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RESEARCH ARTICLE

A Bayesian analysis of adaptation of mountain grassland production to global change

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Abstract

1. In mountains, grasslands managed for livestock production sustain local economies, culture and identity. However, their future fodder production is highly uncertain under climate change: While an extended growing season may be beneficial, more frequent and intense summer droughts could also reduce fodder quantity and quality. Land use and land cover (LULC) changes are another major driver of grassland biomass production, but combined effects of future land use transitions and climate change are rarely quantified.
2. We modelled combined climate and LULC scenarios for grassland production of the Maurienne Valley (French Alps) by 2085. We built a Bayesian Belief Network (BBN) from long-term grassland production monitoring data complemented with expert knowledge. We assessed the potential of two candidate adaptations, intensification as an incremental solution and silvopastoralism as a transformative solution to compensate combined impacts of two climate scenarios and three land use change scenarios.
3. Total biomass production was far more sensitive to LULC than to climate scenarios. Production losses were largest under the conservation LULC scenario (−28% on average between 2020 and 2085), followed by the tourism development scenario (−7%) and the business-as-usual scenario (+3%). Climate change under representative concentration pathways (RCP) 8.5 altered the seasonality of production by increasing potential production from May to July while decreasing summer regrowth.
4. *Synthesis and applications*: Changes in LULC are more decisive for global biomass production than climate change. However, under the most extreme climate change scenario (RCP8.5), the seasonal shift in production and increased interannual variability threaten the current grass-based protected designation of origin (PDO) production system. Only the intensification adaptation solution showed significant gains in total biomass production. Still, the silvopastoralism would require less investment compared to the intensification and have a similar efficiency

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when assessing the gains of biomass by the surface concerned with adaptation solutions. Along with decreased total annual production due to decreasing grassland area compounded by more extreme climate change, the seasonal shift in production and increased interannual variability threaten the current grass-based PDO production system. Further Bayesian modelling co-developed with local stakeholders and experts could greatly contribute to adaptation planning of the regional production system.

KEYWORDS
alpine pastoral system, Bayesian Belief Network, biomass production, climate change, ecosystem services, grasslands, land use and land cover change

1 | INTRODUCTION

In mountain socioecosystems (SES), the history of interactions between humans and ecosystems has shaped complex and multifunctional landscapes (Egarter Vigl et al., 2016). Grasslands are a significant landscape component providing multiple Nature's Contribution to People (NCP) (Lavorel, Grigulis, et al., 2017). Livestock farming depends on biomass supply for grazing and winter fodder production (Jäger et al., 2020). Thus, the biomass production NCP contributes to income from cheese and meat production, directly supporting the quality of life of farmers and more generally maintaining the local economy and a cultural landscape to which collective identity is tied (Bruley et al., 2021; Grosinger et al., 2021). By maintaining grasslands, mountain livestock farming also supports the conservation of genetic resources, water flow regulation, pollination, climate regulation and outdoor recreation (Battaglini et al., 2014). Thus, grasslands and the NCP they provide are often considered as essential components of a desirable future for mountain SES (Bruley et al., 2021).

The future of mountain livestock production systems rests on the future ability of grasslands to provide biomass under the effects of changes in climate, land use and land cover (LULC). Over the past century, major societal changes have reshaped mountain SES and especially agriculture, leading to decreasing land use intensity and abandonment, and hence reduced grassland area (Schirpke et al., 2020). Such landscape transformation directly affects the supply of NCP and human communities that depend on them (Schirpke et al., 2020). In addition to LULC change, the Alps have already experienced significant climate change with an average warming of +2.25°C, exceeding by twice the average temperature increase in the northern hemisphere since the late 19th century (Gobiet et al., 2014).

Knowledge about the combined impacts of future climate and LULC changes on mountain grassland biomass production remains scarce (Jäger et al., 2020). Studies have examined the effects of spatial variation along hydrological and altitudinal gradients (Della Chiesa et al., 2014), heatwave and drought events (Corona-Lozada et al., 2019; Mastrotheodoros et al., 2020), climate (Jäger et al., 2020) or LULC change (Ingrisch et al., 2018) on grassland vegetation or the NCP they provide. Furthermore, models of climate change impacts on their biomass production have often focused on the first growth period to peak biomass: typically May–July (Grigulis & Lavorel, 2020; Jäger et al., 2020), while its effect on the August and autumn growth periods are rarely quantified due to the higher complexity in disentangling climate from management effect on measured biomass regrowth (Choler, 2015). Climate change induces contrasted effects on mountain grassland biomass production, with longer growing seasons expected to shift its amount and more frequent extreme events like droughts reducing it (Carlson et al., 2017; Jäger et al., 2020). Droughts are likely to become prevalent during alpine summers (Calanca, 2007) and evidence suggests that, despite an extended growing season with increased spring productivity (Jonas et al., 2008; Rammig et al., 2010), droughts severely reduce summer growth, leading overall to unchanged total production along with a temporal shift in its supply (Corona-Lozada et al., 2019; Wang et al., 2020). Therefore, integrating the different growth periods into modelling approaches assessing climate change effects is essential. Furthermore, in mountains, interannual climate variability results in highly variable biomass production (Grigulis & Lavorel, 2020), which the livestock farming system must integrate to maintain production (Nettier et al., 2017).

Adaptation solutions are required to limit the negative effects of these changes on landscapes and production systems (Nettier et al., 2017). Modelling the capacity of adaptation measures to cope with future impacts of drivers of change is a critical step in decision-making and adaptation planning for the agropastoral system (Herrero et al., 2016). Understanding how agricultural systems will be modified by climate change and planning adaptation accordingly requires combining specific and local knowledge with global scenarios and knowledge. Addressing this goal, this paper aims to assess combined effects of climate and land use scenarios on grassland biomass production in an alpine valley, and how adaptation solutions can compensate for these impacts. For this, we developed an advanced probabilistic modelling approach for capturing quantitative and expert knowledge and quantifying effects of climate, land use and adaptive practices on annual biomass production, its distribution across the production landscape and its interannual variability.

Increasing availability of data related to climate time series and scenarios, topography, soils or LULC has supported spatial

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modelling of NCP (Lavorel, Bayer, et al., 2017). Among available methods, Bayesian Belief Networks (BBN; Aguilera et al., 2011) are increasingly used in environmental assessment (McCann et al., 2006) and more specifically to quantify NCP (Landuyt et al., 2013; Stritih et al., 2018). BBN are graphical probabilistic models that represent causal relationships among system variables (Ben-Gal, 2008). In environmental modelling, BBN are used to quantify the influence of environmental predictors on variables representing an ecological response (Aguilera et al., 2011). Combined with GIS technology, they provide spatially explicit estimates of NCP supply (Grafius et al., 2019). Main advantages of BBN in NCP assessment are their adaptative modelling framework (Landuyt et al., 2013), their ability to explicitly capture uncertainties (Stritih et al., 2018) and their capacity to combine expert knowledge and empirical data (Aguilera et al., 2011). Their ability to quantify and assess the propagation of uncertainty is especially relevant for NCP assessment in a context of adaptation planning (Dessai & Hulme, 2004; Refsgaard et al., 2013).

Here, we demonstrate how BBN modelling can support the evaluation of: (1) the likely consequences on landscape-scale herbaceous biomass supply of future scenarios of climate change combined with LULC changes that control spatial distribution of grassland surfaces and (2) the efficiency of contrasted adaptation solutions. Using a BBN, we combined published statistical relationships between variables and expert knowledge, to represent respectively early- and late-season climate effects on grassland production. This allowed us to project changes in total grassland production at regional scale, its spatial distribution and interannual variability, and to assess impact mitigation by potential adaptation scenarios.

2 | MATERIALS AND METHODS

2.1 | Study site

We modelled grassland biomass production in the Maurienne Valley, a 120-km-long valley in the French Alps. Its altitude averages 2034 m a.s.l., ranging from 298 and 3571 m. Its centre is located at 45°11′ N–6°39′ E and it covers 1976 km^2. Built up areas cover 2% of the site, mainly in lower part of the valley and with urban sprawl from villages or ski resorts at medium and high altitude. Grasslands cover 26% of the area and shrubs occupy 5% mainly on previously exploited grassland and transitional shrublands (see Supporting Information A). Grasslands follow an altitudinal productivity gradient from the most productive mown meadows at the bottom of the valley managed to feed the herds of the 350 local farms, to the least productive high-altitude pastures mainly used for grazing by local and external herds during the summer transhumance. The Maurienne Valley falls within the perimeter of the protected designation of origin (PDO) label for Beaufort, a cheese made from local cow milk. The PDO requires that 70% of the fodder for dairy cows is locally sourced, which makes the system very sensitive to any of low altitude mowing areas. No ethical approval was required as this is a modelling study.

2.2 | Input spatial data

A 5-m resolution digital elevation model (DEM; IGN, 2001) provided altitude and was transformed into slope, concavity and insolation data. Slope was calculated using the QGIS slope algorithm (QGIS Development Team, 2022). Terrain convexity was calculated using the Terrain Surface Convexity algorithm from SAGA software (Conrad et al., 2015; Iwahashi & Pike, 2007). The r.sun algorithm was used to calculate insolation (direct solar irradiance; Hofierka & Ri, 2002). We used the r.grow.distance from the GRASS toolbox in QGIS to produce a raster of the distance to the nearest road (GRASS Development Team, 2017). The land use and land cover data sets (8 classes of land use and land cover) were provided by the Data Management Authority from the Savoie department for 2006, 2009, 2013, 2016 and 2020. For 64% of the grassland area across the site, we used an existing map comprising six types of increasing productivity (Bernard-Brunet & Bornard, 2004; Bornard & Dubost, 1992).

