28 (PostgreSQL 9.6.6 and Postgis 2.3.3); indicators were computed using Python version 2.7 and R version 3.6.1 (R Core Team 2019).

2.7 Statistical analysis

To characterize past and recent agro-climatic conditions on *alpages*, average values (30-year average) and interannual variability (30-year standard deviation) of indicators were computed per pastoral unit over the 1961–1990 reference past period and the 1991–2018 recent period.

To identify prominent agro-climatic profiles for the recent period, we performed a principal component analysis (PCA) with pastoral units as objects and indicators (average values and interannual variability for the recent

Table 1 Definition and computation rules of agro-climatic indicators at the *alpage*-level.

Agro-climatic indicator	Unit	Definition
GDD-600: start of the pastoral season	Day of the year	Date of reaching 600 degree-days after snow melt-out on at least 25% of pixels of the *alpage*, theoretically indicating the presence of enough forage resource (surface of pasture and phenological stage of vegetation) to allow the start of grazing.
Spread-600: temporal spread of the first vegetation growth cycle	Number of days	Number of days between the time the first pixel of the *alpage* reaches 600 degree-days after snow melt-out and the time the last pixel reaches 600 degree-days after snow melt-out (excluding the 10% of the pixels for which snow melt-out is the earliest and the 10% for which it is the latest). This roughly estimates the time window during which there is available vegetation in a heading-flowering stage in the *alpage* (without considering regrowth cycles).
Frost-600: frequency of late frost events	Number of days	Number of days with minimum temperature below 0°C between snow melt-out date and date of reaching 600 degree-days, in average over all pixels of the *alpage* (excluding the 10% of the pixels for which snow melt-out is the earliest and the 10% for which it is the latest). It represents the frost constraint on the early development of vegetation when plant tissues are the most sensitive to cold damages.
WB-600: water balance during early vegetation growth	mm	Atmospheric water balance computed as precipitation minus reference evapotranspiration from the date of snow melt-out until the date of reaching 600 degree-days, in average over all pixels of the *alpage* (excluding the 10% of the pixels for which snow melt-out is the earliest and the 10% for which it is the latest). It represents the water potentially available for plants during the early

Table 1 (continued)

Agro-climatic indicator	Unit	Definition
		vegetation growth period, in the different parts of the *alpage*.
WB-August: water balance during summer growth	mm	Atmospheric water balance computed as precipitation minus reference evapotranspiration during August, in average over all pixels of the *alpage*. It represents the water theoretically available for plants during the summer growth when herds are usually grazing on highest parts of the *alpage*.
WB-Sept: water balance during fall regrowth	mm	Atmospheric water balance computed as precipitation minus reference evapotranspiration during September, in average over all pixels of the *alpage*. It represents the water theoretically available for plants during the fall regrowth, generally grazed by herds on the lowest part of the *alpage* after they have come down from the higher parts.

period) as variables. Average physical variables derived from pastoral units' rasters (see section 2.5) were plotted as supplementary variables in the analysis using R statistical software version 3.6.1 (R Core Team 2019) with the packages FactomineR and factoextra.

To analyze the spatial distribution of indicators' evolutions, the variations of the indicators' values between past and recent periods were mapped at the spatial resolution of pastoral units across the study area using QGIS software version 3.6.

We then tested the effect of period (past, recent), geographical region (Northern Alps, Central Alps, Southern Alps, Extreme Southern Alps), and the period × region interaction, on 30-year indicators' values, across all pastoral units (n=2779), by using a linear mixed-effect model with pastoral units set as a random effect. Assumptions for linear modeling (normality of the data and homogeneity of variances) were checked prior to the analysis. When tests revealed significant effects of factors period and/or region, post hoc tests (Tukey's honest significant difference method) were performed to assess contrasts among factor combinations (8 groups) and after computing estimated least-squares means in linear models. These analyses were carried out using R statistical software version 3.6.1 (R Core Team 2019) with the packages nlme, lme4, and emmeans.

3 Results and discussion

3.1 Agro-climatic conditions on *alpages* in the French Alps

This first section provides indicator-based agro-climatic conditions on *alpages* and main differences between biogeographic regions of the French Alps for the recent period (1991–2018) (Table 2).

3.1.1 Earliness of the pastoral season (GDD-600)

GDD-600 occurred between May 26th (day of year 147) and July 24th (day of year 206) for 75% of *alpages* in the French Alps (median date = June 24th) with an interannual variation of 7 to 12 days (median = 10 days) (Table 2A). Field data collected at the 25 pilot *alpages* of the "*Alpages Sentinelles*" program over the 2011–2019 period offer an opportunity for validating the order of magnitude of GDD-600, which depicts the potential appropriate date for the start of grazing on summer pastures. Dates of herds' ascent on "*Sentinel*" *alpages* (average date = June 17th, range = June 4th–July 11th, data not provided) confirm the validity of GDD-600 values, given the numerous factors that modulate, each year, on each *alpage*, the vegetation development and to which the climate-independent factors for the ascent of herds must be added (e.g., reservation in advance of animal transport, date of sheepherder hiring, constraint of resource on the farm, Nettier 2016). In addition, our results revealed disparities between regions: GDD-600 occurred the earliest for *alpages* of the Northern and Extreme Southern regions (it occurred about 10–12 days later, in average, in Central and Southern regions) and with the highest interannual variability (Table 2A). For the Northern region, this is because *alpages* are, in average, located at lower altitude than in other regions (average altitude of 1527 m, Fig. 2B), whereas, for the Extreme Southern region, earlier pastoral season is related to the global influence of the latitudinal gradient on temperatures (Durand et al. 2009a).

3.1.2 Temporal spread of the first vegetation growth cycle (Spread-600)

Spread-600 ranged from 4 days to 43 days for 75% of *alpages* in the French Alps (median spread = 21 days) with an interannual variability ranging between 2 and 8 days (median = 5 days) (Table 2B). This indicator gives the time window during which vegetation is theoretically available in an optimal development stage (heading-flowering stage) for grazing on the *alpage* (i.e., the duration of the staggering of phenological development due to the elevation gain or topographic aspects within the

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Table 2 Mean and interannual variability of indicators for the characterization of agro-climatic conditions on *alpages* in four biogeographic regions in the French Alps. Mean is the 30-year average by pastoral unit (1991–2018 period) and interannual variability is the 30-year standard deviation by pastoral unit (1991–2018 period). Given is the median of the distribution of pastoral units, and, in brackets, the 5th–95th percentile range. For the number of pastoral units considered within each region see Fig. 2. For indicator definition see Table 1.

