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Research article

Uncertainties in the adaptation of alpine pastures to climate change based on remote sensing products and modelling

L. Brilli [a,b,*], R. Martin [c], G. Argenti [b], M. Bassignana [d], M. Bindi [b], R. Bonet [e], P. Choler [f], E. Cremonese [g], M. Della Vedova [e], C. Dibari [b], G. Filippa [g], M. Galvagno [g], L. Leolini [b], M. Moriondo [a,b], A. Piccot [d], L. Stendardi [b], S. Targetti [h], G. Bellocchi [c]

[a] National Research Council – Institute of BioEconomy (IBE-CNR), 50145, Sesto Fiorentino, Italy
[b] University of Florence, DAGRI, 50144, Florence, Italy
[c] Université Clermont Auvergne, INRAE, VetAgro Sup, UREP, 63000, Clermont-Ferrand, France
[d] Institut Agricole Régional, 11100, Aosta, Italy
[e] Parc National des Ecrins, Domaine de Charance, 05000, Gap, France
[f] Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, LECA, 38000, Grenoble, France
[g] Climate Change Unit, Environmental Protection Agency of Aosta Valley, Saint-Christophe, Italy
[h] University of Bologna, Department of Agricultural and Food Sciences, Viale Fanin, 50, 40127, Bologna, Italy

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ABSTRACT

Over the last century, the management of pastoral systems has undergone major changes to meet the livelihood needs of alpine communities. Faced with the changes induced by recent global warming, the ecological status of many pastoral systems has seriously deteriorated in the western alpine region. We assessed changes in pasture dynamics by integrating information from remote-sensing products and two process-based models, i.e. the grassland-specific, biogeochemical growth model PaSim and the generic crop-growth model DayCent. Meteorological observations and satellite-derived Normalised Difference Vegetation Index (NDVI) trajectories of three pasture macro-types (high, medium and low productivity classes) in two study areas - *Parc National des Écrins* (PNE) in France and *Parco Nazionale Gran Paradiso* (PNGP) in Italy - were used as a basis for the model calibration work. The performance of the models was satisfactory in reproducing pasture production dynamics (R^2 = 0.52 to 0.83). Projected changes in alpine pastures due to climate-change impacts and adaptation strategies indicate that: i) the length of the growing season is expected to increase between 15 and 40 days, resulting in changes in the timing and amount of biomass production, ii) summer water stress could limit pasture productivity; iii) earlier onset of grazing could enhance pasture productivity; iv) higher livestock densities could increase the rate of biomass regrowth, but major uncertainties in modelling processes need to be considered; and v) the carbon sequestration potential of pastures could decrease under limited water availability and warming.

1. Introduction

Mountain pastures are important livelihood systems in the European Alps, with a multifunctional form of land use encompassing agriculture, outdoor recreation, and tourism as well as conservation needs (Wanner et al., 2021). Rich in terms of biodiversity (Kurtogullari et al., 2020) and cultural heritage (Jourdain-Annequin and Duclos, 2006), alpine pastures fulfil economic, social and environmental functions at the same time (Bengtsson et al., 2019). They provide low-cost fodder for grazing livestock during the summer period and - where traditional transhumance systems are present – represent a complementary resource for Mediterranean pastoral systems (Caballero et al., 2009). Shaped by pastoral activities, alpine pastures have undergone multiple transformations over the centuries, mainly driven by the fragile balance between maximising agricultural productivity and the limits imposed by the temporal and spatial dynamics of the climate and forests-grasslands interactions (Kurz, 2013). However, alpine pastoralism manifests its fragility in the face of the changes induced by recent global warming. Climate changes and their impacts are visible in the alpine region, which has experienced a temperature increase of almost 2 °C over the last

* Corresponding author. National Research Council – Institute of BioEconomy (IBE-CNR), 50145, Sesto Fiorentino, Italy.
E-mail address: lorenzo.brilli@ibe.cnr.it (L. Brilli).

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century, along with an important reduction of precipitation in the summer season (Gobiet et al., 2014). Specifically, droughts have been one of the main manifestations of climate variability. Corresponding to periods of abnormally low precipitation, they alter grassland productivity and quality (Nettier et al., 2010; Dibari et al., 2016) by offsetting the positive effect of summer heatwaves on canopy greenness (Corona-Lozada et al., 2019), as seen in the European Alps following a series of droughts (Calanca, 2007). The response of European mountain plant assemblages to increasing temperatures (thermophilisation) also suggests a progressive decline of cold-tolerant high-altitude grassland communities (Gottfried et al., 2012) and landscape modifications with warming-induced upward range shifts (Engler et al., 2011). This may lead to both a decrease in areas suitable for pasture and a reduction in pasture diversity driven by low-quality vegetation types in the Alpine chain (Dibari et al., 2020), together with changes in grazing practices (Dibari et al., 2021). This is critical because most impacts on grassland ecosystems can be related to overgrazing and changes in the timing of livestock transhumance, with high stocking densities in particular causing a range of negative impacts on plant and animal communities, as observed in central France (Dumont et al., 2009) and in the Italian Maritime Alps (Negro et al., 2011).

In this context, appropriate management can preserve grassland biodiversity, maintain socio-ecological systems (Altaweel et al., 2015; Alessa et al., 2018) and counteract climate-change impacts (Nori and Gemini, 2011; Felber et al., 2016). Specifically for the western Alps, global warming and the increased frequency of extreme climate events such as heatwaves and droughts have raised awareness of the need to adapt, due to the combined effects of climate and changes in pastoral practices (Bonet et al., 2016). However, in many alpine zones, specific measures to manage pastures in the face of climate change are still not implemented, despite the implementation of agri-environmental and climate measures in the Common Agricultural Policy (EC, 2013). Since proper management is needed to ensure the environmental, social and economic sustainability of mountain permanent grasslands, a multi-disciplinary approach is a fundamental starting point, involving the co-responsibility of livestock farmers and local officers, as well as cooperation based on observation, modelling and intervention (Della-Vedova and Legeard, 2012).

This posture forms the basis of the design and implementation of this study started in 2017 in two representative areas of the western alpine territory: the *Écrins* (France) and *Gran Paradiso* (Italy) national parks (PNE and PNGP, respectively). In the pasturelands of the two parks, ground-based and remotely sensed observation systems, as well as model-based simulations were used to identify efficient management strategies able to support pastoral management and the sustainability of pastoral systems. Modelling adaptation strategies was supported by a participatory-based process bringing together different local stakeholders in the two case study areas. The target of the modelling concerned the performance of pastoral systems and in particular the definition of production while minimising environmental impacts. Remote sensing supports such modelling by offering information on the spatial and temporal variation of important canopy state variables which would be difficult to obtain otherwise. The involvement of local pastoralists was the basis for the design and assessment of the analytical framework concerning the climate-change adaptation strategies.

In the context of these alpine pastures, the objectives of this study were: (1) to inform modelling via calibration with remotely sensed data; (2) to use the calibrated models to project climate-change impacts, and (3) to assess a set of adaptation options for pastoral management identified by stakeholders.

2. Materials and methods

2.1. Study areas

In its wide-ranging perspective, the study considered three macro-types of pastoral vegetation (high, medium and low productivity) located at different altitudes (low, medium and high) in two national parks of the western Alps, on either side of the French-Italian border (Standardi et al., 2022; Filippa et al., 2022) (Fig. 1).

Established in 1973, the *Parc National des Écrins* (PNE) covers an area of ~91,800 ha (approximately in the range 44° 03′-45° 05′ N and 06° 05′-06° 35′ E) in the two French departments of Hautes-Alps (region Provence-Alpes-Côte d'Azur) and Isère (region Auvergne-Rhône-Alpes). It includes *c.* 70,000 ha of summer pastureland (~30% of the park area), which is grazed by about 115,000 sheep (75% of the total stocking rate), 5800 cows and >1000 of goats and horses. Transhumance (which is declining across Europe) is still relevant in the study area, with ~1/3 of the total sheep stocking rate in summer pasture being involved in transhumance (Brien, 2018).

The *Parco Nazionale Gran Paradiso* (PNGP) is Italy's oldest national park (founded in 1922), established in the core of the former Piedmontese royal hunting reserve of the alpine ibex, a species of wild goat (*Capra ibex*) that lives in the mountains of the European Alps. It covers over 71,000 ha approximately in the range 45° 25′-45° 45′ N and 07° 00′-07° 30′ E in the two Italian regions of Piedmont and Aosta Valley. Most of the territory (*c.* 60%) is used for non-agricultural purposes, a small part (*c.*11.5%) is covered by forests, while the areas of stable grasslands are constantly decreasing.

The surface of both parks is represented by mountainous environments, located from low valleys to very high mountains, with the highest peaks of 4102 m a.s.l. (Barre des Écrins) and 4061 m a.s.l. (Gran Paradiso Mountain) for the PNE and PNGP, respectively. The territories of the two protected areas are characterised by forests, from broadleaf in the lower parts to coniferous in the higher parts, and by mountain and alpine grasslands and pastures. The climate is generally alpine, but with different microclimatic conditions due to high variability in topographical features (elevation, aspect and slope). In addition, there are different lithological formations. All these complex and variable conditions produce a large typology of different plant communities characterised by a great richness of vegetation.

The territories of the two parks lie within the areas of three vegetation macro-typologies (Table 1), which group the main plant communities that can be found in the subalpine and alpine pastures of the French Southern Alps (Jouglet, 1999), the Vanoise and Aosta Valley (Bornard et al., 2007) and Piedmont in Italy (Cavallero et al., 2007). These typologies have been harmonised in 13 categories of common pastures that were further grouped in three productivity macro-types (Standardi et al., 2022).