2.3 | Building the Bayesian Belief Network

Bayesian Belief Networks are probabilistic models with two elements. First, a directed acyclic graph represents system variables as nodes and their dependencies as directed links. Second, conditional probability tables determine the probability of each state of each variable according to the states of its parent variables. We built a BBN composed of 31 nodes and 71 links using existing data, previous studies, expert knowledge, in the Netica software version 6.09 (Norsys Software Corp, n.d.. https://www.norsys.com/). All nodes and relationships were selected based either on their capacity to predict accurately grassland types, their importance in published statistical models or in the elicitation process used to build the BBN. The model output is the probability distribution of grassland annual biomass production, considering growth for three periods: spring to July, August and September (Figure 1). First, we used statistical relationships between agroclimatic variables and peak biomass growth from spring to July (Deléglise et al., 2019; Grigulis & Lavorel, 2020; Nettier et al., 2017). The data set we used to predict the first growth period used 12 consecutive years of measurements across 67 grassland plots from the nearby Haute-Romanche valley, representative of the six ecological types associated with different landscape position (Grigulis & Lavorel, 2020). Statistical models were established to link biomass production with several climate variables: minimal temperatures, maximal temperatures, mean temperatures, rainfall and growing degree day for several time periods sliced in months. These statistical relationships were fed into the BBN as equations to predict the biomass production during the first growth period (a full description of the statistical models used is available in the Supporting Information B). Second, because no quantitative data or published relationship were available for August and September growth, we used expert knowledge to build causal relationships and fill the conditional probability tables. One of the authors

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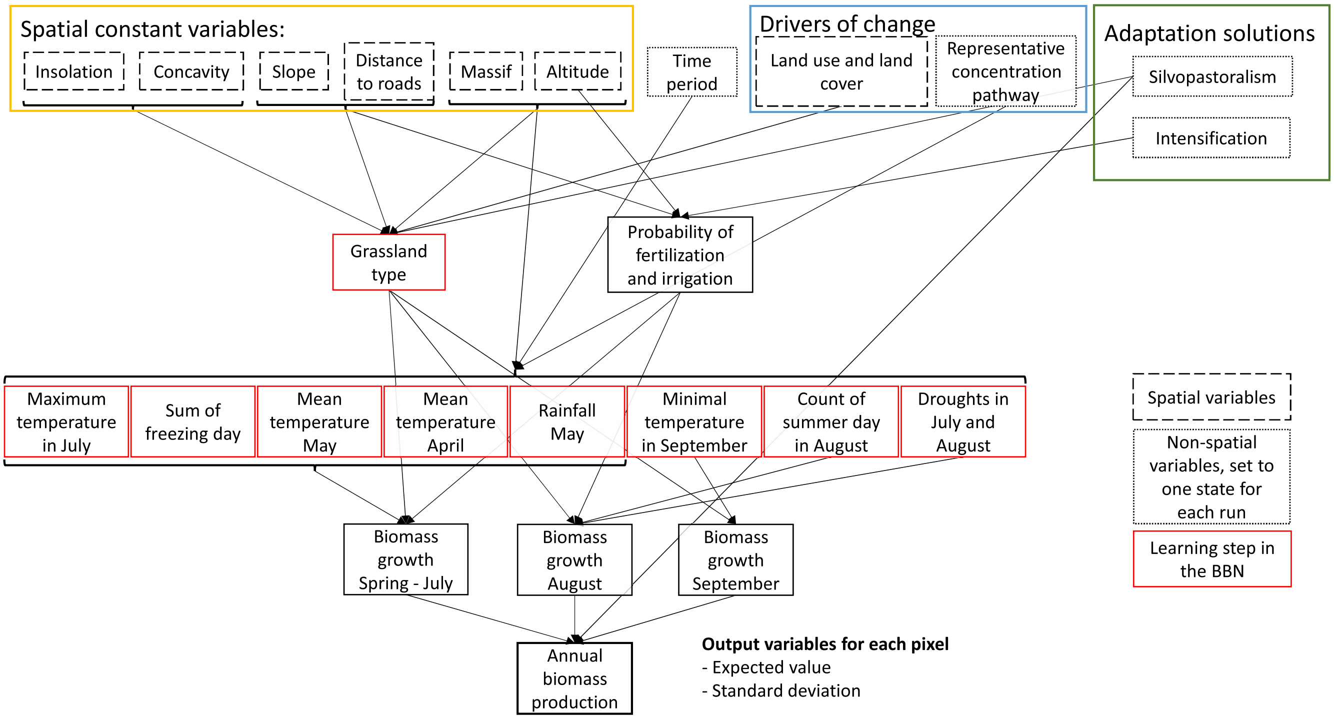

FIGURE 1 Simplified representation of the Bayesian Belief Network graph. Braces are used to group links between variables to simplify the numerous relationships in the graph.

participated in an elicitation process to build these relationships. We elicited experts by firstly, discussing which variables would likely be of prime importance regarding the specific growth period. Second, depending on the growth period, the expert could either produce an estimate of the biomass production according to the combination of several ranges of climate variables (August growth period) or directly propose simple quantitative relations between biomass production and the climate variable identified as the main constrain for biomass production (September growth period). This elicitation process was expanded to provide information on the production of highly fertile, low altitude grasslands during the first growth period and the production of recently encroached grassland used in the silvopastoralism scenario for all growth periods. The adaptative modelling framework of BBN enables information to be updated, and other experts could contribute to improving relations relying on an elicitation process (see Supporting Information B for a full description of the relations used to build the BBN).

The BBN was trained first to learn the distribution of each climate variable according to IPCC representative concentration pathways (RCP), time periods or climate model. The second training was required to complete the mapping of grassland types by learning their distribution according to spatial variables (altitude, slope, insolation, distance to the roads and concavity; Supporting Information C). Lastly, we used the ability of BBNs to explicitly capture uncertainties to assess annual variability in biomass production. This variability reflects the distributions of the climatic parameters that constrain production.

The modelled estimations for first growth were validated against 12 points of field monitoring in the study area. Predictions from the model and field measurements were highly correlated (r^2=0.88, *p* value=0.00014); see Supporting Information C for a complete description of the validation methodology. Estimates for the August and September growth periods would also need to be validated but no data was available.

2.4 | Scenarios of climate and land use and land cover change

To assess the impacts of climate change on grassland productivity, we used a climatic data set produced by the EUROCORDEX project and downscaled with the ADAMONT method for the specific Alpine context by altitudinal bands of 300 m and mountain massifs, including six massifs within our study site (Verfaillie et al., 2017). We selected two medium and high emission pathways RCP 4.5 and 8.5. We obtained data on future drought from the CLIMSEC data set (Habets et al., 2008; Soubeyroux et al., 2012; Vidal et al., 2010), particularly its Standardized Soil Wetness Index (SSWI) which maps future soil wetness anomalies compared to a reference period (here 1958–2008), with scenarios A2 and B1 associated, respectively, with RCP 4.5 and 8.5. To account for climate interannual variability, we extracted all relevant climatic variables for 30 consecutive years, in three time periods centred in 2020, 2050 and 2085. Those climate data sets were implemented into the BBN through learning so that the probabilistic distribution of each climate variable within the model fitted their distribution within the input data set.

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We built three contrasted future LULC scenarios from 2020 to 2085 with the CLUMPY model (Mazy & Longaretti, 2022). The CLUMPY model is an innovative model of land use and land cover change comprising a calibration-estimation module separate from a non-biased allocation module. It is calibrated by using time series of past LULC maps (Mazy & Longaretti, 2022). The model then calculates transition probabilities for each LULC class according to relevant spatial explanatory variables. Next, the model can produce maps of future LULC distributions according to information it learned during the calibration-estimation phase. This model has the benefits of being easy to use, proposing nonbiased allocation methods and producing scenarios of future LULC change either by adjusting manually the matrix of LULC transitions probabilities (used for the conservation and tourism scenarios) or by training the model on specific areas of the past time series (only used for the conservation scenario).

The scenarios were based on the 'Montagne 2040' report that explores potential future for specific alpine region and their associated narratives (Claveranne, 2013). The 'business-as-usual' scenario (BAU) extended the 2006–2016 observed trends. The 'conservation' scenario assumed: the expansion of protected areas, reduced support for agriculture and livestock farming and LULC transitions, that is, from grassland to shrub or forest, and from shrubland to forest (aka landscape encroachment). The 'tourism' scenario assumed the development of ski resorts and mass tourism in the valley, growing urbanization at low and middle altitude, and associated LULC transitions from grassland or shrubland to urban (see Supporting Information D). Scenarios of LULC change only considered broad categories of LULC: urban, forest, shrub and grassland (data set available: Elleaume, 2024a). To complement this, the model has a dedicated node that predicts the likely grassland type according to geomorphological and access parameters: insolation, terrain concavity, slope, distance to roads and altitude. We built the relationships used to predict the grassland type according to these variable through Bayesian learning (Heckerman, 1998) based on a data set containing information on the current distribution of grassland type in the study area (Bernard-Brunet & Bornard, 2004; Bornard & Dubost, 1992); for a description of the module predicting grassland types in the BBN, see Supporting Information C (data set available: Elleaume, 2024b).

The LULC scenario controls available grassland surfaces. Because the BBN was trained to predict grassland types depending on their location, we expected that LULC scenarios would affect biomass production differently as scenarios produced contrasted changes in the spatial distribution of grassland. In the BAU scenario, grasslands decreased slightly. In the conservation scenario, grassland areas decreased drastically, mostly at high altitudes where productivity is low. In the tourism scenario, grassland areas were moderately reduced largely at low and medium altitude, where biomass productivity is high (Figure 2).