	Mean		Interannual variability	
A) GDD-600 (day of year)				
Northern Alps	173.4	(144.1 – 201.6)	10.3	(7.8 – 11.7)
Central Alps	185.1	(148.4 – 208.7)	9.0	(5.7 – 10.6)
Southern Alps	183.8	(147.8 – 208.1)	8.6	(5.3 – 10.4)
Extreme Southern Alps	173.6	(153.4 – 203.8)	11.2	(7.5 – 13.0)
All sub-regions	176.0	(146.8 – 205.9)	9.8	(7.0 – 11.9)
B) Spread-600 (number of days)				
Northern Alps	19.2	(4.0 – 33.9)	4.2	(1.7 – 7.3)
Central Alps	22.5	(5.0 – 42.9)	4.8	(1.5 – 8.2)
Southern Alps	25.4	(4.8 – 49.1)	4.8	(1.3 – 7.9)
Extreme Southern Alps	35.7	(12.1 – 48.8)	7.0	(3.3 – 9.8)
All sub-regions	21.4	(4.4 – 42.7)	4.6	(1.6 – 8.2)
C) Frost-600 (number of days)				
Northern Alps	7.9	(2.4 – 22.2)	6.5	(2.6 – 15.5)
Central Alps	7.9	(1.8 – 29.9)	5.4	(1.8 – 17.0)
Southern Alps	13.2	(3.2 – 33.8)	8.9	(3.1 – 17.5)
Extreme Southern Alps	16.5	(6.4 – 33.1)	11.7	(6.2 – 17.6)
All sub-regions	9.1	(2.5 – 27.4)	7.1	(2.5 – 16.7)
D) WB-600 (mm)				
Northern Alps	80.1	(16.6 – 109.7)	86.8	(60.2 – 117.8)
Central Alps	−10.7	(−39.4 – 23.0)	58.6	(26.7 – 103.6)
Southern Alps	−43.0	(−103.1 – 10.1)	64.5	(40.2 – 112.5)
Extreme Southern Alps	−70.0	(−87.5 – 40.5)	71.5	(42.8 – 94.8)
All sub-regions	20.9	(−79.4 – 105.1)	78.6	(39.1 – 113.2)
E) WB-August (mm)				
Northern Alps	30.4	(2.0 – 43.6)	61.8	(49.0 – 69.0)
Central Alps	−11.0	(−38.8 – 2.8)	40.2	(35.8 – 45.9)
Southern Alps	−52.2	(−65.7 – 34.9)	37.1	(27.1 – 42.2)
Extreme Southern Alps	−68.4	(−81.7 – 61.2)	48.6	(37.5 – 52.8)
All sub-regions	3.9	(−68.9 – 39.7)	50.9	(35.7 – 68.2)
F) WB-Sept (mm)				
Northern Alps	50.5	(27.5 – 64.0)	75.0	(60.0 – 88.1)
Central Alps	15.7	(5.3 – 31.5)	55.2	(38.1 – 82.0)
Southern Alps	7.1	(−20.5 – 27.6)	61.5	(47.6 – 75.4)
Extreme Southern Alps	−0.8	(−11.5 – 18.9)	67.0	(57.1 – 92.1)
All sub-regions	32.0	(−7.7 – 62.8)	68.5	(44.3 – 86.6)

alpage). At first sight, this time window might appear very restricted: it falls below 21 days for 50% of *alpages* when herds graze there for an average of several months. However, restricted time windows below 20 days mainly concerns *alpages* located in the Northern region (median = 19 days, Table 2B) which is related to their small surface and low elevation gradient (Fig. 2B). Also, this matches with the fact that, in the Northern region, *alpages* are mainly used by dairy cattle livestock. In these livestock systems, grazing is organized around a rapid rotation of the animals between the different sectors of the

alpage to ensure high nutritional quality of the vegetation (Nettier 2016). Spread-600 increases from Central to Extreme Southern region, as well as its interannual variability (Table 2B), probably directly in relation to increasing surface and elevation gradient of the *alpages* therein (Fig. 2B). Besides, it should be kept in mind that the indicator Spread-600 is computed for a standard graminoid vegetation reaching the heading stage at 600 degree-days. In real-world pastures, the diversity of vegetation types leads to staggered phenological advancements (see the diversity of pastoral vegetation properties

in Nettier et al. 2017), which likely allows for a larger time window of optimal vegetation development stage on the *alpages*.

3.1.3 Number of frost events after snow melt-out (Frost-600)

Frost-600 ranged between 2 and 27 days for 75% of *alpages* in the French Alps (median value = 9 days), with an interannual variability of 2 to 17 days (median = 7) (Table 2C). This indicator revealed contrasted frost exposures according to regions. Frost exposure after snow melt-out was rather low for a large part of *alpages*, especially those of the Northern and Central regions (50% of which were exposed to less than 8 frost days in an average year). In contrast, exposure to frost was higher in the Southern and Extreme Southern regions, where 50% of *alpages* underwent more than 15 frost events in an average year, with strong year-to-year variability (Table 2C). *Alpages* of south regions of the Alps are, in average, more exposed to frost than the ones of northern latitudes, probably due to a smaller winter snowpack for a given altitude (i.e., less precipitations with decreasing latitude, Durand et al. 2009a). This increases the probability of early snow removal, while temperatures are still very cold in mountains areas.