[1] A-I - Alpine intermediate: sparse vegetation on medium to moderate slopes, windy ridges and bumps in the alpine level (main species: *Carex curvula*, *Trifolium alpinum*, *Avenula versicolor*); SA-II - *Nardus* swards: on lowlands and slopes in the subalpine or alpine level, vegetation of medium height (0.2–0.3 m), not very dense, dominated by *Nardus* stricta (main species: *Nardus stricta*, *Carex sempervirens*, *Trifolium alpinum*, *Festuca rubra*); A-II – nival: sparse vegetation in snow combes and moderate slopes in alpine and nival environment (main species: *Alchemilla pentaphyllea*, *Salix herbacea*, *Carex foetida*, *Plantago alpina*); S-II - subalpine intermediate: vegetation in flatlands and low slopes of the subalpine level with medium-rich soil, 0.3–0.5 m high, dense grassy patches dominated by fine to medium-leaved *Gramineae* (main species: *Festuca rubra*, *Agrostis capillaris*, *Phleum alpinum*, *Alchemilla xanthochlora*); S-III - *Patzkea paniculata* swards: on medium sunny slopes in the subalpine level, vegetation very tall (over 0.5 m), very dense, dominated by *Gramineae* with long, thick leaves, especially *Patzkea paniculata* (main species: *Patzkea paniculata*, *Festuca rubra*, *Carex sempervirens*).

2.2. Data collection

The Normalised Difference Vegetation Index (NDVI) is a standard way to determine vegetation cover and productivity. High NDVI values (approximately >0.7–0.8) indicate healthy vegetation, dense and

Fig. 1. Location and details of the study areas: a) *Parc National des Écrins* (left) and *Parco Nazionale Gran Paradiso* (right) with localization of the high, medium and low productivity macro-types (i.e., green, yellow and red areas); b) Ikonos Panel Sharp (IPS) image from Google Earth showing Italy and the position of the two Nation parks in the alpine chain; c) example of grazing areas in the *Parc National des Écrins* and; d) in the *Parco Nazionale Gran Paradiso*.

Table 1
Description of three pastoral macro-types (HP: high productivity; MP: medium productivity; LP: low productivity) in the two study areas (PNE: *Parc National des Écrins*; PNGP: *Parco Nazionale Gran Paradiso*).

Study area	Description	Unit	Pastoral macro-types		
			HP	MP	LP
PNE	Latitude	degree N	45.04	45.06	45.06
	Longitude	degree E	06.40	06.38	06.37
	Slope	rad	0.14	0.31	0.15
	Aspect	rad	3.06	1.95	2.32
	Elevation	m a.s.l.	2044	2539	2634
	Soil depth	m	0.70	0.65	0.55
	Clay	%	30.3	34.9	27.5
	Silt	%	37.6	40.3	61.1
	Sand	%	32.1	24.8	11.4
	Soil organic carbon	g 100 g^{-1}	4.50	14.00	10.50
	Soil pH	–	5.70	5.05	4.75
	Bulk density	g cm^{-3}	0.800	0.735	0.960
	Saturated soil water content	m^3 m^{-3}	0.490	0.511	0.507
	Field capacity	m^3 m^{-3}	0.312	0.345	0.330
	Wilting point	m^3 m^{-3}	0.170	0.194	0.153
	Reference pasture type[1]	–	S6	S1	A9
PNGP	Latitude	degree N	45.56	45.57	45.58
	Longitude	degree E	07.12	07.19	07.29
	Slope	rad	0.31	0.33	0.16
	Aspect	rad	5.76	1.97	1.80
	Elevation	m a.s.l.	2133	2336	2806
	Soil depth	m	0.70	0.65	0.55
	Clay	%	6.8	6.5	6.1
	Silt	%	20.0	20.0	14.0
	Sand	%	73.2	73.5	79.9
	Soil organic carbon	g 100 g^{-1}	1.88	2.24	1.90
	Soil pH	–	5.5	4.9	5.3
	Bulk density	g cm^{-3}	1.48	1.48	1.51
	Saturated soil water content	m^3 m^{-3}	0.39	0.38	0.37
	Field capacity	m^3 m^{-3}	0.130	0.120	0.098
	Wilting point	m^3 m^{-3}	0.053	0.052	0.041
	Reference pasture type[1]	–	S-II	SA-II	A-I

productive canopies, while low NDVI values indicate land with little or no vegetation or stressed canopies. Satellite-derived NDVI data for the period 2018–2020 were retrieved for the two study areas by processing the Sentinel-2 imagery. The images (10-m spatial resolution, level2A) were atmospherically and topographically corrected with the Sen2Cor processor (https://step.esa.int/main/snap-supported-plugins/sen2cor). The images were filtered on a per-pixel basis with the scene classification (SCL) map, retaining only top quality, and cloud- and shadow-free pixels. The downloading and processing of the data were performed on Google Earth Engine (https://earthengine.google.com) with a dedicated Python (https://www.python.org) script (Hufkens, 2017). Seasonal NDVI trajectories were used to retrieve growing season start and end dates based on a fixed threshold method (20% seasonal amplitude) similar to that proposed by Shen et al. (2015). We obtained a satisfactory agreement between these dates and those obtained from the seasonal pattern of snow cover (Table 1). Aboveground biomass (AGB) and leaf area index (LAI) were measured in both areas following standardised protocols (Filippa et al., 2015). An empirical model was fitted between AGB/LAI observations and the corresponding S2-derived NDVI, and the resulting equations (Supplementary material, section 1) were then used to convert S2-NDVI data in AGB and LAI data for the three productivity macro-types of each study area.

2.3. Climate-change scenarios

Simulated pastoral outputs were obtained by forcing impact models (section 2.5) with daily downscaled weather data, which were selected to map a broad range of climate outcomes for impact modelling (Wilcke and Bärring, 2016). Supplementary material (section 2) describes the methods used in processing and post-processing the climate output used in the generation of climate scenarios.

Climate data from three Regional Climate Models (RCMs) from Med-CORDEX (Ruti et al., 2016) - CNRM-ALADIN (0.11° × 0.11°), ICTP-RGCM4 (0.44° × 0.44°), and CMCC-CCLM4 (0.44° × 0.44°) for the reference period 1981–2010 (near past) and for two future time-slices 2011–2040 (near future) and 2041–2070 (mid future). For near past period ambient CO_2 concentration was fixed to 400 ppm. For future periods, Representative Concentration Pathways 4.5 and 8.5 (RCP4.5, RCP4.5) were selected, with ambient CO_2 concentration at 450 (RCP4.5) and 470 ppm (RCP8.5) for near future and 540 and 670 ppm for mid future.

The delta-change approach was applied as a downscaling procedure, where the observed daily weather data available for each given site were modified using as forcing factors the outcomes obtained from the RCM simulations. These were calculated as the mean absolute monthly differences between the RCM baseline (1981–2010) and the future RCM periods selected for simulations (2041–2070, 2071–2100) for minimum and maximum air temperatures and the percentage variation in monthly cumulated rainfall, wind speed and solar radiation. These differences were then added, month by month, to the observed daily meteorological data from PNE and PNGP to derive future weather data that were used to feed model simulations for future periods. The three daily datasets deriving from RCMs downscaling were finally merged into a single dataset reproducing the mean change in climate conditions for each study area in RCP4.5 and 8.5 for 2031–2040, 2041–2070 and 2071–2100 time-slices.

2.4. Participatory approach

To understand the impact of climatic events and changes in grazing practices, and to preserve (or restore) the sustainable management of these areas, the "Sentinel Alpine Pastures" programme focuses on how to adapt to different phenomena as part of a long-term approach to the complex dynamics of climate change, to anticipate adaptive strategies (Dobremez et al., 2014). These sources of information thus represent a unique opportunity to environmentally characterise these pastoral areas by using advanced techniques such as remote sensing and process-based simulation modelling. As a basis for the design and assessment of the analytical framework, a participatory process was conducted since 2018 with groups of *c.* 100 local stakeholders in each park including farmers, technicians, representatives of the two parks and officials from local institutions. The participatory process involved meetings, interviews and informal discussions that took place in parallel with data collection and territorial analysis (Targetti et al., 2019). Participation addressed three main topics: i) current pastoral practices, related barriers and incentives, and key drivers of socio-economic change; ii) effective adaptation measures already implemented in the western Alps; and iii) which measures should be prioritised (Piccot et al., 2022). In this study, we assessed the effect of prioritised adaptation options from a modelling perspective as it emerged from the participatory approach, recognising the limited set of modelling assumptions contained in the adaptation requests, which represent a fraction of plausible adaptations and a step towards transformative changes (Holman et al., 2019).

2.5. Grassland modelling

Process-based models are important tools in agricultural and environmental research to extrapolate local observations over time and space, and to assess the impact of climate and agricultural practices on the soil-plant-atmosphere continuum through plant-soil feedback effects. These widely tested models are also recognised as effective tools for studying the magnitude and spatial-temporal patterns of C–N (carbon-nitrogen) fluxes, playing a prominent role in testing the effect of specific changes in management, plant properties or environmental factors, and in designing policies specific to the soil, climate and agricultural conditions of a location or region. However, the results from different models often differ, presenting a range of possible impacts and adaptation responses (Brilli et al., 2017), which are influenced by the models' users' knowledge and expertise, and their understanding of the variables determined in the target agroecosystems (Albanito et al., 2022).

Here, the soil-vegetation generic model DayCent (Parton et al., 1994, 1998) and the grassland-specific model PaSim (Riedo et al., 1998) were chosen to simulate alpine pastures. Both provide a mechanistic view of the multiple processes and interactions occurring in grassland systems and are able to simulate grassland productivity and C and N fluxes under alternative management options. DayCent is the daily time-step adaptation of the biogeochemical model CENTURY (Parton et al., 1994), which simulates plant growth, soil C dynamics, N leaching, gaseous emissions (e.g. nitrous oxide) and C fluxes (e.g. net ecosystem exchange) in a variety of managed ecosystems. PaSim is a grassland-specific ecosystem model consisting of detailed sub-models for vegetation, animals, microclimate, soil biology, soil physics and management to simulate grassland productivity and C–N fluxes.