2.5 | Adaptation solutions

We implemented two adaptation solutions to assess their capacity to compensate for the effect of scenarios or possibly increase total biomass production for future periods (2050 and 2085). Two common climate adaptation solutions in the Alps were assessed: understorey grazing (here referred as a 'Silvopastoralism' adaptation solution) and grassland fertilization and irrigation ('Intensification') (Nettier et al., 2017). For Silvopastoralism, we considered only recent transitions from grassland to shrub (<35 years), assuming that recent transitional shrublands still have an exploitable herbaceous layer (Devaux, 2016). This solution would expand the LULC categories considered suitable for grazing and therefore provide additional resources not grazed in the reference situation. The intensification solution is based on expanding current fertilization and irrigation practices. It was implemented in the network with two possible states: 'Lowland intensification' where only grasslands under 1400 m are irrigated and fertilized, and 'Wide intensification' where grassland may be fertilized and irrigated until 2000 m. The slopes and distance to the roads were set as a constrain to calculate the probability of a grassland being irrigated (see Supporting Information B for a full description of the nodes and the relations between variables).

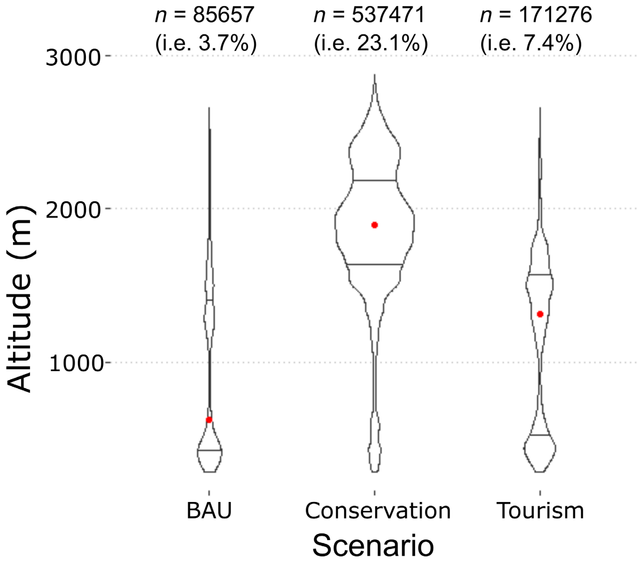

FIGURE 2 Grassland loss between 2020 and 2085 by scenarios and altitude. n indicates the total number of pixels of grassland losses and the associated percentage refers to transitions relative to the total site area. Lines refer to quartiles and the red dot to median value. Violin widths represent the total number of transitions under the three scenarios.

3 | RESULTS

3.1 | Baseline biomass production

Our model simulated an average biomass production of 348×10^3 kg.km^{-2}.year^{-1} across the Maurienne valley in 2020, with a strong altitudinal decrease in production (Figure 3). This value is substantially lower than the Alpine Convention area average (980×10^3 kg.km^{-2}.year^{-1}, Jäger et al., 2020) and explained by the Maurienne's steep

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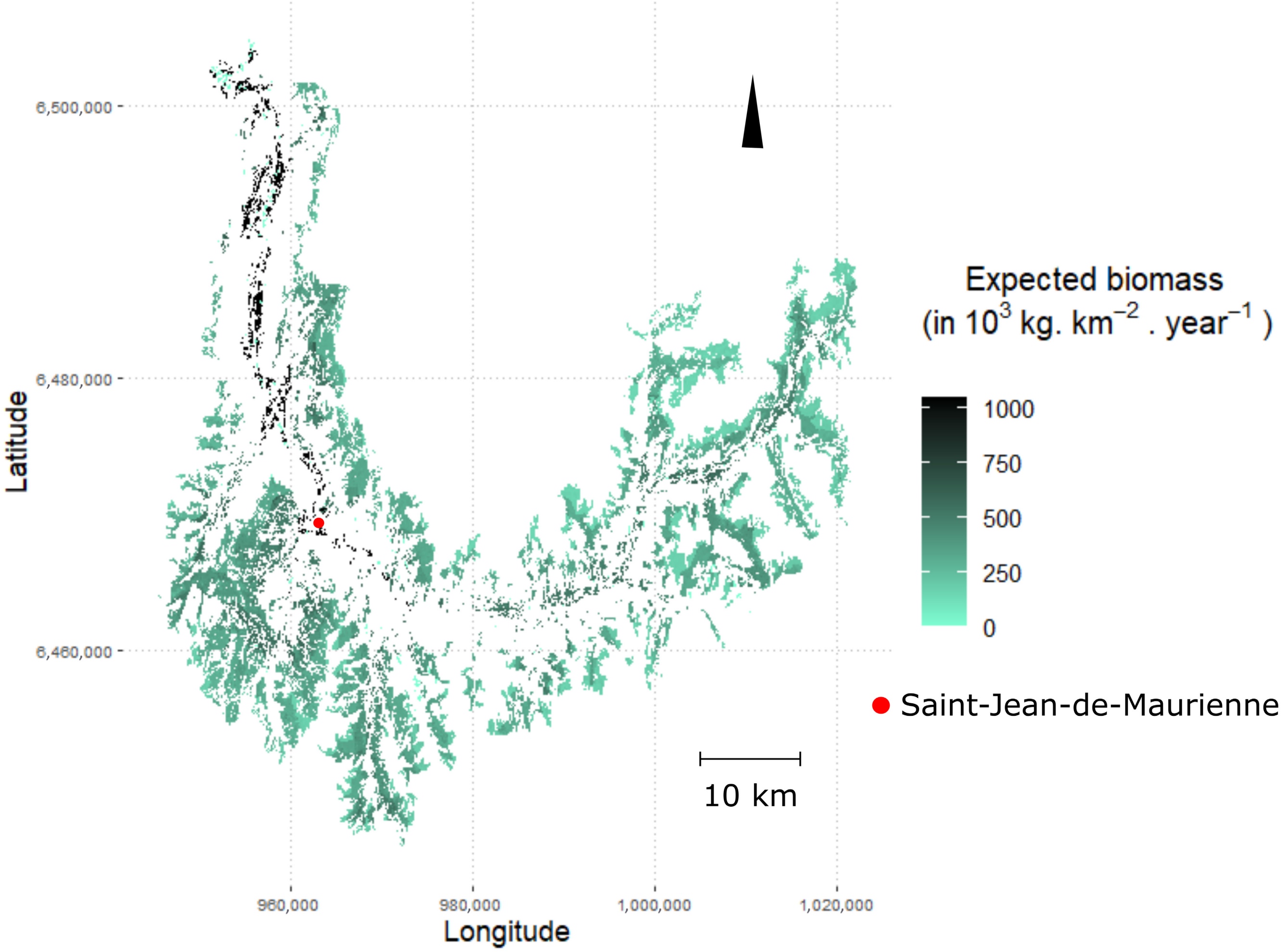

FIGURE 3 Potential biomass production for 2020 under current management.

terrain, where very few lowlands are available for intensively managed productive grassland. The flat lowlands in the western part of the valley (<800 m) produced 903×10^3 kg.km^{-2}.year^{-1}, contrasting with high-altitude locations (>2400 m) at 272×10^3 kg.km^{-2}.year^{-1} on average. Interannual variability was high for all grassland types (CV = 27%–77%; average: 56%). Predictability of biomass supply decreased from an average coefficient of variation of 45% for grasslands under 1400 m, to 55% at medium altitude (1400–2000 m) and 58% for higher altitude summer pastures (>2000 m).

3.2 | Response of total biomass production to future drivers of change without adaptation

Across combined climate and LULC scenarios, total annual grassland biomass production of the valley was mostly influenced by future LULC scenarios. LULC scenarios differed significantly in their effects on changes in biomass production between 2020 and 2085 (Table 1), reflecting their respective changes in grassland area (see Table 7: Supporting Information D). Accordingly, total biomass production was most reduced under the conservation scenario due to the large grassland reduction, with a statistically significant mean decrease of −28.3% of the total biomass as compared to BAU when averaging across RCP or time periods (*p*-value <0.05, see Supporting Information E). The tourism scenario decreased total biomass production somewhat less (−6.6%) than the conservation scenario (no significant difference with BAU; Supporting Information E), despite large reductions in high productivity grasslands at low and medium altitudes (Figure 2).

Climate change scenarios did not significantly impact total annual biomass production. The two climate scenarios did not differ significantly in their effects on total annual biomass between 2020 and 2085 (*p*-value >0.05, see Supporting Information E). By 2085, production tended to slightly increase under both RCP, as depicted by the BAU scenarios compared to the 2020 reference situation.

However, the negligible effects of climate change on total annual production mask very large disparities when examining seasonal growth periods (Figure 4). To tease out the effect of CC on future biomass production during the different growth periods, we firstly only considered the effect of CC while keeping current LULC. Climate change in 2085 modified the annual distribution of production, with increased production during the

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TABLE 1 Total biomass production across RCP, LULC scenarios and time periods assuming no adaptation solution. Change for each time period represents the relative difference with 2020.