3.1.4 Water balances for different periods of the vegetation growing season (WB-600/WB-August/WB-September)

Our estimations of water balance followed a seasonal pattern: the more negative water balances were observed in summer (WB-August, Table 2E), when the temperatures are high and evapotranspiration demand is the highest (e.g., Vitra et al. 2019), whereas the more positive water balance were observed in autumn. WB-600, the water balance during the period of the first growth cycle, was negative (i.e., indicating exposure to water stress) for 42% of *alpages* in the French Alps (median = 21 mm), with an important interannual variability (median = 79 mm) (Table 2D). WB-August, the water balance during the summer growth, was negative for 45 % of *alpages* (median = 4 mm), also with an important interannual variability (median = 51 mm) (Table 2E). For both periods, water balance reached values below −70 mm for 5% of *alpages*, which revealed exposure to severe water stress for these *alpages* (Table 2D–E). WB-Sept, the water balance during the fall regrowth, was negative for only 10% of *alpages* (median = 32 mm), but interannual variability was high (median = 70 mm) (Table 2F), which revealed that even *alpages* with positive water balance in an average year may be exposed to water deficit certain years at this period. Globally, and whatever the period, we observed an important gradient of decreasing water balance from Northern to Extreme Southern regions, revealing an increased exposure to water deficit directly related to both gradients of increasing temperature and decreasing precipitations with decreasing latitude (Durand

et al. 2009a). To give an order of magnitude, atmospheric water deficit of −50 mm (that is reached, according to our indicator, by 17% of the *alpages* in summer in an average year) corresponds to a dozen consecutive days without precipitation, with a daily evapotranspiration on a rain-free day of about 4 to 4.5 mm for a standard subalpine vegetation (Körner 2003). An atmospheric water deficit of this magnitude can already have a moderate negative impact on plant growth and reduce productivity in mountain grasslands, as shown by modeling work and field data (e.g., Calanca et al. 2016). Besides, while we reported exposure to water deficit during the first growth period, it is worth noticing that soils at this time are likely to get recharged by the melting of winter snowpack. This factor was not accounted for in our computation and might preserve the first vegetation growth from water deficit in most cases. An analysis of productivity data from *alpage* pastures in the Central French Alps has indeed shown that water is not a limiting factor in the early growth, contrary to temperatures (Grigulis and Lavorel 2020), and, consistently, Vitra et al. (2019) have shown that mountain pastures are more sensitive to water limitation after the growth peak (i.e., summer) than before (i.e., spring).

3.2 Agro-climatic profiles of *alpages*

This second section summarizes three main types of agro-climatic profile of *alpages* in the French Alps, defined according to a principal component analysis (Fig. 3) and examines the explanatory power of geographic and topographic factors.

The first profile type of *alpage* is not exposed, in an average year, to water deficits for plant growth, although subjected to high interannual variability in water balances, and presents restricted temporal spread of the first growth cycle (i.e., right direction on Axis 1, Fig. 3A). This profile corresponds to *alpages* of the Northern region, except those of high altitude (i.e., individuals located on the right part of the ACP plan, Fig. 3B). These pastures are at low elevation and with rather weak elevation gradient, small size, and gentle slope (correlations of ALTI, ELEG, SURF, and SLOP_max with axis 1 are respectively: r = −0.70; −0.56; −0.49; −0.39). This profile is neither characterized by the earliness of the pastoral season (neither very early, nor very late), nor by the exposure to frost events (neither absent, nor extreme).

The second profile type of *alpage* is characterized by a late start of the pastoral season and is not exposed to frost events (i.e., bottom direction on Axis 2, Fig. 3A). This profile is weakly exposed to water deficits although less watered than the first profile. This profile applies to highest elevation *alpages* and/or with the highest longitude within each region (i.e., internal part of the Alps) and, secondarily, to north-facing *alpages* (correlations of ALTI, LONG and ORI_North with axis 2 are respectively: r = −0.47; −0.32; −0.24) (i.e.,
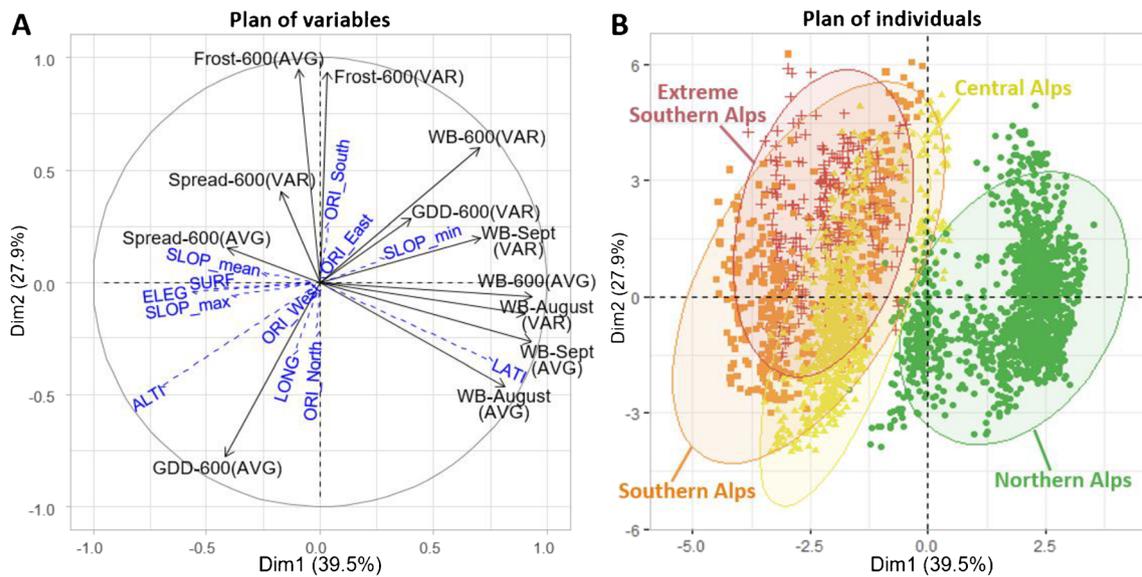
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Fig. 3 Agro-climatic profiles of *alpages* revealed though a principal component analysis of 2779 pastoral units (individuals) according to the mean and standard deviation values of agro-climatic indicators (variables). Main variables are plain lines (black). Supplementary variables plotted into the factorial plan are shown in blue (dotted lines). Data was centered and reduced before analysis. For indicator definition, see Table 1. AVG = mean over 1991–2018; VAR = standard deviation over 1991-2018. Meaning of supplementary variables: ALTI: average altitude; ELEG: elevation gradient; LATI: latitude; LONG: longitude; ORI_East: proportion of the pastoral unit oriented East; ORI_North: proportion of the pastoral unit oriented north; ORI_South: proportion of the pastoral unit oriented south; ORI_West: proportion of the pastoral unit oriented West; SLOP_max: maximum slope value; SLOP_mean: average slope value; SLOP_min: minimum slope value; SURF: surface area.

individuals located in the bottom and left part of the ACP plan, Fig. 3B).