2.6. Simulation design

The modelling work was carried out in three suites of simulations: suite 1 with observational data (model calibration), suite 2 with projected scenarios of climate change (impact projections), and suite 3 with altered management under projected scenarios of climate change (adaptation assessment).

Model calibration (suite 1) was carried out over the years 2018–2020 in the two parks, setting management practices (grazing intensity and periods) as defined in Table 2 (one or two short periods with short-term, intensive management), on a set of parameters (Table S1 and Table S2) to which model sensitivity was determined in previous studies for both DayCent (e.g. Fitton et al., 2014; Necpálová et al., 2015) and PaSim (e.g. Ben Touhami et al., 2013; Ma et al., 2015; Pulina et al., 2018; Sándor et al., 2018). The agreement between simulated and observed dry matter (DM) was assessed by inspection of time-series graphs (fluctuations of output variables over time), and numerically, through two commonly used performance metrics of model evaluation (Richter et al., 2012): root mean square error (best, g DM m^{-2} $0 \leq RMSE < +\infty$ g DM m^{-2}, worst) and coefficient of determination (worst, $0 \leq R^2 \leq 1$, best).

With suite 2, we assessed the projected response of DayCent and PaSim to climate-change forcing options described in section 2.3. Impacts of climate change were calculated on the changes in a set of climate and ecosystem variables related to biomass production and C–N fluxes (Table 3).

With the adaptation assessment (suite 3), we show the simulated outputs using the two grassland models fed with the following adaptation practices, defined during the participatory process (section 2.4) combined with climate-change forcing: the stocking rate in the pasture was increased or decreased by 20% (LD-20% and LD+20%, respectively), and the grazing period was advanced by 14 days (GDadv).

Simulation results are presented separately per study area, comparing DayCent and PaSim outputs with satellite-derived AGB data

Table 3
Climate-change impact metrics.

Type	Output	Acronym	Unit	Description
Date	Snow cover start	SCs	day of year (doy)	First of 10 consecutive days of the year with snow cover ≥5 cm
	Snow cover end	SCe		First of 10 consecutive days of the year with snow cover ≤5 cm
	Growing seasons start	GSs		First day of the year with aboveground biomass (SCe + 1 day)
	Growing seasons end	GSe		Last day of the year with aboveground biomass (SCs – 1 day)
	Biomass peak date (period 1)	BP1a		Day of the year with the highest value of aboveground biomass before the first grazing period
	Biomass peak date (period 2, HP)	BP2a		Day of the year with the highest value of aboveground biomass after the first grazing period and before the second grazing period
Count	Snow cover length	SC	days	Number of days between SCs and SCe
	Growing season length	GS		Number of days between the GSs and GSe
Amount	Biomass peak (period 1)	BP1b	kg DM m^{-2}	Aboveground biomass value at the first peak date
	Biomass peak (period 2, HP)	BP2b		Aboveground biomass value at the second peak date
	Above ground biomass	AGB	kg DM m^{-2} yr^{-1}	Annual mean aboveground biomass
	Net ecosystem exchange	NEE	kg C m^{-2} yr^{-1}	C–N fluxes (they include emissions from ecosystem respiration (RECO = plant + soil + animal respiration), as well as estimates of the plant production of organic compounds from atmospheric CO_2 (GPP) and other system variables: NEE = RECO - GPP, NPP = GPP - plant respiration, enteric emissions of CH_4 from grazing animals and N_2O emissions from the N cycle)
	Net primary production	NPP		
	Ecosystem respiration	RECO		
	Gross primary production	GPP		
	Methane	CH_4	kg C m^{-2} yr^{-1}	
	Nitrogen dioxide	N_2O	kg N m^{-2} yr^{-1}	
	Soil water content	SWC	m^3 m^{-3}	Soil water content

Table 2
Management of three pastoral macro-types (HP: high productivity; MP: medium productivity; LP: low productivity) in the two study areas (PNE: *Parc National des Écrins*; PNGP: *Parco Nazionale Gran Paradiso*). Grazing 1 and Grazing 2 refer to the first and second (if present) grazing periods expressed as days of the years, respectively, over the investigated macro-types. Livestock Standard Unit (LSU) refers to a dairy cow producing 3000 kg of milk per year, without additional concentrated feed (EC, 2008).

Site	Pasture macro-type	Grazing 1st						Grazing 2nd					
		Period (days of year)			Stocking density ($LSU\ ha^{-1}\ d^{-1}$)			Period (days of year)			Stocking density ($LSU\ ha^{-1}\ d^{-1}$)		
		2018	2019	2020	2018	2019	2020	2018	2019	2020	2018	2019	2020
PNE	HP	196–197	197–198	191	120	113	126	287–288	272–273	262	43	37	76
	MP	213–214	213–214	214–215	51	49	62	–	–	–	–	–	–
	LP	217	220	217	12	10	9	–	–	–	–	–	–
PNGP	HP	194–195	198	196–197	104	98	84	261	264	264	102	106	118
	MP	229–230	230–231	229–230	79	75	57	–	–	–	–	–	–
	LP	217–218	202	222–223	30	14	20	–	–	–	–	–	–

(suite 1). Time-series graphs are presented to illustrate the dynamics of selected variables (AGB, SWC, C fluxes and CH_4 and N_2O emissions) for suites 2 and 3, as well as two-dimensional colour data visualisations (heatmap graphs).

3. Results

For greater clarity in the presentation of results and discussion, we present in detail only the results obtained in the high productivity macro-type for which a full modelling analysis is available. We also briefly present the results obtained in the medium and low productivity macro-types, which are fully provided in the Supplementary material.

3.1. Climate analysis

The monthly distribution of air temperatures in the two study areas (Fig. 2), averaged from the outputs of the ICTP-REGCM4, CMCC-CCLM4 and CNRM-ALADIN climate models, showed an overall increase in temperature towards the far future, similar for both parks, with a distinct seasonal trend, with the highest increases in summer (+4 °C at PNE and +3.7 °C at PNGP under the warmest scenario) and the lowest in autumn-winter (+2.5 °C at PNE and +2.3 °C at PNGP under the warmest scenario). Analysis of simulated monthly rainfall data (Fig. 2) showed increases in autumn-winter (November–February) relative to the baseline in both scenarios and sites (PNE: +3.3% and +9.9%; PNGP: +5.4% and +9.5%, for RCP4.5 and RCP8.5, respectively), while spring-summer exhibited a strong decrease in rainfall, more pronounced in the PNE (−11.7% and −18.8%, for RCP4.5 and RCP8.5, respectively) than in the PNGP (−10% in both scenarios). In both parks, no clear trend was observed, nor was a clear pattern evident when analysing the differences between time-slices, as there was no trend of increasing/decreasing monthly precipitation in the progression from the near to the far future.

3.2. Suite 1 of simulations: model evaluation against observed data

The resulting sets of parameter values allowed the outputs of the two impact models to be compared for each study area. Plant parameters served to accommodate changes in the sward structures driven by local environmental conditions and management. Although no formal sensitivity analysis was conducted for the model parameters, the calibration applied separately to each study area allowed us to explore the variability of parameter values between the two parks. An indication from the calibration work is that, for both models, the parameter values can be considerably different across alternative conditions (Table S1 and Table S2). For instance, the different vegetation patterns in the two parks are reflected in the PaSim parameter “maximum specific leaf area”, whose lower values tend to be associated with the PNGP (e.g. for the high-productivity pastoral vegetation macro-type, the value decreased from ~37 m^2 kg^{-1} in the PNE to ~22 m^2 kg^{-1} in the PNGP). Photosynthetic rates estimated with PaSim (Table S1) were lower in the PNGP during the reproductive stage (*pmco2rep*~25 μmol C m^{-2} s^{-1} against ~32 μmol C m^{-2} s^{-1} in the PNE) and higher during the vegetative stage (*pmco2veg*~16 μmol C m^{-2} s^{-1} against ~13 μmol C m^{-2} s^{-1} in the PNE). With DayCent, air temperature thresholds (optimal and maximum), the number of soil layers influencing water and nutrient availability, and the allocation of C to different plant organs influenced plant growth and C fluxes. Specifically, for the high-productivity pastoral vegetation macro-type, the coefficient for calculating potential monthly aboveground biomass production as a function of solar radiation outside the atmosphere lowers from 4.1 in the PNGP to ~1.0 m^2 kg^{-1} in the PNE, while the thresholds for optimal air temperatures were slightly higher in the PNGP than in the PNE (Table S2).