		2020	2050			2085		
		_	BAU	Conservation	Tourism	BAU	Conservation	Tourism
RCP 4.5	Total production (10^6 kg)	31.04	31.32	22.45	29.33	32.08	22.46	29.01
	Change from 2020 (%)	_	0.9	−27.7	−5.5	3.4	−27.6	−6.5
RCP8.5	Total production (10^6 kg)	_	30.66	21.99	28.68	31.93	22.39	28.85
	Change from 2020 (%)	_	−1.2	−29.2	−7.6	2.9	−27.9	−7.1

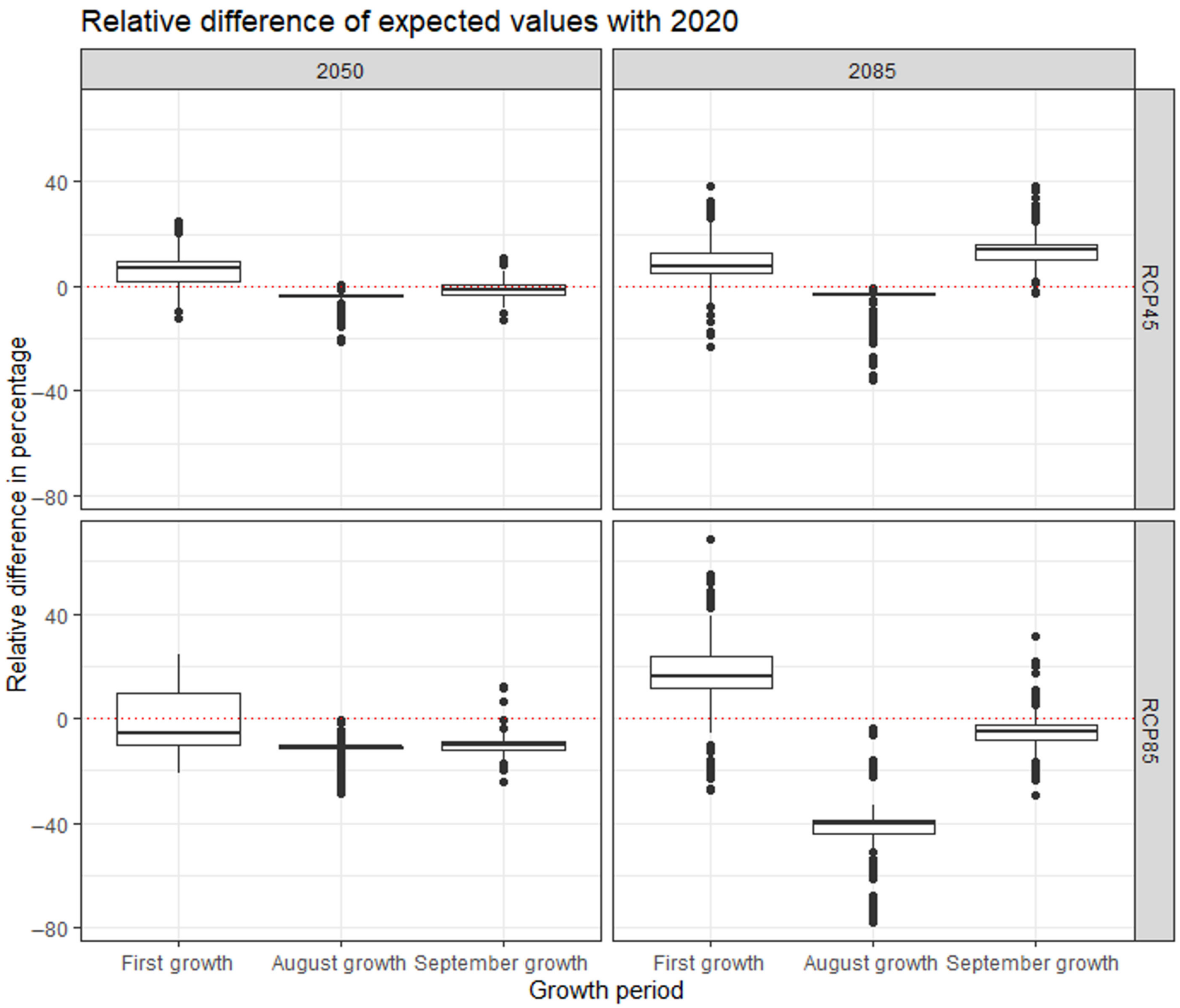

FIGURE 4 Relative difference in biomass production between the present and the 2050 and 2085 time periods across the three growth periods and under the two scenarios of climate change. Land use and land cover were considered as constant to only assess the effect of climate scenarios. Boxplot whiskers are calculated with 1.5*Interquartile range, the box upper, middle and bottom are, respectively, the last quartile, median and first quartile of the relative difference distribution.

first growth period for both RCP and a substantial loss in summer growth, especially under RCP 8.5 (mean: −40%). September growth was enhanced under RCP 4.5 and reduced under RCP 8.5. This phenological shift in the seasonal availability of biomass is a major threat to the pastoral system considering the high biomass demand for grazing during summer.

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3.3 | Adaptation solutions for coping with scenarios impacts

Adaptation based on an intensification of grassland management significantly increased biomass production in 2085 compared to 2020 (Supporting Information E). As future LULC scenario controls the area of recently transitioning shrubs (the surfaces exploited under the Silvopastoralism adaptation solution), we expected a significant interaction between LULC scenario and Silvopastoralism, but this was not the case (Supporting Information D). The Silvopastoralism solution was never sufficient to compensate for negative effects of climate or LULC changes in any scenario or RCP (Figure 5). Intensification solutions showed largest increases in total biomass in all scenarios, especially under the wide implementation, where fertilization and irrigation are extended to medium altitudes. Except for the conservation scenario, total biomass production increased in all cases of wide intensification.

Maintaining the current total production under the BAU trajectory would not require any adaptation solution under RCP 4.5, while the lowland intensification solution would be enough to maintain current production under RCP 8.5. No adaptation solution could prevent the loss of total biomass due to LULC change in the conservation scenario. Under the tourism scenario, production losses were only compensated by wide intensification. Under all LULC scenarios, lowland productive grasslands incurred the largest changes of biomass production. Extreme losses or gains were observed where transitions occurred from or to grassland.

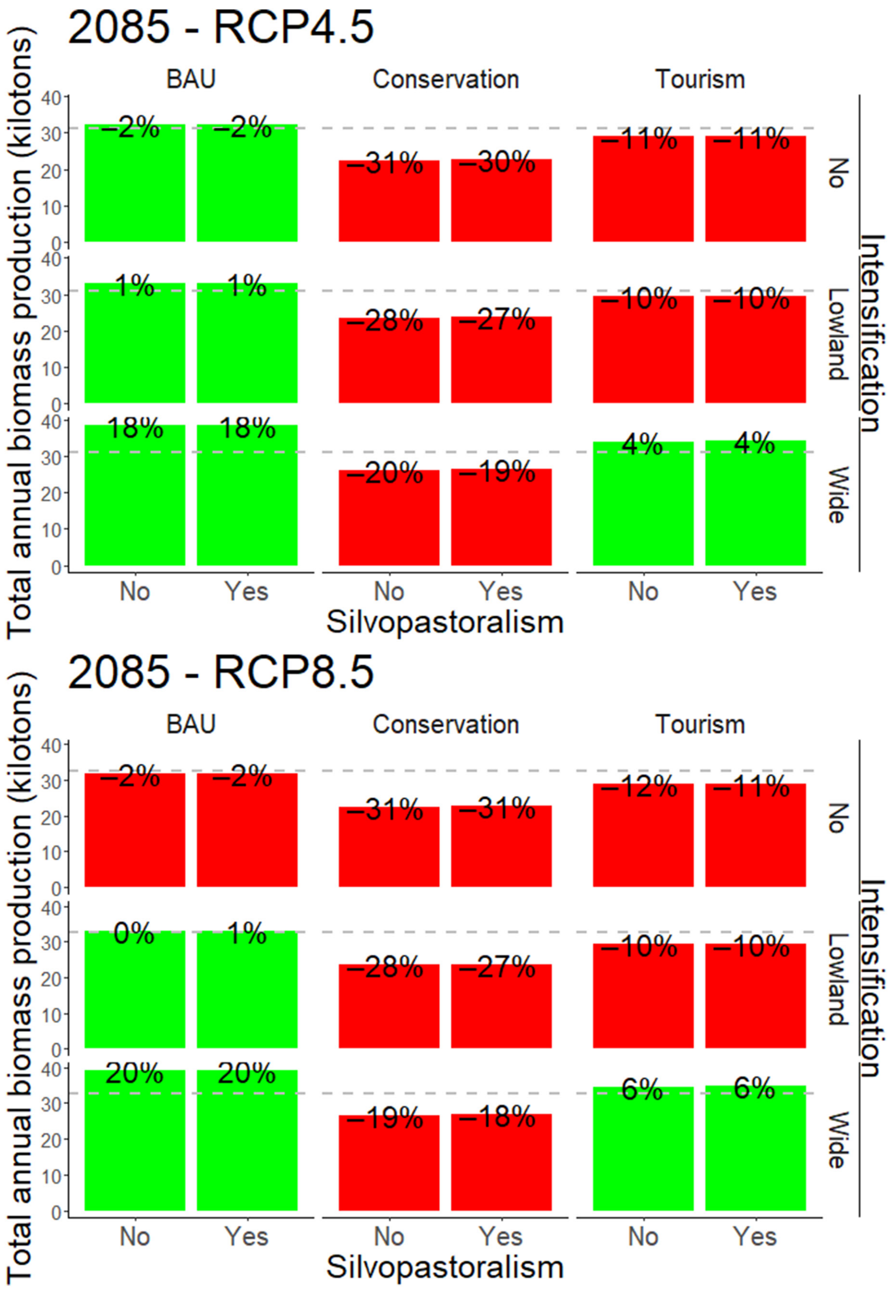

FIGURE 5 Total annual biomass production change across LULC scenario, RCP scenario and adaptation solutions. The grey line refers to the 2020 baseline value. Percentage labels indicate the relative difference in biomass production between 2020 and 2085. Colours indicate a positive (green) or (negative) change compared to 2020.

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3.4 | Efficiency of adaptation solutions

As each adaptation alternative is associated with different available areas of grassland, we evaluated their efficiency relative to the mobilized area for each time period and scenario (i.e. the newly available areas of shrub that can be grazed under the Silvopastoralism scenario and the area of grassland being fertilized and irrigated under the intensification scenario). As there were only very small differences between the two RCP in gains by unit area of adaptation solution, we present average gains per area across the two RCP (Table 2). Overall, when averaging across time periods and LULC scenarios intensification (66×10^3 kg per km^2 for lowland intensification, 64×10^3 kg per km^2 for wide intensification) was far more effective than silvopastoralism (48×10^3 kg per km^2; Table 2).