The third type of *alpage* cumulates the most climatic constraints for forage resource and management: early and variable start of the pastoral season, high exposures to frost events and to water deficits (i.e., left and top directions on axis 1 and axis 2 respectively, Fig. 3A). This profile applies to *alpages* at the lowest altitude and/or from the external parts of the Central, Southern, and Extreme Southern regions (correlations of ALTI and LONG with axis 2 are respectively: r = −0.47; −0.32) (cf. individuals located on top and left part of the ACP plan, Fig. 3B). Secondarily, these *alpages* are south-facing (correlation of ORI_South with axis 2: r = 0.26).

Globally, this analysis revealed that latitude and altitude are the major determinants of agro-climatic conditions on *alpages* (correlations of ALTI and LATI with Axis 1 are respectively: r = −0.70; 0.76, and with axis 2: r = −0.47; −0.35). Indeed, in the French Alps, latitude determines to a large extent the amplitude of the annual cycle of temperature as well as the amplitude of precipitations in relation to the influence of the north westerly atmospheric flow on precipitations (Durand et al. 2009a). The determinism of altitude for the alpine climate is also well established (Durand et al. 2009a), and known to explain the vertical distribution of mountain vegetation (e.g., Körner 2003). Following these determinisms, potential risks of climate impacts on the forage resource on *alpages* primarily increase from North to South regions of the French Alps, and secondarily, from East to West, but decrease with altitude. For instance the highest *alpages* are protected from the frost risk, even in the Extreme South of the Alps. We also found that with increasing altitude, the exposure of *alpages* to interannual variability of agro-climatic conditions globally decreased (Fig. 3A). Further, this analysis confirmed the important roles of local topographic features (i.e., altitude, elevation gradient, slope, and orientation) to determine, for given latitude and longitude, the local agro-climatic conditions on *alpages* (Fig. 3A).

3.3 Recent evolutions of agro-climatic conditions on *alpages*

This third section brings insights on recent evolutions of agro-climatic conditions and their interannual variability, highlighting the trends arising in relation to climate change on the *alpages* (Fig. 4 and Fig. 5).

3.3.1 Evolution towards an earlier start of the pastoral season

We found that GDD-600 happened constantly earlier over the last 60 years, especially since the end of the 1980s (Fig. 4A). The earlier occurrence affected all regions and was of about 10 to 15 days in average at regional scale between the past (1961–1990) and recent (1991–2018) periods (Fig. 5A). At the French Alps scale, this represents an advance of about 2.2 days per decade, likely due to global warming, as demonstrated by Liu et al. (2017). In general, our indicator captures
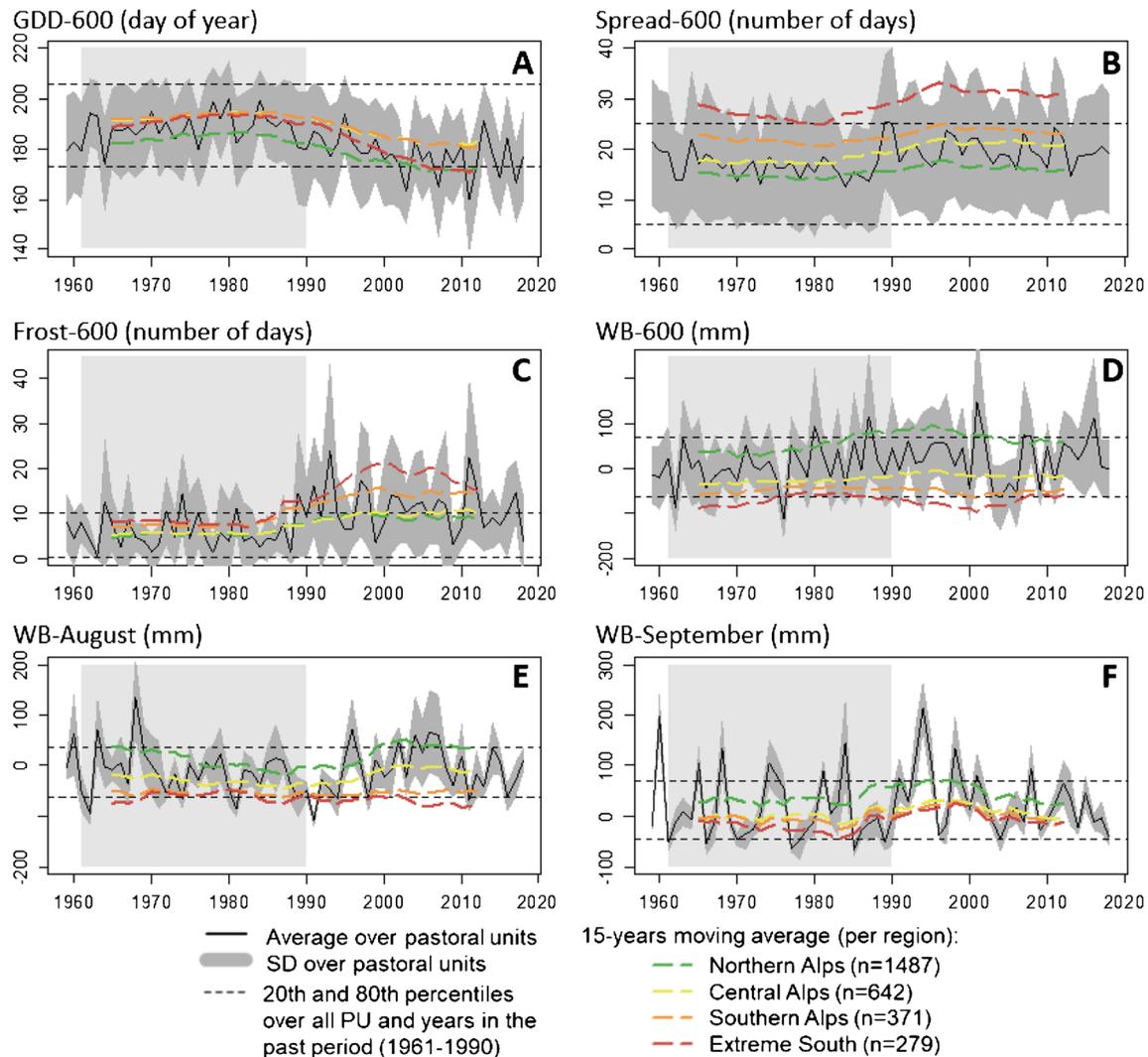
Fig. 4 Time-series plots showing the evolution of agro-climatic indicators from 1959 to 2018. The shaded light grey area represents the 30-year reference past period (1961–1990). The full black line indicates, each year, the average over the 2779 pastoral units and the dark grey area represents, each year, the standard deviation over the 2779 pastoral units. Colored dotted lines indicate centered 15-year moving average per region, i.e., the average over the pastoral units in each region and over 15 years. The two dotted black lines indicate the 20th and 80th percentiles in the past period (1961–1990). For indicator definition, see Table 1.