Standing biomass simulations (Fig. S2; Table S3) indicate that estimates substantially reflect patterns of vegetation dynamics ($R^2 > 0.50$) although some departures from observed data are noted. RMSE values (>70 g DM m^{-2}) are comparable with results from previous modelling

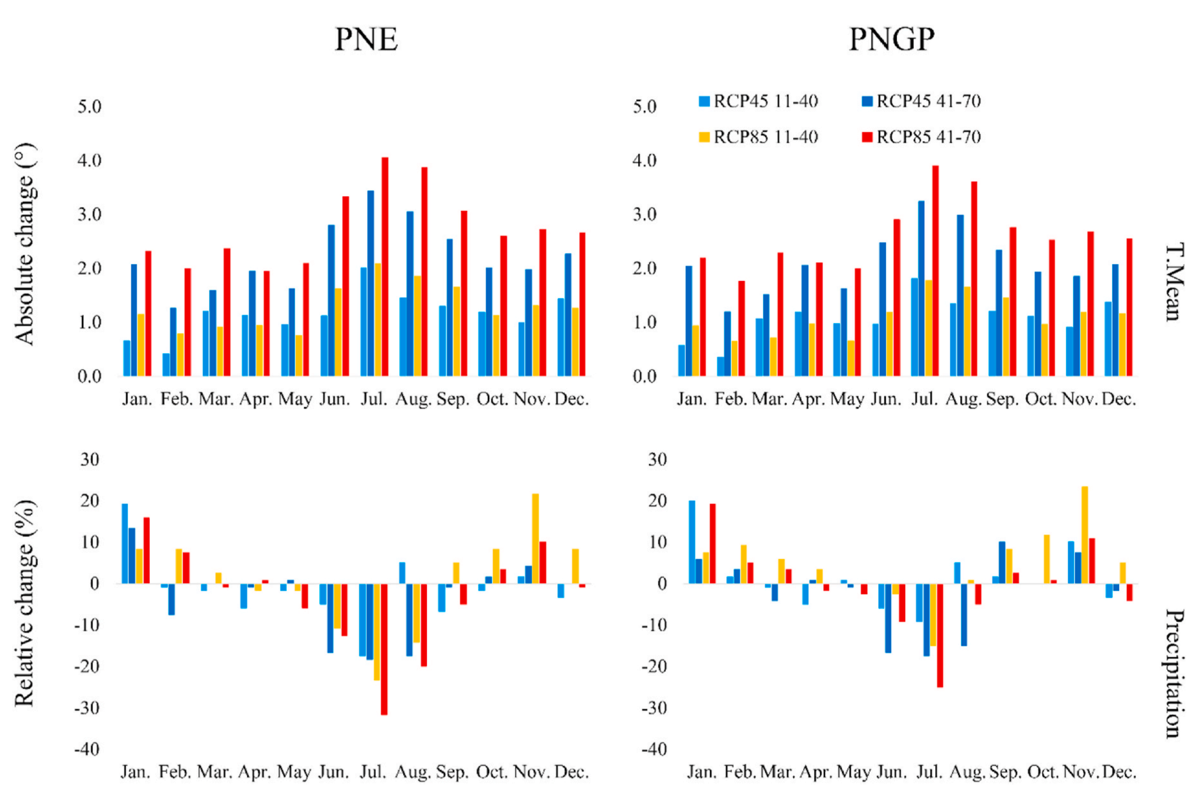

Fig. 2. Absolute change (°C) in monthly mean air temperature (top graphs) and relative change (%) of monthly cumulated rainfall (bottom graphs) generated in the two study areas with the RCM ensemble (ICTP-REGCM4, CMCC-CCLM4 and CNRM-ALADIN) for two climate scenarios (RCP4.5, RCP8.5) and two future periods - 2011–2040 and 2041–2070 - over the baseline period 1981–2010.

studies (e.g. Sándor et al., 2018), with simulations for grasslands being generally less accurate compared to arable crops (e.g. Kollas et al., 2015). We also note that the great deal of fundamental research incorporated into the most mechanistic PaSim model has not always improved the results.

3.3. Suite 2 and 3 of simulations: impacts of future scenarios and adaptation strategies

For both parks, we assessed the sensitivity of the two grassland models to (suite 2) climate change (RCP4.5 and RCP8.5 for the near and far future) with business-as-usual (BaU) management and to (suite 3) management scenarios (GDadv and LD±20%). Multi-year mean responses for selected production (AGB), biophysical (SWC) and biogeochemical (C–N fluxes) outputs are presented below.

3.4. Growing season

Under the climate-change scenarios, with both grassland models, the estimated length of the snow season decreases in both areas due to earlier spring snowmelt and later autumn/winter snowpack accumulation. This condition leads to an earlier onset and later end of the growing season (GS) in both parks, especially in the far future (i.e. 2041-2070) (Fig. 3). Specifically, using DayCent, the start of the growing season (GSs) was on average 11 and 28 days earlier in the PNE, and 12 and 39 days earlier in the PNGP, for the 2011–2040 and 2041–2070. The end of the growing season (GSe) was delayed on average 8 and 17 days in the PNE, and 17 days in the PNGP for 2041–2070. In contrast, no changes in GSe were observed in PNGP for the period 2011–2040.

Using PaSim, GSs was advanced by 14 and 31 days on average in the PNE, and by 7 and 19 days in the PNGP for the periods 2011–2040 and 2041–2070. GSe was delayed by 5 and 23 days on average for the periods 2011–2040 and 2041–2070 in the PNE, and by 36 days in the PNGP for both time-slices.

The MP and LP macro-types showed similar growing season patterns to those observed in the HP macro-type, with GSs advanced and GSe delayed towards the end of the century, with the largest impacts using RCP8.5. For all three macro-types, DayCent reported a mean GS extension ranging between 15 and 40 days in the PNE, and between 12 and 45 days in the PNGP for the periods 2011–2040 and 2041–2070, respectively. Using PaSim, the increase in GS ranged between 17 and 44 days in the PNE, and between 23 and 35 days in the PNGP for the periods 2011–2040 and 2041–2070, respectively (Fig. S3 and Fig. S4). Overall, both models suggested a longer growing season of 2–5 weeks when approaching the warmest scenarios.

3.5. Soil water content (0.30 m topsoil)

Under the climate-change scenarios, both models indicated an earlier decline in SWC, near or below the permanent wilting point (Table 1), especially during the warm season in both parks (Fig. 4). PaSim showed less pronounced oscillations in SWC (~0.30–0.40 m^3 m^{-3} in the PNE and ~0.15–0.25 m^3 m^{-3} in the PNGP), while DayCent interpreted the increased water supply projected by climate modelling in winter (Fig. 2) to amplify seasonal differences (i.e. an excess SWC in winter followed by a deficit in summer), with ~0.15–0.60 m^3 m^{-3} in the PNE and ~0.05–0.35 m^3 m^{-3} in the PNGP (i.e. even below the permanent wilting point). Despite the differences between the two models, for both parks the simulated patterns suggest that with drier summer conditions, grassland growth may be limited by water in summer (Fig. 4).

The MP and LP macro-types showed SWC patterns similar to those observed for the HP macro-type, with a reduction in SWC when approaching warmer scenarios and less pronounced SWC oscillations in PaSim compared to DayCent (Fig. S5 and Fig. S6). In the MP macro-type, the SWC simulated by DayCent ranged over ~0.20–0.65 m^3 m^{-3} in the PNE and ~0.05–0.40 m^3 m^{-3} in the PNGP, whereas with PaSim, the SWC was in the range ~0.30–0.45 m^3 m^{-3} in the PNE and ~0.12–0.24 m^3 m^{-3} in the PNGP (Fig. S5). In the LP macro-type, the SWC simulated by DayCent ranged from ~0.20 to 0.65 m^3 m^{-3} in the PNE and ~0.05–0.40 m^3 m^{-3} in the PNGP, while with PaSim, the SWC was in the range ~0.32–0.48 m^3 m^{-3} in the PNE and ~0.12–0.22 m^3 m^{-3} in the PNGP (Fig. S6).

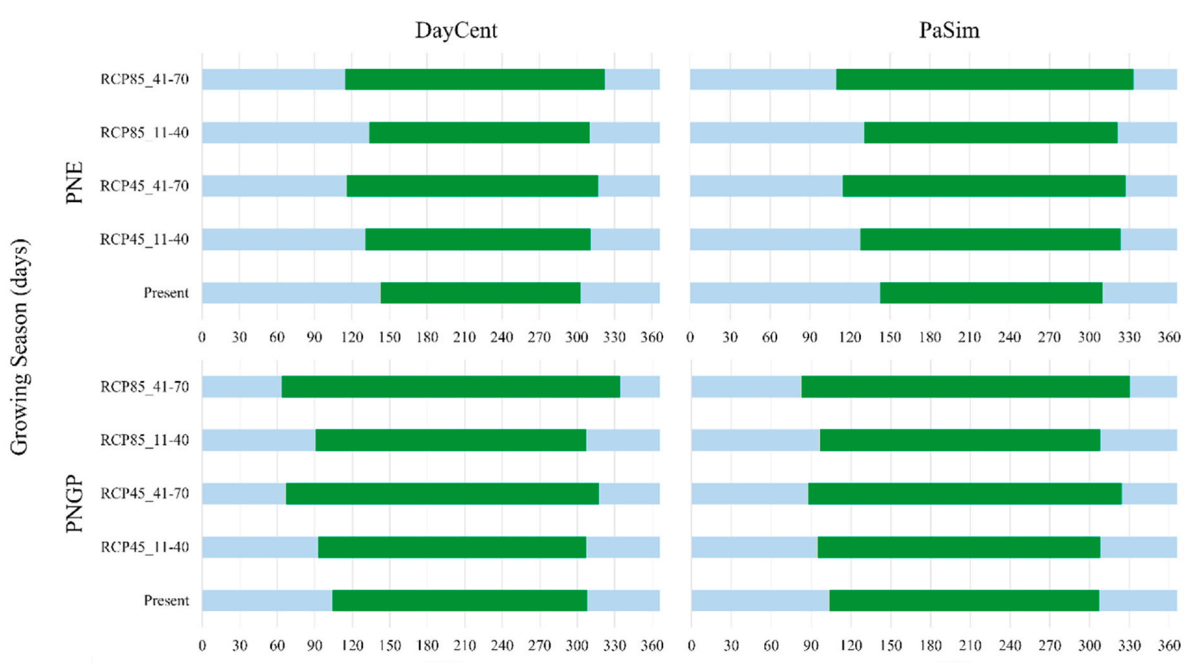

Fig. 3. Estimated durations (20-year mean values) of snow-cover periods (SC, grey bars) and vegetation growing seasons (green bars) with two grassland models for baseline and climate-change scenarios under business-as-usual management in both parks for the high productivity (HP) macro-type. The annual pattern was reported at daily time-step (DOY: day of the year).