The efficiency of most combinations of LULC scenarios and adaptation solutions increased slightly over time. However, there were large drops in efficiency for the BAU scenario with lowland intensification and for the tourism scenario with both intensification solutions (Table 2). Under the tourism scenario, this was explained by the altitudinal distribution of grassland losses, with greatest grassland conversion of low altitude, highly productive grasslands and a substantial loss of medium altitude grassland between 2020 and 2085 (Figure 2). As a result, only a diminishing portion of medium to high productivity grasslands remained, which reduced the efficiency of intensification whatever its extent. The conservation of medium altitude grasslands in BAU underpinned the efficiency of wide intensification. Lastly, the tourism scenario showed the highest efficiency for any adaptation solution between 2050 and 2085, allowing silvopastoralism to reach the same efficiency as lowland intensification by 2085 (Table 2). The local implementation of silvopastoralism may generate high gains, especially if deployed over recently transitioning productive grasslands.

3.5 | Effects of climate change and adaptation solutions on interannual variability of biomass production

All future LULC and climate scenarios increased 30-year interannual variability of biomass production whatever the adaptation solution, especially by 2085 (Figure 6). By 2085, increases in interannual variability were predicted for more than 90% of the grassland area under RCP 8.5 and for approx. 75% of the area under RCP 4.5, generating very high uncertainty for the pastoral system. The BAU and tourism scenarios showed very similar trends across time and RCP. Under the conservation scenario, interannual variability increased in a smaller area than under the other two scenarios. Furthermore, this scenario substantialy decreased interannual variability overall. None of the two silvopastoralism solutions changed variability whatever the RCP or period. In contrast, increased biomass production under intensification was associated with increased variability.

4 | DISCUSSION

4.1 | Effects of climate and land use land cover scenarios on biomass production

Our simulations revealed that LULC change will affect future grassland biomass production in the Maurienne valley much more than climate change, due to considerable losses in the area available for fodder production. LULC transitions and landscape modifications have been identified as a major driver of change for past grassland biomass production (Kanianska et al., 2014; Schirpke et al., 2017) and we demonstrate that they are likely to be as critical to its future trajectory. Each future LULC scenario produced a specific pattern of grassland conversion across altitude and the BBN was able to simulate the likely consequences for the overall biomass of the valley under the several assumptions underlying the future scenarios. We selected contrasting scenarios to test boundary cases for the future of the valley (Thompson et al., 2020). For example, the conservation scenario is based on the premise that almost the entire study site becomes a protected area with extremely limited support for agriculture, a scenario that has been considered in the Montagne 2040 futuring exercise by the Rhône-Alpes region (Claveranne, 2013). This assumption may be improbable in the current context, but a more limited but significant extension of protected areas is credible. Our approach enabled us to simulate how these assumptions would firstly translate spatially in terms of grassland conversion, and then how overall biomass production would respond to this assumption. Each scenario is linked with narratives underpinned by different assumptions for the future (Vannier et al., 2019). These narratives

TABLE 2 Efficiency of adaptation solutions across time periods and future land use and land cover scenarios. Gains were averaged over the two RCP scenarios.

	2050			2085		
	BAU	Conservation	Tourism	BAU	Conservation	Tourism
Silvopastoralism (10^3 kg biomass per km^2 of implementation)	56.7	31.8	38.9	61.1	34.4	51.9
Lowland intensification (10^3 kg biomass per km^2 of implementation)	76.4	63.9	68	73.7	60.4	52.7
Wide intensification (10^3 kg biomass per km^2 of implementation)	61.3	59.3	58.6	65.7	62.7	61.3

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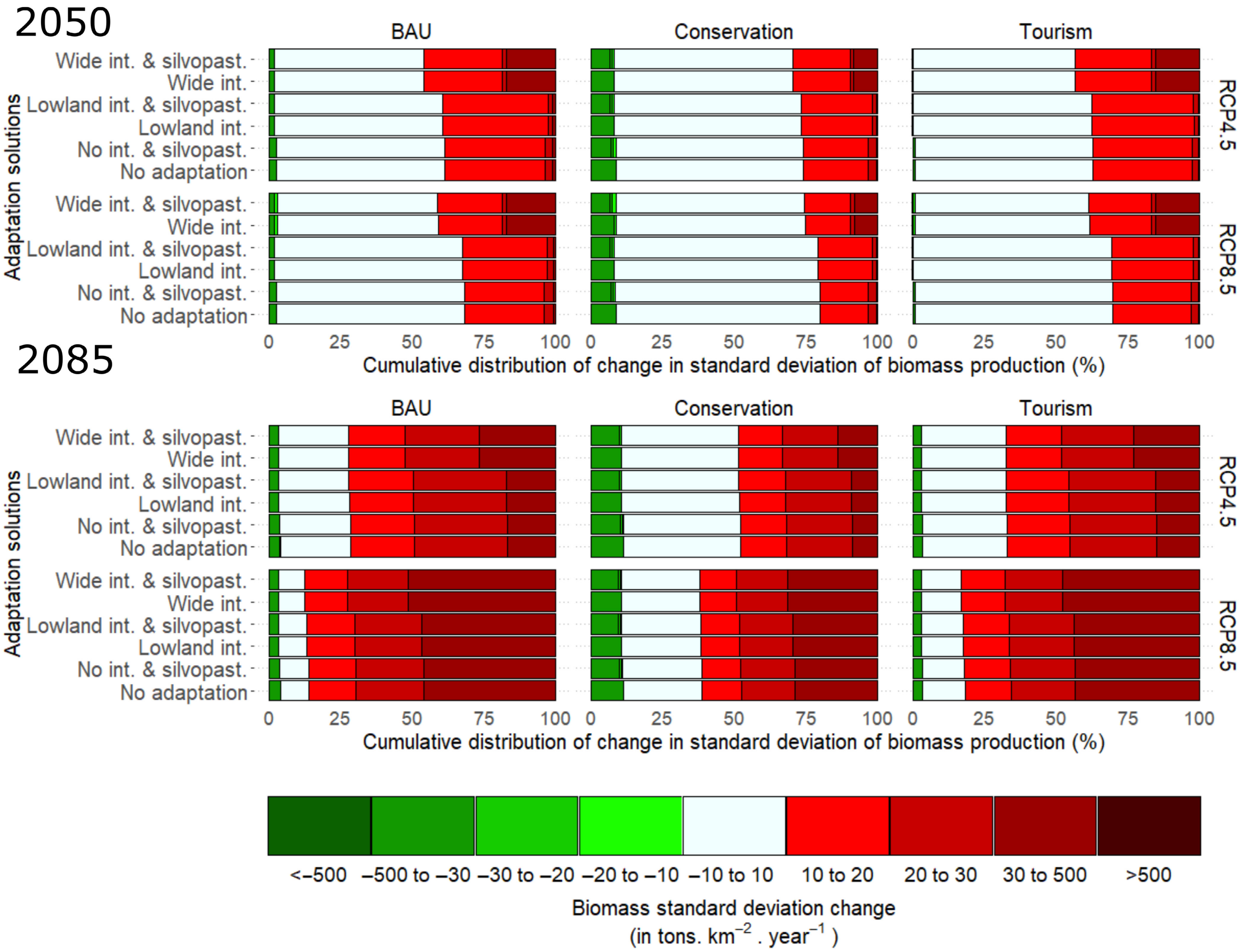

FIGURE 6 Cumulative distribution of change in annual variability of biomass production (expressed as absolute change in standard deviation between the future and 2020 with no adaptation solutions) across RCP, time windows and adaptation solutions. Int., Intensification; Silvopast., silvopastoralism.

are themselves linked to values that condition LULC management. Under the conservation scenario, biomass production is no longer a priority, while regulating and non-material (symbolic, cultural and recreational) NCP linked to the new shrublands and forests are more valued. Under the tourism scenario, the valley also faces a limited encroachment compared to the conservation scenario but still, the new surfaces of shrub and forest, would be valued for their supplies of non-material NCP linked to recreation.

Consistent with earlier projections for our study site, total potential production only slightly increased under RCP 4.5 and slightly decreased under RCP 8.5 (Jäger et al., 2020). Importantly, we revealed that climate change is expected to modify the seasonal pattern of biomass production with increased growth to peak vegetation and reduced August and September regrowth, especially under the high emissions pathway (RCP 8.5) and by 2085. These results concur with an analysis over 35 years in a Tibetan alpine grassland showing that while grassland phenology shifted due to climate change, total biomass production remained unchanged due to summer drought (Wang et al., 2020). The projected seasonal shift in biomass growth is consistent with statistical models for Switzerland showing increased production to peak biomass due to early snow melt (Jonas et al., 2008; Rammig et al., 2010) and with observed negative effects of higher temperatures and drought intensity and frequencies in August and September (Corona-Lozada et al., 2019; De Boeck et al., 2016). These findings highlight the need to include different growth periods in predictive studies of climate change impacts on grasslands (Choler, 2015; Wang et al., 2020). This temporal shift in production may cause demand to be desynchronized from supply unless pastoral and farming systems adapt to low fodder supply during summer and autumn. Solutions to respond to this summer shortage include: reducing stocking, compensating with increased fodder storage during favourable years, grazing areas that are not currently exploited (too remote or with very poor vegetation types) or purchasing external fodder, an adaptation that is restricted under current PDO rules (Grosinger et al., 2021) and would need to evolve (Darnhofer et al., 2017). Lastly, interannual variability of biomass production increased across all scenarios and adaptation solutions, posing a further threat to the viability of the livestock production system.

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When combining these climate effects with large losses in production from LULC changes, the current livestock system of the Maurienne valley could be highly threatened, with considerable losses in biomass production especially under the most extreme RCP 8.5. Still, those two drivers of change are not of the same nature: Contrary to landscape changes and LULC transitions, actions within the region are marginal for mitigating climate change. Although related to external drivers, LULC is mostly constrained by endogenous factors: local natural processes, farmers practices and responses to economic opportunities, local governance, environmental management or urban planning, all of which interact over time to control locally how LULC transitions occur and shape the overall trajectory of landscape change (Grosinger et al., 2022). They and their interactions over time form a set of potential levers for the adaptation of the forage system (Opdam et al., 2009).