an evolution with an order of magnitude similar to that reported in other studies, through field vegetation measurements (Studer et al. 2005; Vuffray et al. 2016) or qualitative management monitoring (Herzog and Seidl 2018). Based on phenological records in grasslands, Studer et al. (2005) found a significant advance in vegetation development of 1 to 2.8 days per decade over 1951–2002 for different altitudes in Switzerland, and showed that these patterns are driven by temperatures whereas precipitations had only little influence. Herzog and Seidl (2018) found similar trends in the Jura and Central Switzerland, based on interviews of farmers indicating that the summer grazing season in mountains had started about 1 week earlier over the last decades.

Along with this evolution, we observed an increased frequency of abnormally early years in the recent period compared to the past (i.e., increased number of years between 1991 and 2018 below the 20th percentile of the 1961–1990 distribution), while there were still late years (i.e., close to the 80th percentile) (Fig. 4A). This means that the interannual variability in the possible start date of the pastoral season increased over the last decades.

In terms of spatial distribution of evolutions, the delta map shows that the advance in GDD-600 was most pronounced in the Extreme Southern region, where most of *alpages* were submitted to an advance of more than 15 days in the recent period compared to the past (Fig. 5A). It also highlights a

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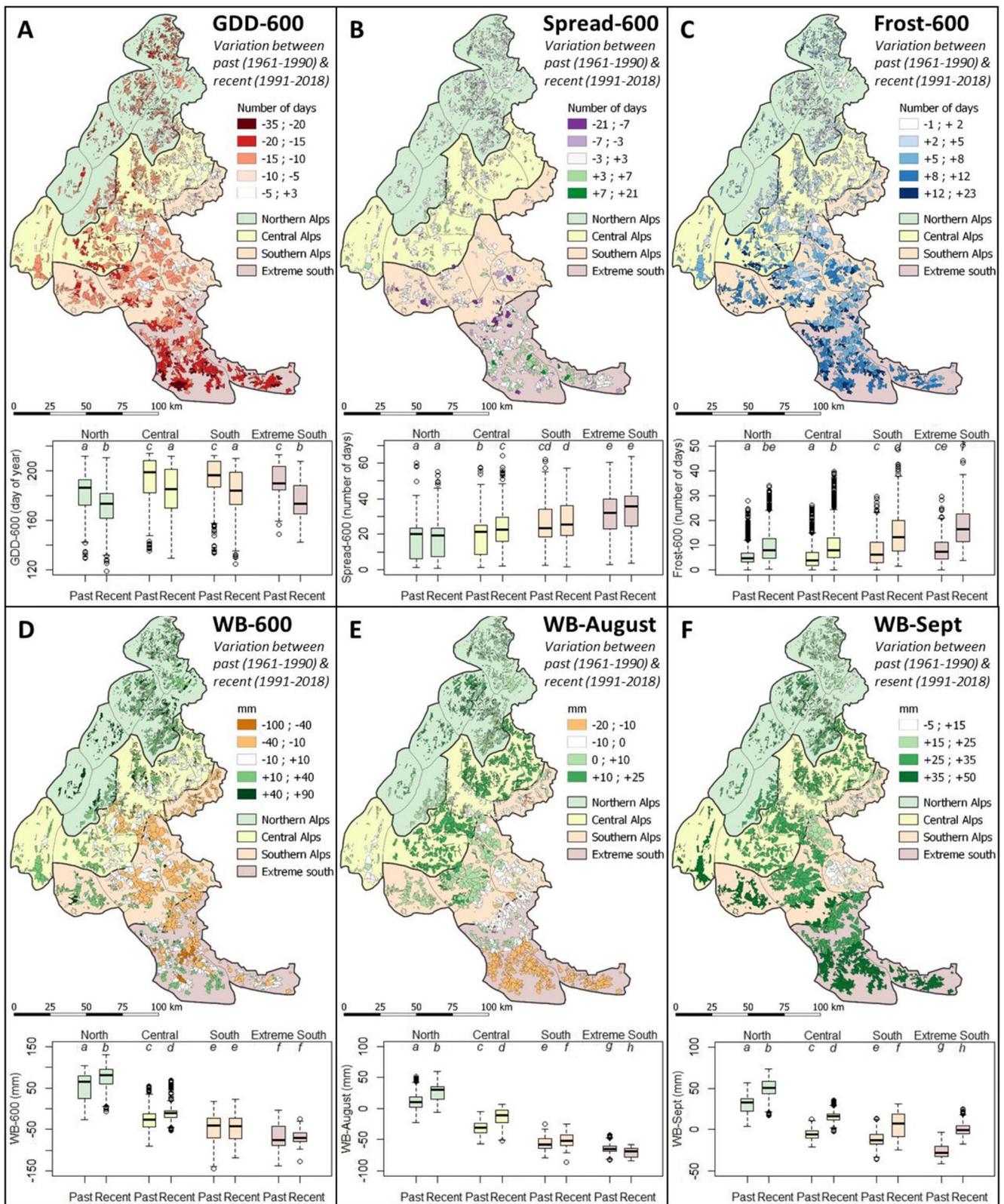
Fig. 5 "Delta" maps. Differences between past (1961–1990) and recent (1991–2018) 30-year means of indicators at the pastoral unit level. For indicator definition see Table 1. At the bottom of each panel, boxplots of indicator' 30-year average are represented for each region and each period (past, recent). In each boxplot, different letters (given in italics) indicate significant differences (<0.001) between regions and periods, after post hoc multiple pairwise comparison tests (see methods for details).