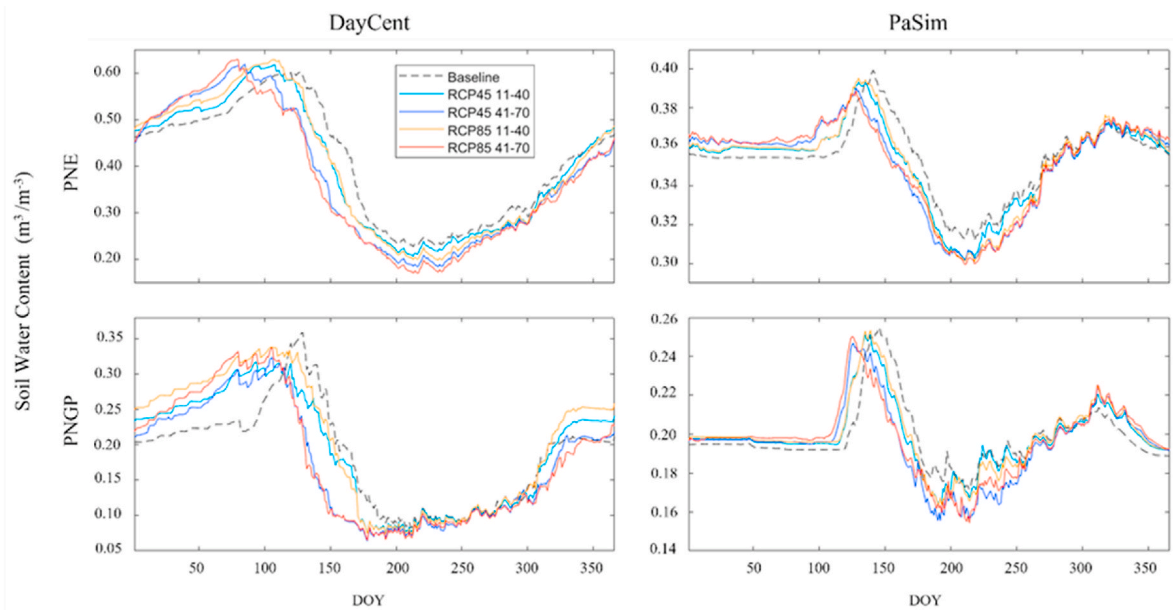

Fig. 4. Simulated annual pattern (20-year mean values) of 0.30-m soil water content (SWC) with two grassland models (DayCent, PaSim), for baseline and climate-change scenarios under business-as-usual management in both parks for the high productivity (HP) macro-type. The annual pattern was reported at daily time-step (DOY: day of the year).

3.6. Aboveground biomass

Fig. 5 shows the yearly average AGB production patterns under baseline management in both parks for the HP macro-type as obtained with the two grassland models, while the yearly average AGB patterns obtained with all alternative management options can be found in the Supplementary material (Figs. S7-S10). The main differences in AGB patterns among alternative management and climate scenarios were assessed based on changes in peak biomass dates (BP1a and BP2a) and corresponding AGB values (BP1b and BP2b), which strongly influence stakeholders' and farmers' decisions in choosing the most suitable periods for grazing.

Under the baseline climate scenarios, DayCent reported the first biomass peak (BP1a) on day 189 (±9 standard deviation) and 190 (±8 standard deviation) for the PNE and PNGP, respectively. Under future climate scenarios, the model indicated an advance of BP1a of 7–10 days for the PNE and 3–7 days for the PNGP (Table S4). In contrast, the biomass peak simulated by PaSim was mainly driven by the effect of grazing, showing only a slight advance under the future scenarios (i.e. 2-3 days) for both PNE (194 ± 4) and PNGP (196 ± 5, Table S5).

For the second biomass peak (BP2a), DayCent indicated that biomass peaks were at day 267 (±14 standard deviation) in the PNE and day 244 (±13 standard deviations) in the PNGP under the baseline scenarios, while future scenarios suggested advanced biomass peaks of 3–15 days

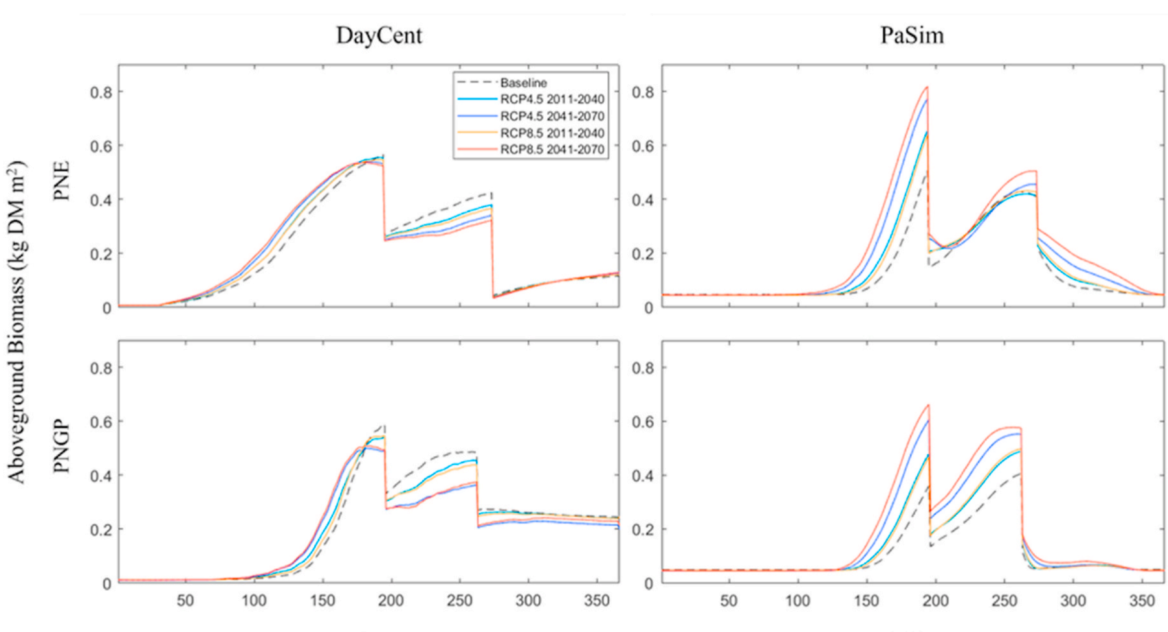

Fig. 5. Simulated annual pattern (20-year mean values) of aboveground biomass (AGB) with two grassland models, for baseline and climate-change scenarios under business-as-usual management in both parks for the high productivity (HP) macro-type. The annual pattern was reported at daily time-step (DOY: day of the year).

in the PNE and contrasting patterns (from −3 to +2 days) in the PNGP (Table S4). PaSim indicated that BP2a was on day 262 (±7 standard deviation) in the PNE and on day 260 (±2 standard deviation) in the PNGP under baseline scenarios, while the future scenarios indicated no or slight delay (1–5 days) in the PNGP and PNE, respectively (Table S5).

In the baseline scenarios, the biomass production of the first peak (BP1b) is similar with both models in the PNE (~0.52 ± 0.06 kg DM m^{-2}), while in the PNGP it is ~38% lower with PaSim compared to DayCent (~0.61 ± 0.17 kg DM m^{-2}). For the second peak (BP2b), the biomass value provided by DayCent (0.44 ± 0.06 kg DM m^{-2}) was close to that provided by PaSim (0.43 ± 0.08 kg DM m^{-2}) in the PNE, while at the PNGP the biomass simulated by DayCent (0.52 ± 0.14 kg DM m^{-2}) was higher compared to that provided by PaSim (0.41 ± 0.06 kg DM m^{-2}). Future patterns for BP2b partly mirror those of BP1b, with PaSim providing an increase in biomass production of ~18% in the PNE and ~41% in the PNGP as the warmer scenarios are approached, while DayCent reported a decrease in biomass production of ~20% in both study areas (Table S4 and Table S5). These results mainly reflect calibration against observational patterns (Fig. S2), with the PaSim production profile indicating faster plant growth in spring, with a distinct peak biomass, and rapid regrowth in summer. This behaviour is much more evident in the climate-change scenarios, resulting in differences in AGB that are about 38–45% higher at the peak with PaSim than with DayCent (Fig. 5), likely due to the absence of sensible water deficits simulated by PaSim (Fig. 4).

For the MP and LP macro-types (Tables S6-S9), the biomass peaks (BP1b and BP2b) partly reflect the trends found in the HP macro-type. Specifically, while PaSim reported an increase in peak biomass value of 50–100% with warmer scenarios in all macro-types for both parks, DayCent indicated a decrease of 3–20% with the sole exception of the LP macro-type in the PNE, where biomass production increased of ~25%. For the impact of adaptation strategies, the value of peak biomass obtained with alternative management practices (i.e. BaU + adaptation management options) was compared with the peak biomass of business-as-usual (BaU) management under projected scenarios. To simplify the reading, only the first biomass peak of the HP macro-type in both parks is reported here (Fig. 6), while the dynamics of the second peak (Fig. S11) and those of the MP and LP macro-types are reported in the Supplementary material (Tables S6, S7, S8 and S9).