4.2 | Adaptation solutions to climate and LULC change

The silvopastoralism adaptation was never sufficient to offset negative impacts on grassland biomass production. However, this solution showed the highest gains in efficiency over time, especially under the tourism scenario where large gains of transitional shrublands occurred at low altitude on highly productive grasslands. Silvopastoralism may thus be part of adaptation solutions, although it requires transforming production systems from bovine to caprine livestock with large implications for feeding requirements and the overall economic model. Further assessments of the balance between the supply and the demand of biomass could help to better understand how the overall viability of the livestock systems could be modified. As the intensification solution substantially increased biomass production, it could be important to offset climate change impacts. Intensification would however entail considerable investments, especially because a wide application would require irrigation and fertilization where slope or remoteness increases costs. This solution would thus need to be deployed with care, especially considering that efficiency was greatest when restricted to productive grasslands. It would also come with high environmental risks from water pollution by fertilizers and water overharvesting by irrigation (Botter et al., 2021) while decreasing in plant diversity (Stampfli et al., 2018; Tello-García et al., 2020). Irrigation would also potentially create conflicts on water sharing in a context of increased drought frequency and summer heatwaves (Jäger et al., 2020a; Meisser et al., 2013). Lastly, a limitation of the implementation of the intensification adaptation solution in our model and this study is that we did not consider the interaction of fertilization and summer droughts on grasslands. The joint effects of irrigation and droughts were implemented simply by considering that irrigation offsets the negative effects of drought, in line with observations and previous trait-based modelling in the nearby Haute-Romanche valley (Lamarque et al., 2014). It has been shown that the addition of nutrients increases the detrimental effects of drought on above biomass production in grasslands (Van Sundert et al., 2021), but that these interactions between nitrogen application and drought are also highly variables in space (Hartmann et al., 2013) and depend on specific plant communities (Carlsson et al., 2017; De Boeck et al., 2018). In particular, detrimental effects have been reported in higher fertility levels than those relevant to mountain grasslands like the Maurienne valley's (Zwicke et al., 2013).

An adaptation strategy for the Maurienne valley would need to define spatial and temporal priorities and how different adaptation options are combined. For example, a gradual deployment of silvopastoralism could target areas of shrubland expansion. According to the intensity of climate change and to the magnitude of LULC change, lowland intensification could subsequently support high production gains. Still, those solutions must be co-developed with local stakeholders to avoid potential environmental conflicts. Lastly, simulations showed that the efficiency of adaptation solutions is not necessarily maintained or increased over time but depends largely on LULC change and more specifically on the altitudinal distribution of grassland conversion. Therefore, understanding likely grassland conversions is essential for planning adaptation of the forage system. Adaptive management at the landscape scale could allow regular updates of knowledge and decisions regarding the system as a whole, its trajectory and the governance of adaptation solutions (Rist et al., 2013). Our analysis assessed the effects of only two adaptation solutions but others should be analysed, including the introduction of seed mixtures with drought-resistant species (Frenck et al., 2018; Peratoner et al., 2018). Further research could also account for adaptation costs in assessing the efficiency of solutions. Silvopastoralism would require a switch in herd composition with an initial financial and capability investment but limited later costs, contrary to intensification where both initial and long-term investments would be required.

4.3 | Bayesian Belief Network modelling for capturing uncertainties

BBN can be a limiting modelling framework as they do not support the analysis of feedback loops or spatial interactions over close pixels (Forio et al., 2020; Landuyt et al., 2013). In this study, a feedback loop was never necessary within the graph supporting the links between the variables representing the biomass production process, so this first limitation of the BBN was not a concern. Second, the absence of pixel interactions inside the modelling approach can produce local discrepancies among specific areas, but those discrepancies are due to the structure of the data set used as input variable. Our climate data set is structured by altitude slices of 300 m, with potential discrepancies among close pixels at the edge of each slice. Still, as BBN can always be updated with new information and data. This limitation could be overcome by using downscaled climate data sets at higher spatial resolution as input variables when those become available for the French Alps.

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The probabilistic nature of BBN is a major advantage for modelling NCP as it quantifies uncertainties in ecosystem service assessments (Landuyt et al., 2013). Assessing annual variability of biomass growth is crucial as year-to-year fluctuations can strongly affect production systems (Albrich et al., 2018). While mean biomass production was driven more by LULC than climate scenarios, its annual variability was more sensitive to climate than LULC. We found that the uncertainty of biomass production will increase especially under the extreme climate change scenario (RCP 8.5) and in the far future (2085). Although intensification significantly increases biomass production, it also increases variability, more so than silvopastoralism. This reduced resistance to climate variability and extreme events is known for intensively managed grasslands (Ingrisch et al., 2018) but also in grasslands with moderate management intensity (Grigulis & Lavorel, 2020). Our uncertainty analysis could consider other sources, including LULC or climate models (Hamel & Bryant, 2017) and the structure of our own model (Ascough et al., 2008). Also, implementing climatic drivers to the module predicting grassland type within our BBN could improve the assessment of climate change effects by accounting for potential compositional change and transformation to alternative states (Kohler et al., 2017). Integrating NCP demand into the BBN could also enable the analysis of future NCP flows and thus test adaptation solutions based on the spatial matching of NCP supply and demand (Schirpke et al., 2019). Lastly, BBNs have been shown to be good support tools for adaptive management given their ability to continuously update knowledge or information within the model (Nyberg et al., 2006).

5 | CONCLUSIONS

We combined for the first time published statistical relationships and complementary expert knowledge into a BBN to evaluate the effects of future LULC and climate change on grassland biomass production, its seasonal and interannual variability. Our analysis in the Maurienne valley revealed stronger impacts on total biomass production of the future LULC trajectory than of climate change. Still, climate change would significantly reduce biomass production under the high emission scenario and especially modify its seasonal growth pattern, where August regrowth may drastically be reduced due to more frequent and intense drought events. In addition, the interannual variability of biomass production will likely increase in the future, especially under the high emission scenario. These changes are expected to threaten the current grass-based pastoral system and require adapting PDO rules which limit the external purchase of fodder. The two adaptation solutions tested in our analysis showed contrasted results with intensification supporting an increase in total production contrary to silvopastoralism. Still, both solutions showed comparable efficiencies and may be considered as complementary under adaptation pathways. Further developing such Bayesian models could support territorial adaptation planning and adaptive management through co-production processes between researchers and stakeholders.

AUTHOR CONTRIBUTIONS

Nicolas Elleaume was involved in conceptualization, methodology, software, formal analysis, model validation, data visualization, writing—original draft; Bruno Locatelli was involved in conceptualization, methodology, software, formal analysis, writing—review & editing, project administration, supervision, funding acquisition; Emilie Crouzat was involved in writing—review & editing; Johan Oszwald was involved in project administration, supervision, funding acquisition; Sandra Lavorel was involved in conceptualization, formal analysis, writing—review & editing, project administration, supervision, funding acquisition.

CONFLICT OF INTEREST STATEMENT

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

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.pg4f4qrxd (Elleaume, 2024a) and https://doi.org/10.5061/dryad.83bk3jb0h (Elleaume, 2024b).

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REFERENCES

Aguilera, P. A., Fernández, A., Fernández, R., Rumí, R., & Salmerón, A. (2011). Bayesian networks in environmental modelling. *Environmental Modelling & Software*, *26*(12), 1376–1388. https://doi.org/10.1016/j.envsoft.2011.06.004

Albrich, K., Rammer, W., Thom, D., & Seidl, R. (2018). Trade-offs between temporal stability and level of forest ecosystem services provisioning under climate change. *Ecological Applications*, *28*(7), 1884–1896. https://doi.org/10.1002/eap.1785

Ascough, J. C., Maier, H. R., Ravalico, J. K., & Strudley, M. W. (2008). Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecological Modelling*, *219*(3), 383–399. https://doi.org/10.1016/j.ecolmodel.2008.07.015

Battaglini, L., Bovolenta, S., Gusmeroli, F., Salvador, S., & Sturaro, E. (2014). Environmental sustainability of alpine livestock farms. *Italian Journal of Animal Science*, *13*(2), 3155. https://doi.org/10.4081/ijas.2014.3155

Ben-Gal, I. (2008). Bayesian networks. In F. Ruggeri, R. S. Kenett, & F. W. Faltin (Eds.), *Encyclopedia of statistics in quality and reliability* (p. eqr089). John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470061572.eqr089

Bernard-Brunet, J., & Bornard, A. (2004). Outils pour les diagnostics pastoraux et la gestion des milieux pâturés d'altitude. *Sciences Eaux & Territoires*, (Spécial Ingénieries-EAT-19), 69–80. https://revue-set.fr/article/view/607

Bornard, A., & Dubost, M. (1992). Diagnostic agro-écologique de la végétation des alpages laitiers des Alpes du Nord humides: Établissement et utilisation d'une typologie simplifiée. *Agronomie*, *12*(8), 581–599. https://doi.org/10.1051/agro:19920802

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Botter, M., Zeeman, M., Burlando, P., & Fatichi, S. (2021). Impacts of fertilization on grassland productivity and water quality across the European Alps under current and warming climate: Insights from a mechanistic model. *Biogeosciences*, *18*(6), 1917–1939. https://doi.org/10.5194/bg-18-1917-2021

Bruley, E., Locatelli, B., & Lavorel, S. (2021). Nature's contributions to people: Coproducing quality of life from multifunctional landscapes. *Ecology and Society*, *26*(1), art12. https://doi.org/10.5751/ES-12031-260112

Calanca, P. (2007). Climate change and drought occurrence in the alpine region: How severe are becoming the extremes? *Global and Planetary Change*, *57*(1–2), 151–160.