strong spatial heterogeneity of variation within each region, with variations at the *alpage*-level ranging between −35 to +3 days (Fig. 5A).

3.3.2 The temporal spread of the vegetation growth period remains unchanged

We found Spread-600 to be relatively stable over the last 60 years at the French Alps scale as shown by the time-series plot (Fig. 4B), with almost no significant variations between the past and recent periods at the regional scale (Fig. 5B). At the *alpage* level, variations of Spread-600 between past and recent periods range from −21 days to +21 days but with a large dominance of close to zero variations (Fig. 5B). This means that while GDD-600 (i.e., the reaching of 600 degree-days after snow melt-out on the early part of the *alpage*) happened earlier over the last 60 years, the reaching of 600 degree-days in the latest part of the *alpage* has advanced concomitantly. Nevertheless, for a few *alpages*, the advance in the reaching of 600 degree-days was stronger in the early part than in the late part, which leads to a significant increase in Spread-600 over the last decades (i.e., more than a week, Fig. 5B). This pattern is found in *alpages* with the highest elevation gradient, revealing that the global temperature accumulation advance in spring (Liu et al. 2017) is attenuated at high altitude (e.g., Vuffray et al. 2016).

3.3.3 Evolution towards higher exposure to frost events after snow melt-out

The number of frost days has increased sharply since the mid-1980s (Fig. 4C), with a rise of about 5 days between the past and the recent period in average for all *alpages* at the French Alps scale. This pattern is notably pronounced for *alpages* in the Southern and Extreme Southern regions, where the number of frost days has approximately doubled in average, locally representing an increase of +5 to +23 frost days in the recent period compared to the past (Fig. 5C). A minority of *alpages* in the Northern and Central Alps can also locally experience an increase in the frost risk, but in general, they remain less impacted than in Southern regions in terms of absolute values (Fig. 5C). Along with this evolution, we observed an impressive increase in the frequency of years with extreme number of frost days (i.e., almost all years in the recent period were above the 80th percentile of the past distribution) in average at the French Alps scale (Fig. 4C). Different studies have reported that due to an advance in snow removal, and despite global warming, mountain vegetation is more frequently exposed to negative temperatures at the beginning of the growing season (Inouye 2008, Arnold et al. 2014, Wheeler et al. 2014). At the alpine scale, this earlier snow removal–induced frost exposure is probably, for the moment, mostly visible in Southern regions and/or at low altitude. For instance, in the Swiss Alps

(northernmost and innermost compared to the French Alps), Klein et al. (2018) have found that the frost risk to plants during their early development stage has been unchanged over the last decades, due to the fact that minimum and maximum air temperatures have risen at approximately the same rate, which has advanced in the same way the phenology of alpine plants and the latest frost events.

3.3.4 Water balances show no significant evolution trend

We did not find evident evolution trends of the water balances for the different periods, towards either drier or wetter years nor a clear increased interannual variability over the past 60 years at the French Alps scale (Fig. 4D–F). When we considered water balances at the regional scale, variations between the past and recent periods were generally low (i.e., marginal variations from the forage resource perspective) or slightly positive, except for the water balance in August in the Extreme Southern region for which variations were slightly negative (Fig. 5E). Although stable or positive at the regional level, variations could be negative at the *alpage*-level (Fig. 5D–F). Negative variations mainly concerned *alpages* from the Southern and Extreme Southern regions for the first growth period (range of negative variations: 0 to –100 mm) and *alpages* of the Extreme Southern region in summer (range of negative variations 0 to –20 mm) (Fig. 5D–F). Amplitude of variations was higher for the water balance of the first growth period (range = −100 mm / + 90 mm, Fig. 5D) than for the water balance of August and September, because the first growth period encompasses a larger temporal period (about 2 months), more likely to capture larger changes.

Over the last decades, our indicators of theoretical water availability for vegetation growth show rather small changes from the forage production perspective, however hiding spatial disparities between north and south regions within the French Alps. In the southern regions, *alpages* were the most exposed to a water deficit risk (see section 3.1.4) and were also the most exposed to unfavorable evolution of this risk. This is not necessarily related to a greater increase in the frequency and intensity of drought events in the southern Alps compared to the northern Alps (Haslinger and Blöschl 2017), but probably to the rise of the drier Mediterranean climate in the mountains of the Southern Alps.

3.4 Synthesis: potential implications of agro-climatic evolutions for livestock farming systems

At first glance, an advanced start of the pastoral season over the past decades prefigures an extended period for the exploitation of *alpages*, likely to be more frequent in the future. Predictive models have indeed shown an increased productivity potential of mountain grasslands due to advanced onset of growth, for instance in the Swiss Alps (Rammig et al. 2010).

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Lengthening of the summering grazing season and general increased productivity is also perceived by Swiss alpine farmers (Herzog and Seidl 2018). This is in line with trends of increased greening patterns observed through remote sensing techniques in subalpine and alpine zones, due to the lengthening of the growing season (e.g., Choler et al. 2021).

However, the view that earlier snow melt-out may only come with the beneficial effects of a prolonged vegetation period and subsequent increased forage supply is probably too simplistic. Rammig et al. (2010) indeed concluded that an earlier onset of growth up to 3 weeks would lead to substantial changes in vegetation phenology, likely to change pastures' productivity and composition. Dibari et al. (2020) further showed that substantial compositional changes towards less palatable vegetation are expected in mountain pastures due to climate change, which will potentially reduce the forage quality for livestock feeding.