Using DayCent, in the PNE under RCP4.5 (blue), on average, the

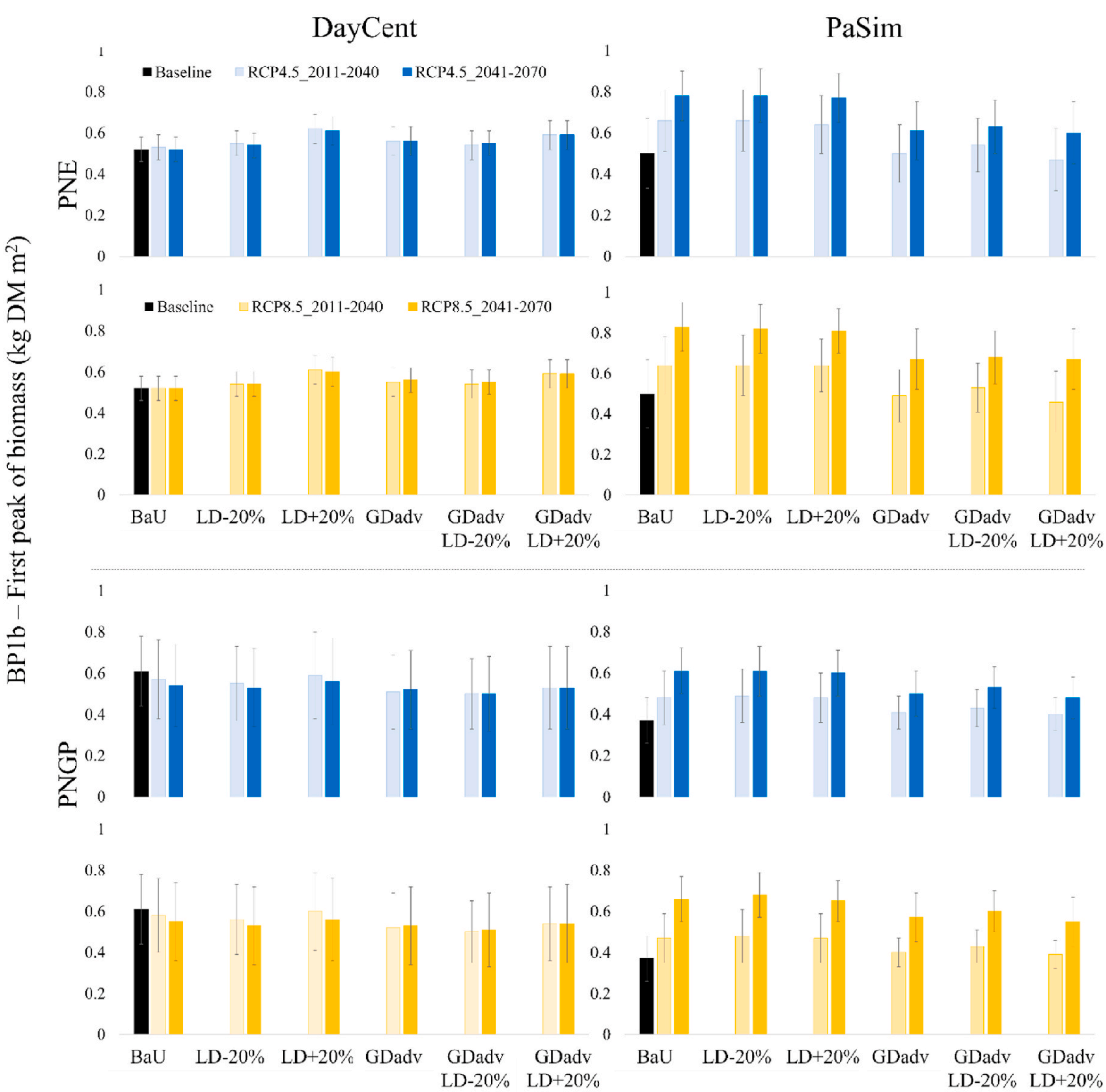

Fig. 6. Changes in the first (BP1b) peak aboveground biomass (kg DM m^{-2}) between business-as-usual management (BaU) under baseline climate (black histogram) and all alternative management options under RCP4.5 (cyan and blue histograms) and RCP8.5 (clear and dark orange histograms) for high productivity pasture (HP) in both parks as provided by DayCent and PaSim. Vertical bars are standard deviations.

highest AGB values at the first biomass peak compared to BaU (0.52 ± 0.06 kg DM m^{-2}) was obtained with LD+20% at both current (+18.3%) and advanced (+13.5%) dates (Fig. 6). Only a slight increase was observed with the other strategies (+1 to +7.7%). Under RCP8.5 (orange), BP1b shows a similar pattern to that observed under RCP4.5, with higher values occurring with the adoption of the LD+20% strategy at both current (+16.3%) and advanced (+13.4%) dates, and a slight mean increase using other strategies (+3.8 to +6.7%). In the PNGP, under RCP4.5, a decrease in BP1b values compared to current BaU (0.61 ± 0.17 kg DM m^{-2}) was observed with all alternative strategies, with the smallest decrease when adopting LD+20% (−5.4%) and the highest when using GDadv_LD-20% (−18%). Under RCP8.5 (Fig. 6b), BP1b showed a similar pattern and magnitude to those observed under RCP4.5, with the largest decrease when adopting Gdadv_LD-20% (−17.2%) and the lowest when using LD+20% (−4.9%).

Using PaSim, all management options showed an increase in peak biomass under all climate scenarios and time-slices. Specifically, in the PNE under RCP4.5, higher BP1b values compared to BaU (0.50 ± 0.17 kg DM m^{-2}) were observed, on average, when the same grazing dates were maintained with all management options (+43%) while a smaller increase was observed when grazing dates were advanced (+11.7%). Under RCP8.5, BP1b shows a similar pattern to that observed under RCP4.5, with higher values occurring when both current (+46%) and advanced (+16.7%) grazing dates are adopted. In the PNGP, under RCP4.5, BP1b values compared to BaU (0.37 ± 0.11 kg DM m^{-2}) were observed, on average, both maintaining the same grazing dates with all management options (+47.3%) and advancing grazing dates (+23.9%). Under RCP8.5, BP1b showed the same pattern as under RCP4.5, with higher values at both current (+53.6%) and advanced (+32.4%) grazing dates. Overall, DayCent showed less variability in peak biomass production in the PNE than in the PNGP, with increasing variability as we approach the far future (2041–2070) with the warmest scenario (i.e. RCP8.5) in both parks. In contrast, PaSim indicated greater variability in peak biomass production in the PNE than in the PNGP, with decreasing variability towards the far future with the warmest scenario in the PNE and contrasting patterns in the PNGP.

For the MP and LP macro-types, PaSim suggested a generalised increase in biomass production that was particularly large (>50%) in the PNE and smaller in the PNGP across all macro-types. In contrast, DayCent reported no decline or a decrease (−6%) in production for the MP macro-type in both parks, regardless of advanced grazing management, while for the LP macro-type it showed contrasting patterns. Specifically, a slight decrease in productivity (−4%) was observed in the PNGP when approaching the warmest scenario, irrespective of management, while a 10–20% increase in productivity was found in the PNE when approaching the warmest scenario at the current grazing date and with different livestock densities (i.e. BaU, LD-20% and LD+20%).

3.7. *Carbon-nitrogen fluxes*

Under current climate and management conditions, PaSim shows limited non-CO_2 emissions in both parks, i.e. 1.9 and 1.6 g C m^{-2} yr^{-1} for CH_4 and 1 and 3 g N m^{-2} yr^{-1} for N_2O emissions, while the C exchanges (NEE) vary from a limited sink in the PNE (−41 g C m^{-2} yr^{-1}) to a limited source in the PNGP (+96 g C m^{-2} yr^{-1}). DayCent represents a higher sinking pattern (−350 and −308 g C m^{-2} yr^{-1}) and lower CH_4 emissions (2.5E-04 and 1.2E-04 g C m^{-2} yr^{-1}) in both parks, while N_2O emissions (0.5 and 3.8 g N m^{-2} yr^{-1}) are in agreement with PaSim (Table 4).

The absolute values of C–N fluxes (Fig. S12) indicate that both models agree in representing the magnitude of these fluxes, and the differences are explained by the inherent features of the two model structures (i.e. animal respiration, enteric fermentation). Heatmaps of the % differences between current conditions (i.e. baseline climate and BaU management) and combinations of alternative climate and management scenarios allow the impact of altered climate and management changes on gas emissions in the two parks to be assessed (Fig. 7).

Table 4
C–N emissions (NEE: net ecosystem CO_2 exchange; CH_4: methane; N_2O: nitrous oxide) from the two study areas (baseline climate), estimated (20-year mean ± standard deviation) using two grassland models. The estimated components of the C budget (GPP: gross primary production; NPP: net primary production; RECO: ecosystem respiration) can be found in Supplementary material (Table S10).

Site	Model	NEE	CH_4	N_2O
		g C m^{-2} yr^{-1}		g N m^{-2} yr^{-1}
PNE	DayCent	−350 ± 14	2.5E-04±~0.0	0.5 ± 0.1
	PaSim	−41 ± 12	1.9 ± 0.9	1.0 ± 0.7
PNGP	DayCent	−308 ± 19	1.2E-04±~0.0	3.8 ± 1.3
	PaSim	96 ± 11	1.6 ± 1.0	3.0 ± 0.9

For NEE, in particular, the PaSim heatmaps show overall trends towards C uptake (more negative NEE values) in both parks (red colour) by moving towards extreme climate conditions (i.e. RCP8.5 and time-frame 2041–2070), reducing livestock density and advancing grazing dates, thus reflecting the baseline AGB pattern (Fig. 5) and the inclusion in the model of an animal component explicitly representing animal respiration and enteric fermentation (Graux et al., 2011).

In contrast, DayCent reports an increase in C sourcing (more positive NEE values) of up to 30% in both parks (green colour) when extreme climate conditions are approached, which is higher when livestock density is reduced. An increase in C uptake of up to 30% was observed at both current grazing date and advanced grazing date when the livestock density is increased.

As for CH_4 emissions, the PaSim heatmap indicates that emissions are higher (~>20%) as livestock density increases. While this pattern is clearly observed in the PNE, the results in the PNGP are more contrasted, as the earlier grazing date also leads to increased CH_4 emissions, even when livestock density is reduced. Projected climate conditions do not appear to influence the pattern of emissions, which are mainly driven by management. In contrast, the CH_4 emissions estimated by DayCent are conditional on climatic conditions, with the highest emission values (up to ~30%) occurring towards the end of the century (i.e. in the period 2041–2070).