Carlson, B. Z., Corona, M. C., Dentant, C., Bonet, R., Thuiller, W., & Choler, P. (2017). Observed long-term greening of alpine vegetation—A case study in the French Alps. *Environmental Research Letters*, *12*(11), 114006. https://doi.org/10.1088/1748-9326/aa84bd

Carlsson, M., Merten, M., Kayser, M., Isselstein, J., & Wrage-Mönnig, N. (2017). Drought stress resistance and resilience of permanent grasslands are shaped by functional group composition and N fertilization. *Agriculture, Ecosystems & Environment*, *236*, 52–60. https://doi.org/10.1016/j.agee.2016.11.009

Choler, P. (2015). Growth response of temperate mountain grasslands to interannual variations of snow cover duration. *Biogeosciences Discussions*, *12*(3), 3025–3055. https://doi.org/10.5194/bgd-12-3025-2015

Claveranne, J.-P. (2013). *La montagne en 2040*. CESER. http://deliberations.rhonealpes.fr/RecueilsPDF/2013/CESER%20Rapport%20Section/2013_03%20montagne%202040%20.PDF

Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., & Böhner, J. (2015). System for automated geoscientific analyses (SAGA) v. 2.1.4. *Geoscientific Model Development*, *8*, 1991–2007. https://doi.org/10.5194/gmd-8-1991-2015

Corona-Lozada, M. C., Morin, S., & Choler, P. (2019). Drought offsets the positive effect of summer heat waves on the canopy greenness of mountain grasslands. *Agricultural and Forest Meteorology*, *276–277*, 107617. https://doi.org/10.1016/j.agrformet.2019.107617

Darnhofer, I., Schermer, M., Steinbacher, M., Gabillet, M., & Daugstad, K. (2017). Preserving permanent mountain grasslands in Western Europe: Why are promising approaches not implemented more widely? *Land Use Policy*, *68*, 306–315.

De Boeck, H. J., Bassin, S., Verlinden, M., Zeiter, M., & Hiltbrunner, E. (2016). Simulated heat waves affected alpine grassland only in combination with drought. *New Phytologist*, *209*(2), 531–541. https://doi.org/10.1111/nph.13601

De Boeck, H. J., Bloor, J. M. G., Kreyling, J., Ransijn, J. C. G., Nijs, I., Jentsch, A., & Zeiter, M. (2018). Patterns and drivers of biodiversity–stability relationships under climate extremes. *Journal of Ecology*, *106*(3), 890–902.

Deléglise, C., Dodier, H., Garde, L., François, H., Arpin, I., & Nettier, B. (2019). A method for diagnosing summer mountain pastures' vulnerability to climate change, developed in the French Alps. *Mountain Research and Development*, *39*(2), D27–D41.

Della Chiesa, S., Bertoldi, G., Niedrist, G., Obojes, N., Endrizzi, S., Albertson, J. D., Wohlfahrt, G., Hörtnagl, L., & Tappeiner, U. (2014). Modelling changes in grassland hydrological cycling along an elevational gradient in the Alps. *Ecohydrology*, *7*(6), 1453–1473. https://doi.org/10.1002/eco.1471

Dessai, S., & Hulme, M. (2004). Does climate adaptation policy need probabilities? *Climate Policy*, *4*(2), 107–128. https://doi.org/10.1080/14693062.2004.9685515

Devaux, C. (2016). *Résilience des services écosystémiques à l'échelle du paysage: Un cadre conceptuel et une analyse pour un socio-écosystème de montagne*. Université Grenoble Alpes.

Egarter Vigl, L., Schirpke, U., Tasser, E., & Tappeiner, U. (2016). Linking long-term landscape dynamics to the multiple interactions among ecosystem services in the European Alps. *Landscape Ecology*, *31*(9), 1903–1918. https://doi.org/10.1007/s10980-016-0389-3

Elleaume, N. (2024a). Data from: Biomass production at 2085 horizon for the Maurienne valley (French Alps) estimated using a Bayesian belief network. *Dryad Digital Repository* https://doi.org/10.5061/dryad.pg4f4qrxd

Elleaume, N. (2024b). Data from: Land use and land cover scenarios for the Maurienne valley (French Alps) at 2085 horizon produced using CLUMPY model. *Dryad Digital Repository* https://doi.org/10.5061/dryad.83bk3jb0h

Forio, M. A. E., Villa-Cox, G., van Echelpoel, W., Ryckebusch, H., Lock, K., Spanoghe, P., Deknock, A., de Troyer, N., Nolivos-Alvarez, I., Dominguez-Granda, L., Speelman, S., & Goethals, P. L. M. (2020). Bayesian belief network models as trade-off tools of ecosystem services in the Guayas River basin in Ecuador. *Ecosystem Services*, *44*, 101124. https://doi.org/10.1016/j.ecoser.2020.101124

Frenck, G., Leitinger, G., Obojes, N., Hofmann, M., Newesely, C., Deutschmann, M., Tappeiner, U., & Tasser, E. (2018). Community-specific hydraulic conductance potential of soil water decomposed for two Alpine grasslands by small-scale lysimetry. *Biogeosciences*, *15*(4), 1065–1078.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., & Stoffel, M. (2014). 21st century climate change in the European Alps—A review. *Science of the Total Environment*, *493*, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050

Grafius, D. R., Corstanje, R., Warren, P. H., Evans, K. L., Norton, B. A., Siriwardena, G. M., Pescott, O. L., Plummer, K. E., Mears, M., Zawadzka, J., Richards, J. P., & Harris, J. A. (2019). Using GIS-linked Bayesian belief networks as a tool for modelling urban biodiversity. *Landscape and Urban Planning*, *189*, 382–395. https://doi.org/10.1016/j.landurbplan.2019.05.012

GRASS Development Team. (2017). *Geographic resources analysis support system (GRASS GIS) software, version 7.2*. Open Source Geospatial Foundation. http://grass.osgeo.org

Grigulis, K., & Lavorel, S. (2020). Simple field-based surveys reveal climate-related anomalies in mountain grassland production. *Ecological Indicators*, *116*, 106519.

Grosinger, J., Grigulis, K., Elleaume, N., Buclet, N., & Lavorel, S. (2022). Community-based institutions shape cheese Co-production in a French Alpine Valley. *Mountain Research and Development*, *42*(3), R25–R34.

Grosinger, J., Vallet, A., Palomo, I., Buclet, N., & Lavorel, S. (2021). Collective capabilities shape the co-production of nature's contributions to people in the alpine agricultural system of the Maurienne valley, France. *Regional Environmental Change*, *21*(4), 1–17.

Habets, F., Boone, A., Champeaux, J. L., Etchevers, P., Franchistéguy, L., Leblois, E., Ledoux, E., le Moigne, P., Martin, E., Morel, S., Noilhan, J., Quintana Seguí, P., Rousset-Regimbeau, F., & Viennot, P. (2008). The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France. *Journal of Geophysical Research: Atmospheres*, *113*(D6), D06113. https://doi.org/10.1029/2007JD008548

Hamel, P., & Bryant, B. P. (2017). Uncertainty assessment in ecosystem services analyses: Seven challenges and practical responses. *Ecosystem Services*, *24*, 1–15. https://doi.org/10.1016/j.ecoser.2016.12.008

Hartmann, A. A., Barnard, R. L., Marhan, S., & Niklaus, P. A. (2013). Effects of drought and N-fertilization on N cycling in two grassland soils. *Oecologia*, *171*(3), 705–717. https://doi.org/10.1007/s00442-012-2578-3

Heckerman, D. (1998). A tutorial on learning with Bayesian networks. In M. I. Jordan (Ed.), *Learning in graphical models* (pp. 301–354). Springer Netherlands. https://doi.org/10.1007/978-94-011-5014-9_11

Herrero, M., Addison, J., Bedelian, C., Carabine, E., Havlík, P., Henderson, B., Van De Steeg, J., & Thornton, P. K. (2016). Climate change and pastoralism: impacts, consequences and adaptation: -EN- -FR- Le changement climatique et le pastoralisme: effets, conséquences

13652664, 2024, 6, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.14655 by Cochrane France, Wiley Online Library on [09/07/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

et adaptation -ES- Cambio climático y pastoreo: efectos directos, repercusiones y adaptación. *Revue Scientifique et Technique de l'OIE*, *35*(2), 417–433. https://doi.org/10.20506/rst.35.2.2533

Hofierka, J., & Ri, M. (2002). The solar radiation model for Open source GIS: Implementation and applications. In *Proceedings of the Open Source GIS-GRASS Users Conference* [Preprint].

IGN. (2001). *BD ALTI®|Géoservices*. https://geoservices.ign.fr/bdalti

Ingrisch, J., Karlowsky, S., Anadon-Rosell, A., Hasibeder, R., König, A., Augusti, A., Gleixner, G., & Bahn, M. (2018). Land use alters the drought responses of productivity and CO_2 fluxes in mountain grassland. *Ecosystems*, *21*(4), 689–703. https://doi.org/10.1007/s10021-017-0178-0

Iwahashi, J., & Pike, R. J. (2007). Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature. *Geomorphology*, *86*(3), 409–440. https://doi.org/10.1016/j.geomorph.2006.09.012

Jäger, H., Peratoner, G., Tappeiner, U., & Tasser, E. (2020). Grassland biomass balance in the European Alps: Current and future ecosystem service perspectives. *Ecosystem Services*, *45*, 101163.

Jonas, T., Rixen, C., Sturm, M., & Stoeckli, V. (2008). How alpine plant growth is linked to snow cover and climate variability. *Journal of Geophysical Research: Biogeosciences*, *113*(G3), G0313. https://doi.org/10.1029/2007JG000680

Kanianska, R., Kizeková, M., Nováček, J., & Zeman, M. (2014). Land-use and land-cover changes in rural areas during different political systems: A case study of Slovakia from 1782 to 2006. *Land Use Policy*, *36*, 554–566. https://doi.org/10.1016/j.landusepol.2013.09.018

Kohler, M., Devaux, C., Grigulis, K., Leitinger, G., Lavorel, S., & Tappeiner, U. (2017). Plant functional assemblages as indicators of the resilience of grassland ecosystem service provision. *Ecological Indicators*, *73*, 118–127.