Potential positive effects are also likely to be bypassed by more frequent seasonal water limitations (e.g., Corona-Lozada et al. 2019), especially in the Southern Alps and at low altitude (Jäger et al. 2020). Positive effects could also be bypassed by an increased frost risk, likely to strengthen in the future due to increasingly advanced snow melt-out with climate change (Klein et al. 2016). The impact of frost on mountain pastures' vegetation is still poorly documented, but we can assume that freezing damages to young plant tissues in the onset of growth will decrease productivity and quality of the forage resource to come (Chaix et al. 2017; Grigulis and Lavorel 2020) besides altering ecosystem functioning (Arnold et al. 2014, Wheeler et al. 2014).

From a management perspective, livestock systems would not necessarily be able to take advantage of an advance in the grazing period on *alpages*, for instance because of constraints in the articulation between the use of the *alpage* and the farm functioning (e.g., breeding calendar that constraint the herd ascent period, Nettier 2016). This is especially true if this general advance is combined with increased interannual variability, i.e., an increased occurrence of very early years alternating with late years. Adaptation to such changes is likely to require additional flexibility at the livestock farming system level (i.e., on farms), whereas *alpages* are precisely providing some flexibility for farms to face forage supply variability in the lowlands (Rigolot et al. 2014). Also, we have estimated that the time window during which vegetation is at an optimal grazing stage did not substantially change for a majority of *alpages*. This prefigures no important gain of flexibility for grazing management coming from this aspect in the future, although locally there may be exceptions for large *alpages* with a high elevation gradient.

Overall, our results revealed rather negative agro-climatic evolutions on *alpages* in the French Alps, such as an increased risk of altered growth conditions early in the season. Additionally, for *alpages* most exposed to a water deficit threat in summer, this risk tends to increase. Thus, our results highlight the spatial disparity of the risk and its evolution between north and south parts of the French Alps: *alpages* in the southern parts, especially at low altitude, are the most exposed to unfavorable conditions and have also experienced the most negative changes over the last decades. However, agro-pastoral livestock systems using *alpages* in the Southern Alps are often extensive suckler cow and sheep systems that are intrinsically configured to cope with strong interannual and seasonal climatic variability, as illustrated by research on Mediterranean rangeland–based systems (Guérin et al. 2009). For instance, in these extensive systems, animal breeds and/or type of productions can withstand variable feed-intake periods. Also, during the *alpage* season, buffer and safety practices are commonly implemented, for instance: delayed grazing of coarse vegetation thanks to animal habituation, and maintenance of shrubby and wooded environments as buffer areas maintaining freshness during dry and warm periods (Nettier et al. 2017). These *alpages* are also the largest, sometimes with steep relief, compared to small *alpages* with smoother relief in the Northern Alps, which confer intrinsic flexibility of use (e.g., diversity of pastoral vegetation types and of phenological development, oversizing of pastures compared to stocking rates, Nettier et al. 2017). In contrast, *alpages* from the Northern massifs encounter less adverse agro-climatic conditions and changes. They are probably only rarely water limited and more likely to take advantage of global higher temperatures for the forage production (Herzog and Seidl 2018; Jäger et al. 2020). However, vegetation types may be much more sensitive to water stress (Bornard et al. 2007). In addition, dairy livestock farming, highly prevalent in the Northern Alps (Dobremez et al. 2016), has a higher expected productivity and a necessity for a regular production, which would limit its flexibility. Although *alpages* of the north of the French Alps are less exposed, intrinsic sensibility and lower adaptive capacities of systems using these *alpages* may finally increase the effective risk of impacts due to the occurrence of climatic hazards such as severe droughts (Nettier et al. 2011; Deléglise et al. 2019).

3.5 Towards an operational tool to support adaptation

In this paper, we introduced an approach that for the first time allowed defining the agro-climatic profile for a total of 2779 *alpages* in the French Alps (i.e., almost 90% of *alpages* referenced in the French Alps). This approach relies on a specific set of agro-climatic indicators co-constructed by researchers and practitioners, likely to make sense for end-users (Nettier 2016). We contend that our ad hoc indicators precisely bring a real added value compared to classical climatic indicators in agriculture, which either cannot take into account the

specificities of the mountain environment (e.g., snowmelt dynamic, elevation gradient) or are not available at the management unit level and therefore not easily transferable into an operational tool to support adaptation. To address our operational concern, it is indeed essential to provide indicators at the individual level of each *alpage*, especially when the spatial heterogeneity of agro-climatic conditions is strong within massifs assumed to be climatically homogenous (Fig. 5).

From a practical use perspective, agro-climatic profiles are available for practitioners through a web-based visualization tool (Fig. 6) providing different informative elements: (i) 30-year indicators' average and interannual variability, and the *alpages* relative position to each other, (ii) intra-*alpage* spatial heterogeneity of indicators on the basis of 25 × 25 m pixel values, and (iii) evolution of indicators at the *alpage*-level on an annual scale over the last 60 years. These descriptive elements can be used as inputs for pastoral diagnostic by experts and users of the *alpage*, after their critical interpretation considering micro-conditions and local specificities. To assess the effective risk due to climate change and variability for the use of the *alpage*, this step can then be completed with sensitivity

and vulnerability factors at the socio-ecological level (e.g., analysis of vegetation properties, pastoral management, functioning of livestock systems using the *alpage*, elements of local context) (Deléglise et al. 2019). By enhancing farmers' perceptions about climate change, and more globally by contributing to a shared, integrative understanding among stakeholders of the complexity of the climatic challenge on each *alpage* system, we hope that this tool will foster local adaptation efforts and decrease the risk of impacts.