Finally, the N_2O emissions estimated by PaSim were mainly driven by the type of management adopted in the two parks, where an increase in livestock density leads to higher emissions (up to ~40%), while a decrease in livestock density reduces emissions to ~50%. Unlike PaSim, DayCent shows contrasting patterns between the two parks. Specifically, N_2O emissions in the PNE are mainly driven by management, where increasing livestock density leads to increased emissions (up to ~30%), while in the PNGP, N_2O emissions are mainly driven by the climate scenarios, with the highest emissions (up to ~40%) for the period 2041–2070 under both RCPs (4.5 and 8.5).

Under the baseline scenario, PaSim-simulated NEE for the LP macro-type showed contrasting patterns. Simulated NEE in the PNE (195 ± 193 g C m^{-2} yr^{-1}) decreased as the warmest scenarios were approached (107 ± 181 g C m^{-2} yr^{-1}), while simulated NEE in the PNGP (151 ± 72 g C m^{-2} yr^{-1}) increased as the warmest scenarios were approached (163 ± 97 g C m^{-2} yr^{-1}), making both parks sources of C (Fig. S14 and Fig. S15). For the MP macro-types, NEE decreased in both parks as warming scenarios approached, with the PNE still being a source of C (448 ± 388 g C m^{-2} yr^{-1}) while the PNGP turned into a sink of C (−91 ± 81 g C m^{-2} yr^{-1}) (Fig. S14 and Fig. S15). In contrast, under the baseline climate scenario, DayCent-simulated NEE in both MP (−126 ± 36 and −163 ± 135 g C m^{-2} yr^{-1}) and LP (−9±19 and −66 ± 41 g C m^{-2} yr^{-1}) macro-types showed negative values in both parks. Under the warmest scenarios, NEE tended to decrease for all macro-types in both parks, with the sole exception of the LP macro-type in the PNE, where it showed a significant increase (+90%) in C uptake (Fig. S13 and Fig. S14).

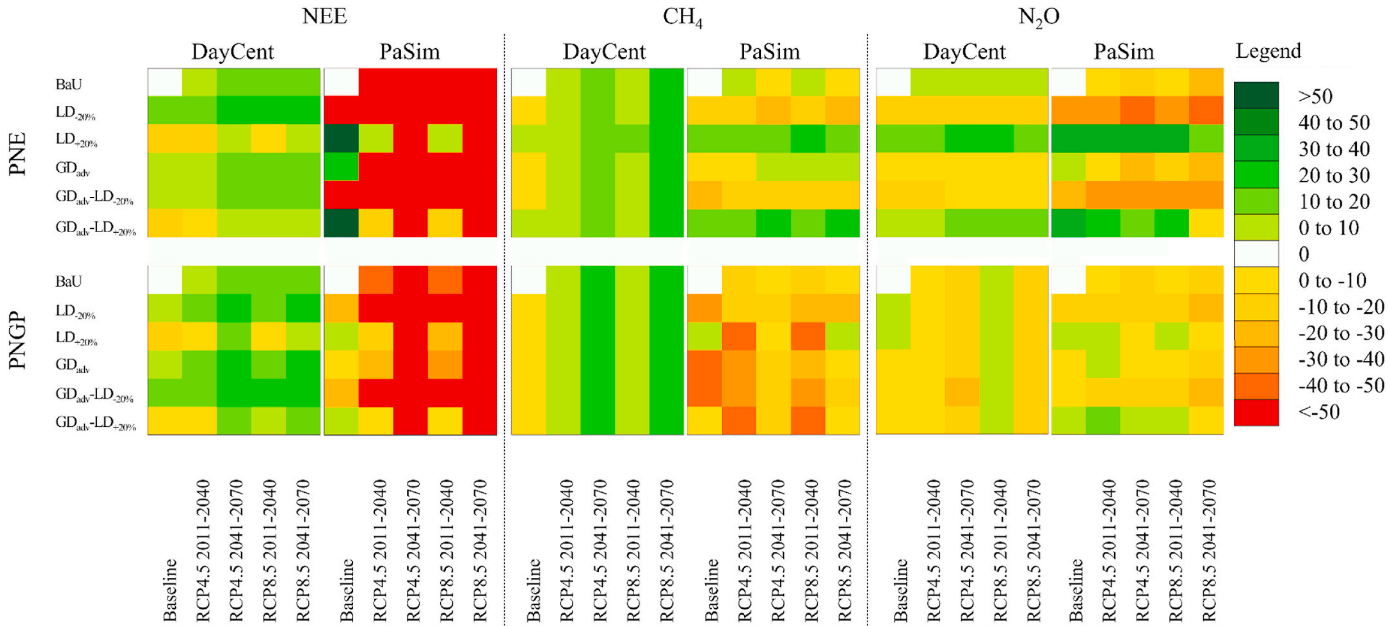

Fig. 7. Heatmap visualization of the relative differences (%) between the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to the current climate and management in the *Parc National des Écrins* (PNE) and *Parco Nazionale Gran Paradiso* (PNGP). Absolute values are given in the supplementary material (Fig. S10).

The patterns of simulated CH_4 and N_2O emissions for the LP and MP macro-types matched those reported for the HP macro-type, where the estimates provided by DayCent were mainly driven by climatic conditions whilst those of PaSim were mainly related to the different management types (Fig. S13 and Fig. S14).

4. Discussion

4.1. Uncertainty in climate-change impact assessments

The issue of uncertainty in model outputs remains a real challenge for the implementation of a modelling framework in decision-making or information processes. Uncertainty can arise from several sources (model structure, parameterisation, input data, initialisation), and the way it manifests itself in model estimates can be difficult to determine and requires interpretation by stakeholders. In this study on climate-change and impact projections in alpine pasturelands, there are different levels of uncertainty on multiple elements (e.g. biophysical, socio-economic). The lack of certainty about the future is primarily related to prospective views at various scales: global (socio-economic scenarios), regional (land and soil use) and field (pastoral systems and management). In addition, the chaotic character of the climate system, with its interannual variability, limits the reliability of climate projections. For instance, the CNRM-ALADIN RCM used to derive forcing factors for downscaling in the alpine context (Rousselot et al., 2012) is considered relevant for high temporal frequency climate studies in the Euro-Mediterranean region (Nabat et al., 2020), but substantial improvement in simulating spatial patterns and annual cycles can be achieved with an ensemble of RCMs (Fantini et al., 2018). In our study, the use of ensemble-mean results to estimate mean trends for alternative RCMs does not take into account the variability associated with different RCMs, which respond differently to the same emission scenarios (Supplementary material, section 3), and represents a simplification in the modelling design.

Also in the case of vegetation response to CO_2 enrichment, there are large uncertainties in the (complex) climate model projections and underlying scenarios. The extent of our imperfect knowledge of the processes (and their interactions) embedded in models (epistemic uncertainties) is reflected in climate modelling, where it mainly concerns atmospheric and biosphere physics, ocean-atmosphere coupling, embedded empirical relationships, parameterisation and spatial resolution. At smaller scales, impact models (such as the grassland models used here) may suffer from the omission or lack of consideration of long-term climate-related processes (e.g. plant acclimation; Sándor et al., 2018) and their interactions (model structure), as well as changes in parameter values due to new climate conditions (which may require re-parameterisation of the model, e.g. Ben Touhami and Bellocchi, 2015). Estimates of future conditions should be presented for review by stakeholders, who can then assess the different levels of uncertainty in the multiple elements and estimate their own relevant projections based on their own area of expertise. In climate-change impact studies, a range of emission scenarios are used to feed climate models and, in turn, impact models. Uncertainty accumulates and propagates throughout the process of climate-change projection and impact assessment, which is carried out by developing fine-scale climate data from coarse-scale climate models and feeding the resulting local-scale scenarios into impact models to determine impacts and assess possible adaptations (Bellocchi et al., 2015). Emission scenarios are neither forecasts nor policy recommendations (Moss et al., 2010) but are selected to map a broad range of climate outcomes for further research and assessment, including impact-modelling studies. In particular, policies contrary to those established to discuss extreme situations (Cao et al., 2022) should not lead to a misuse of RCP8.5 as a no-climate-policy baseline (Pielke and Ritchie, 2021).

Our work demonstrates the value gained by conducting a process to assess the ability of a modelling framework and remotely sensed products to represent past (observational) and future (projected) conditions (two-time frames), based on the outputs of two climate scenarios (radiative forcing), three climate models (climate forcing) and two grassland models (impacts and adaptations). For the latter, the study identified grassland models sufficiently contrasted in their ability to represent processes controlling the dynamics of energy, water and C–N cycles. This choice was made in order to better assess changes in model estimates as a result of changing assumptions and to identify the most significant ones that reflect reality. In addition, this approach helps to identify the range of variability over which model outputs may vary. In the selection phase, two models were identified in which processes are represented at different levels of detail. While PaSim is a complex (grassland-specific) model, simulating C–N and water cycles in detail (with a module dedicated to livestock impact and livestock-atmosphere feedbacks), DayCent is a more empirical (generic) model, with relatively simple relationships between driving variables and fluxes. The two models differ in the representation of soil properties, vegetation type, agricultural practices and environmental forcing, as well as in the initialisation of C pools. The common feature of both models is that they were both designed to be applied considering the grassland community as a crop with parameters describing the morphological and physiological characteristics of the vegetation set at values that should represent the mean traits of the community. Consequently, their ability to characterise interactions in multi-species grasslands is limited, beyond simple mixtures of legumes and grasses (Van Oijen et al., 2020).