Lamarque, P., Lavorel, S., Mouchet, M., & Quétier, F. (2014). Plant trait-based models identify direct and indirect effects of climate change on bundles of grassland ecosystem services. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(38), 13751–13756.

Landuyt, D., Broekx, S., D'hondt, R., Engelen, G., Aertsens, J., & Goethals, P. L. M. (2013). A review of Bayesian belief networks in ecosystem service modelling. *Environmental Modelling & Software*, *46*, 1–11. https://doi.org/10.1016/j.envsoft.2013.03.011

Lavorel, S., Bayer, A., Bondeau, A., Lautenbach, S., Ruiz-Frau, A., Schulp, N., Seppelt, R., Verburg, P., Teeffelen, A., Vannier, C., Arneth, A., Cramer, W., & Marba, N. (2017). Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches. *Ecological Indicators*, *74*, 241–260. https://doi.org/10.1016/j.ecolind.2016.11.015

Lavorel, S., Grigulis, K., Leitinger, G., Kohler, M., Schirpke, U., & Tappeiner, U. (2017). Historical trajectories in land use pattern and grassland ecosystem services in two European alpine landscapes. *Regional Environmental Change*, *17*(8), 2251–2264. https://doi.org/10.1007/s10113-017-1207-4

Mastrotheodoros, T., Pappas, C., Molnar, P., Burlando, P., Manoli, G., Parajka, J., Rigon, R., Szeles, B., Bottazzi, M., Hadjidoukas, P., & Fatichi, S. (2020). More green and less blue water in the Alps during warmer summers. *Nature Climate Change*, *10*(2), 155–161. https://doi.org/10.1038/s41558-019-0676-5

Mazy, F.-R., & Longaretti, P.-Y. (2022). A formally and algorithmically efficient LULC change model-building environment. *arXiv:2203.17078 [stat]* [Preprint]. http://arxiv.org/abs/2203.17078.

McCann, R. K., Marcot, B. G., & Ellis, R. (2006). *Bayesian belief networks: Applications in ecology and natural resource*. p. 10.

Meisser, M., Deléglise, C., Mosimann, E., Signarbieux, C., Mills, R., Schlegel, P., Buttler, A., & Jeangros, B. (2013). Effects of a severe drought on a permanent meadow in the Jura mountains. *Agrarforschung Schweiz*, *4*(11/12), 476–483.

Nettier, B., Dobremez, L., Lavorel, S., & Brunschwig, G. (2017). Resilience as a framework for analyzing the adaptation of mountain summer pasture systems to climate change. *Ecology and Society*, *22*(4). https://www.jstor.org/stable/26799004

Norsys Software Corp. (n.d.). Bayes Net Software. https://www.norsys.com/

Nyberg, J. B., Marcot, B. G., & Sulyma, R. (2006). Using Bayesian belief networks in adaptive management. *Canadian Journal of Forest Research*, *36*(12), 3104–3116. https://doi.org/10.1139/x06-108

Opdam, P., Luque, S., & Jones, K. B. (2009). Changing landscapes to accommodate for climate change impacts: A call for landscape ecology. *Landscape Ecology*, *24*(6), 715–721. https://doi.org/10.1007/s10980-009-9377-1

Peratoner, G., Resch, R., Figl, U., Florian, C., Bodner, A., & Vitalone, L. (2018). Performance of seed mixtures containing tall fescue (*Festuca arundinacea* Schreb.) for permanent meadows in mountain areas. *Grassland Science in Europe*, *23*, 316–318.

QGIS Development Team. (2022). *QGIS geographic information system*. QGIS Association.

Rammig, A., Jonas, T., Zimmermann, N. E., & Rixen, C. (2010). Changes in alpine plant growth under future climate conditions. *Biogeosciences*, *7*(6), 2013–2024. https://doi.org/10.5194/bg-7-2013-2010

Refsgaard, J. C., Arnbjerg-Nielsen, K., Drews, M., Halsnæs, K., Jeppesen, E., Madsen, H., Markandya, A., Olesen, J. E., Porter, J. R., & Christensen, J. H. (2013). The role of uncertainty in climate change adaptation strategies—A Danish water management example. *Mitigation and Adaptation Strategies for Global Change*, *18*(3), 337–359. https://doi.org/10.1007/s11027-012-9366-6

Rist, L., Campbell, B. M., & Frost, P. (2013). Adaptive management: Where are we now? *Environmental Conservation*, *40*(1), 5–18. https://doi.org/10.1017/S0376892912000240

Schirpke, U., Kohler, M., Leitinger, G., Fontana, V., Tasser, E., & Tappeiner, U. (2017). Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their resilience. *Ecosystem Services*, *26*, 79–94. https://doi.org/10.1016/j.ecoser.2017.06.008

Schirpke, U., Tappeiner, U., & Tasser, E. (2019). A transnational perspective of global and regional ecosystem service flows from and to mountain regions. *Scientific Reports*, *9*(1), 6678. https://doi.org/10.1038/s41598-019-43229-z

Schirpke, U., Tscholl, S., & Tasser, E. (2020). Spatio-temporal changes in ecosystem service values: Effects of land-use changes from past to future (1860–2100). *Journal of Environmental Management*, *272*, 111068. https://doi.org/10.1016/j.jenvman.2020.111068

Soubeyroux, J.-M., Kitova, N., Blanchard, M., Jean-Philippe Vidal, E., Martin, E., & Dandin, P. (2012). Caractérisation des sècheresses des sols en France et changement climatique: Résultats et applications du projet ClimSec. p. 26.

Stampfli, A., Bloor, J. M. G., Fischer, M., & Zeiter, M. (2018). High land-use intensity exacerbates shifts in grassland vegetation composition after severe experimental drought. *Global Change Biology*, *24*(5), 2021–2034. https://doi.org/10.1111/gcb.14046

Stritih, A., Bebi, P., & Grêt-Regamey, A. (2018). Quantifying uncertainties in earth observation-based ecosystem service assessments. *Environmental Modelling & Software*, *111*, 300–310. https://doi.org/10.1016/j.envsoft.2018.09.005

Tello-García, E., Huber, L., Leitinger, G., Peters, A., Newesely, C., Ringler, M. E., & Tasser, E. (2020). Drought- and heat-induced shifts in vegetation composition impact biomass production and water use of alpine grasslands. *Environmental and Experimental Botany*, *169*, 103921. https://doi.org/10.1016/j.envexpbot.2019.103921

Thompson, J. R., Plisinski, J. S., Lambert, K. F., Duveneck, M. J., Morreale, L., McBride, M., MacLean, M. G., Weiss, M., & Lee, L. (2020). Spatial simulation of codesigned land cover change scenarios in New England: Alternative futures and their consequences for conservation priorities. *Earth's Future*, *8*(7), e2019EF001348. https://doi.org/10.1029/2019EF001348

13652664, 2024, 6, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.14655 by Cochrane France, Wiley Online Library on [09/07/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Van Sundert, K., Arfin Khan, M. A. S., Bharath, S., Buckley, Y. M., Caldeira, M. C., Donohue, I., Dubbert, M., Ebeling, A., Eisenhauer, N., Eskelinen, A., Finn, A., Gebauer, T., Haider, S., Hansart, A., Jentsch, A., Kübert, A., Nijs, I., Nock, C. A., Nogueira, C., … Vicca, S. (2021). Fertilized graminoids intensify negative drought effects on grassland productivity. *Global Change Biology*, *27*(11), 2441–2457.

Vannier, C., Bierry, A., Longaretti, P. Y., Nettier, B., Cordonnier, T., Chauvin, C., Bertrand, N., Quétier, F., Lasseur, R., & Lavorel, S. (2019). Co-constructing future land-use scenarios for the Grenoble region France. *Landscape and Urban Planning*, *190*, 103614.

Verfaillie, D., Déqué, M., Morin, S., & Lafaysse, M. (2017). The method ADAMONT v1. 0 for statistical adjustment of climate projections applicable to energy balance land surface models. *Geoscientific Model Development*, *10*(11), 4257–4283.

Vidal, J.-P., Martin, E., Franchistéguy, L., Baillon, M., & Soubeyroux, J. M. (2010). A 50-year high-resolution atmospheric reanalysis over France with the Safran system: A 50-year high-resolution atmospheric reanalysis over France. *International Journal of Climatology*, *30*(11), 1627–1644. https://doi.org/10.1002/joc.2003

Wang, H., Liu, H., Cao, G., Ma, Z., Li, Y., Zhang, F., Zhao, X., Zhao, X., Jiang, L., Sanders, N. J., Classen, A. T., & He, J. S. (2020). Alpine grassland plants grow earlier and faster but biomass remains unchanged over 35 years of climate change. *Ecology Letters*, *23*(4), 701–710. https://doi.org/10.1111/ele.13474

Zwicke, M., Alessio, G. A., Thiery, L., Falcimagne, R., Baumont, R., Rossignol, N., Soussana, J. F., & Picon-Cochard, C. (2013). Lasting effects of climate disturbance on perennial grassland above-ground biomass production under two cutting frequencies. *Global Change Biology*, *19*(11), 3435–3448.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supporting Information A. Land use and land cover, climate and livestock system of the Maurienne valley in 2016.

Supporting Information B. Variables descriptions and relations in the BBN model.

Supporting Information C. Confusion matrix for the grassland type prediction module and partial model validation for the first growth period.

Supporting Information D. Scenarios of LULC change: transition matrix and maps of LULC gain and losses for 2085 compared to 2020.

Supporting Information E. Statistical effects of future drivers of change on biomass production.

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