An extension of the present tool is currently under development. It is intended to give access to the aggregation of indicators at the massif and/or distinct administrative scales over the French Alps, in order to monitor the evolution of the climatic context of *alpages* within targeted regions and/or group of *alpages* with particular risk due to climate change. Extension in the number of indicators is also intended, to take into account additional hazards such as heat waves, likely to increasingly impact the pastoral season, even in altitude, under future climate conditions (e.g., Corona-Lozada et al. 2019). The aim is to generate yearly updated spatialized risk information, for the traditional exploitation of *alpages*, and we
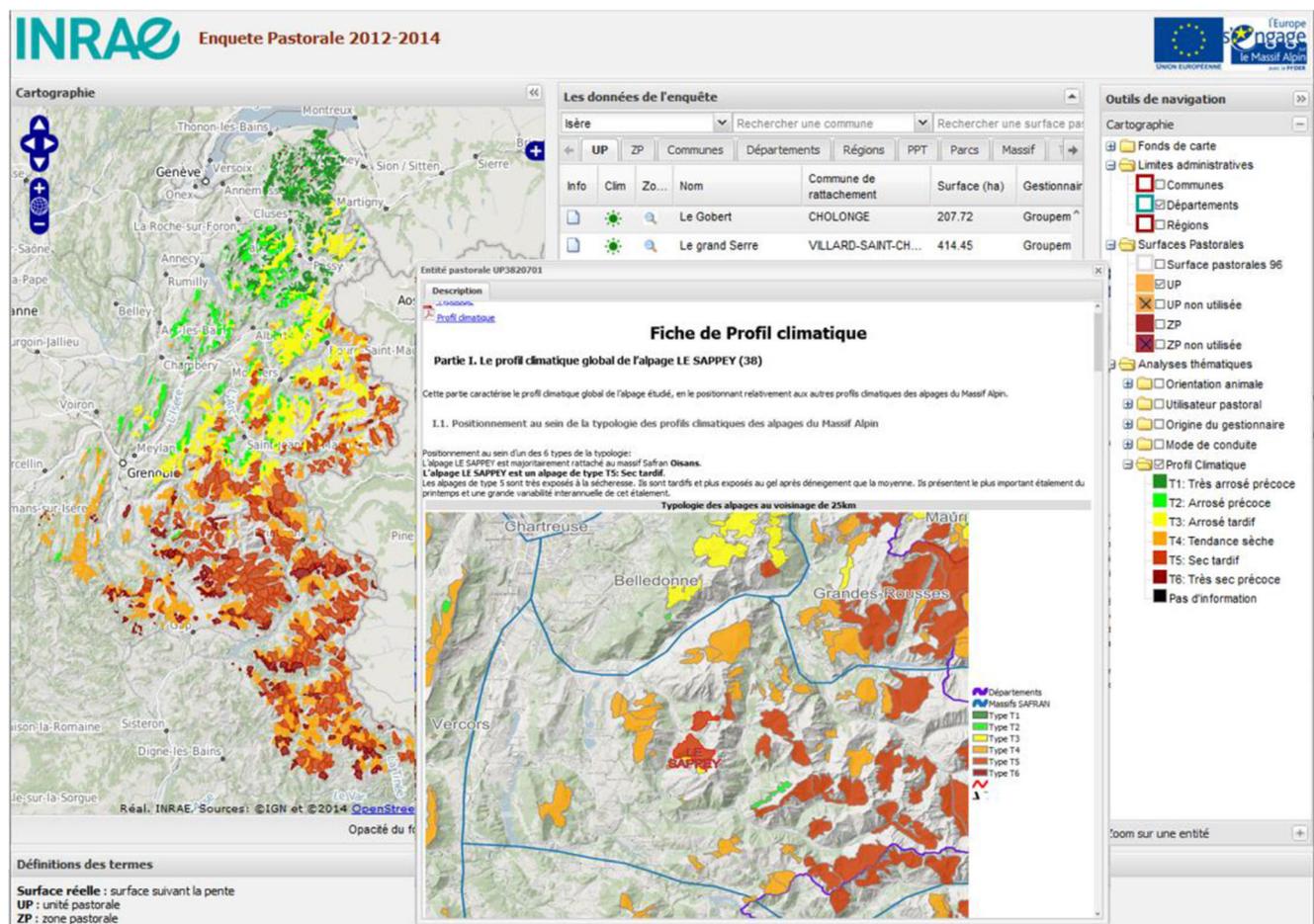
Fig. 6 Screenshot of the web interface for the visualization of agro-climatic profiles of *alpages* in the French Alps.

hope it will provide useful input to the design of relevant policies supporting adaptation in pastoralism in the different French alpine regions.

4 Conclusion

Our findings bring new and detailed insights into the climatic context for forage resources and pastoral management on *alpages* in the French Alps, in a very operational way thanks to ad hoc and *alpage*-level indicators available through a web-based visualization tool. This is a first step towards a climate risk assessment at the socio-ecological level of *alpage* systems in the French Alps (Deléglise et al. 2019). Besides, the unique method we have developed in this study provides the basis for exploring the future agro-climatic conditions on *alpages*, by using projected climate change scenarios of the IPCC locally adjusted for mountain areas (Verfaillie et al. 2017).

To conclude, by revealing recent evolutions of the agro-climatic context of *alpages*, this work highlights future challenges for the sustainable use of these socio-ecological systems, and given the co-evolution between climate, ecosystems and management practices (Nettier et al. 2017). More broadly, it raises the issue of the adaptability of livestock farming systems and of related institutions to such changes to foster the sustainability of mountain agriculture and pastoralism, in a context of uncertainties (Darnhofer et al. 2010; Joyce and Marshall 2017).

Availability of data and material

- The S2M meteorological and snow data reanalysis dataset is available on the AERIS repository : https://doi.org/10.25326/37
- Digital terrain models are available from IGN own open access data website: https://geoservices.ign.fr/documentation/diffusion/telechargement-donnees-libres.html#bd-alti-25-m
- The French Alpine pastoral inventory dataset is available (under convention) on the dedicated website: https://enquete-pastorale.inrae.fr/
- The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request

Code availability

- Preliminary metrics: code available on reasonable request from raphaelle.samacoits@meteo.fr
- Indicators computation: code available on reasonable request from hugues.francois@inrae.fr

Declarations

Competing interests   The authors declare no competing interests.

Ethics approval   Not applicable

Consent to participate   Not applicable

Consent for publication   Not applicable

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