4.2. Analysis of climate-change impacts and adaptation strategies

The two impact models adopted agreed in the representation of impacts such as the timing and extent of the growing season and C–N fluxes, whilst divergences were observed for other outputs (e.g. biomass production and peak production). The longer growing season simulated by both models was mainly driven by the extension of the potential growing season in spring, whilst it was limited during autumn-winter, reflecting long-term observations in large alpine regions (Barichivich et al., 2013; Ernakovich et al., 2014; Chen and Yang, 2020). The agreement in the GS outputs suggests the ability of the models to reproduce the changing seasonality of photosynthesis in vegetation, including the beginning and end of the growing season. Although both models were widely applied in various contexts (e.g. Calanca et al., 2007; Abdalla et al., 2010; Vital et al., 2013; Ma et al., 2015; Ben Touhami and Bellocchi, 2015; Pulina et al., 2018; Fitton et al., 2019; Fuchs et al., 2019; 2020; Melo-Damian et al., 2021), this is one of the few studies reproducing the dynamics in alpine pastoral environments, whose multifaceted structure of territory and vegetation coupled with extreme weather conditions is difficult to parameterise due to limited ground-based data for initialisation, calibration and assessment, the complex response of the vegetation growth and information on critical thresholds (e.g. air temperatures, water needs, radiation use efficiency) for mixed plant communities. As evidence of this, the mean plant growth trend simulated with both models (20-year means, Fig. 5) does not seem to reflect the observed pattern of very slow or no growth during the snow season, followed by a rapid increase in biomass accumulation as the snow melts. Generally, after the onset of growth in May or early June, plants grow rapidly, and daily dry matter accumulation can reach a maximum within a few weeks. Grassland models in their current state are not designed to properly represent such a progression of biomass accumulation with the rapid attainment of the first biomass peak. If this behaviour was roughly captured with the calibration work (over three years of AGB data; Fig. S2), and discrepancies appeared less evident with PaSim. Also, the lack of overlap between snow-cover periods and vegetation growing seasons was due to inherent limitations in modelling complex ecosystems. Specifically, biogeochemical models are often unable to discriminate the presence of snow and biomass at the same time in a given surface unit but work separately over it. Thus, to avoid speculation on the residual amount of snow cover and period overlap, the two components were showed separately. Considering that biophysical data show a large degree of variability, and that discrepancies between model estimates and actual data are common despite calibration efforts, research avenues can be opened from this assessment to improve simulation models for such harsh environments as high altitude mountains, where snow beds melt late and plants grow rapidly, but the rapid growth period is short during the middle of the growing season, and this pattern evolves with changing climate (e.g. Wang et al., 2020). The extension of data series is indeed critical, as while calibrated models provide an adequate description of the available data, they may not capture known trends over long time horizons (Bellocchi et al., 2010).

Regarding C–N fluxes, the two grassland models agreed to some extent across study areas and pasture macro-types, with differences in magnitude and patterns likely associated with the inherent structure of each specific C and N sub-model (e.g. Cavalli et al., 2019). The higher C uptake estimated by DayCent compared to PaSim (Figs. S12, S13 and S14) reflects the fact that PaSim estimates the animal contribution to ecosystem respiration, which is not accounted for in DayCent's C budget. Similarly, DayCent estimated limited CH_4 emissions since (unlike PaSim) it does not account for fermentative digestion in its C–N sub-model. The magnitude of N_2O emissions was instead similar between the two models for each study area and macro-type. Overall, the analysis also revealed that GHG dynamics were mainly driven by weather variables in DayCent and by livestock management in PaSim. In this way, PaSim estimates of CH_4, and CO_2 emissions may better reflect observational studies that underpin the impact of management on the annual C cycle of grassland systems (as well as cropping systems), in addition to the variability of local environmental drivers (Pinares-Patiño et al., 2007; Ceschia et al., 2010; Zeeman et al., 2010, 2019). In particular, the importance of quantifying direct CO_2 emissions from grazing animals is emphasised (e.g. Pinares-Patiño et al., 2007). In the absence of observational data to compare with the simulation results, we refer to the literature on the C sequestration capacity of grasslands, which reports contrasting results similar to those of Table 4, which do not exclude that mountain grasslands may oscillate between being sinks and moderate sources (e.g. Zeeman et al., 2010).

Although the two grassland models generally agree in their impact projections, they often differ in essential details, for instance with regard to future peak pasture production. Among the reasons for these different results is the uncertainty inherent in the structure of the models, as well as uncertainty in their parameterisation (and the generalisation of the resulting sets of parameter values to broad regional studies), which in turn makes the projections themselves uncertain. When considering the influence of these uncertainties on the interpretation and understanding of the projections, but also on the direction of the research, it is of great value to know the factors behind these uncertainties (Dietze et al., 2018). DayCent and PaSim showed different responsiveness to water-related factors. The water-limited growth of DayCent rather hinders biomass growth, which, according to climate scenarios, peaks before the start of grazing. With DayCent, the projected scenarios indicate that the water deficit could be the limiting factor for summer growth, which could be lower than in the near-past climate baseline. Consequently, DayCent projections towards a greater C sourcing in the PNE are logically associated with water stress and water-limited biomass production estimated by this model under future scenarios (Fig. 7), which limits photosynthetically assimilated C (gross primary production). This condition requires further study of the uncertainty associated with the model processes. Thus, the mean responses of alpine pasture production (and related outputs) to climate change, obtained with two impact models, should be considered as two extreme situations with respect to plausible future realisations: without water stress (liberal PaSim approach) and with water stress (conservative DayCent approach).

However, there may also be biases in the simulation of SWC, with grassland models that may not be accurate enough to estimate these dynamics. This is often associated with an unrealistically low amplitude of the annual cycle (fluctuation damping, after Wu et al., 2002) of the soil water content curve compared to field measurements (Sándor et al., 2017). It is known that the quality of soil water content simulations can seriously affect model outputs. In case of poor estimation of soil water content, model calibration may result in biased parameter values. Several factors, such as permanent wilting point, root distribution and maximum transpiration rate, are in fact related to the rate of water infiltration into the soil during precipitation events and snowmelt periods (Philip, 1993), which would require detailed datasets for an accurate description. Because of the known role of soil water content in determining evapotranspiration rates, stomatal conductance and other processes, this issue has obvious implications for sites and seasons where water shortage is a typical feature. The response of the models to water-limited conditions is thus questionable, which means that the applicability of the models in semi-arid or arid pastoral systems may not always be supported. This is to some extent related to the ability of roots to extract water from the soil (Volaire and Lelièvre, 2001). The usefulness of soil water content estimation is not as straightforward as for other variables and it is clear the development of improved models is fundamentally necessary for soil hydrology, to rectify structural errors in models and to avoid systematic errors associated with some of the model parameters. These may involve further study of runoff, diffusion and percolation processes, while accounting for features such as ponding water formation, and snowmelt and groundwater movement (Hidy et al., 2016).

4.3. Effect of adaptation measures

The climate-change scenarios exhibited an increase in the air temperature together with higher winter precipitation and prolonged drier conditions during the spring-summer period. This condition logically translates into an accentuation of seasonality, with faster snowmelt and a longer growing season (i.e. +15 to +40 days), providing higher estimated yields and evapotranspiration in both study areas. In this perspective, earlier grazing dates and changes in livestock density, which were *a priori* hypothesised as adaptation options, proved to be coherent to cope with these projected changes.

The earlier grazing date better matched the future biomass peaks simulated by DayCent, also agreeing with observations in alpine regions (i.e. Xu et al., 2016) and thus resulting in a more efficient use of pastures. Although this pattern paved the way for increasing the number of grazing events during the growing season, reduced biomass regrowth due to dry summer conditions inhibited the possibility of further grazing. Reduced soil water availability and increased number of days of heat stress can lead to stomatal closure and inhibit biomass production in summer, which must be taken into account in addition to the increase in plant photosynthetic rates with increasing CO_2 concentration in the atmosphere, not to mention the possible degradation of grasslands due to severe summer drought episodes (Moreau et al., 2007). For that, any excess water in winter can be used to reduce the water deficit when the soil is drier than the field capacity. While this would hint at the possibility of using irrigation even at high altitudes to extend the number of grazing events, the balance between costs (e.g. of energy and irrigation systems) and benefits (e.g. increased end product) would need to be thoroughly investigated. In contrast, in the scenario depicted by PaSim, which would be too liberal in the sense that it simulates optimal growing conditions in midsummer (i.e. without an expectation of summer water stress), this adaptation strategy would not be necessary.

The model results indicate higher biomass production when LD is increased (although changes in livestock density do not particularly modify production levels). This result is likely due to a higher N availability to plants provided by a higher amount of N excreted in faeces and urine which, together with a simulated non-linear effect of grazing on production, led to a faster and higher biomass regrowth rate. While both models consider N from excretion and the effect of grazing on production, detrimental effects on biomass production due to the impact of soil compaction when animal density increases were not considered. However, higher animal numbers may increase soil compaction, resulting in poor water retention and altered (slower) mineralisation processes that may reduce biomass regrowth and forage quality (Li et al., 2017). In this perspective, the response of biomass growth to changes in LD could be partly overestimated or affected by a certain level of uncertainty in both models. Despite these limitations, we can conclude that the alpine region is set to become warmer and wetter, and that yields in these areas are highly dependent on both water availability and the type of management adopted. The projected climate scenarios and adaptation options considered are not expected to substantially worsen the GHG balance, although a caveat is that C sequestration by pasturelands may be reduced in a warmer climate. However, there is a need to further develop and evaluate grassland models for key processes and outputs, such as CO_2 and non-CO_2 emissions, as well as to systematically and more accurately characterise the extent and timing of human intervention in a range of grazing areas covering broader climatic gradients.

5. Concluding remarks

Research on mountain pastures in two western alpine parks shows that variations in climate-change impacts and adaptations of these systems are linked to natural and anthropogenic factors to different degrees depending on the pastoral macro-type class studied (defined by an altitudinal productivity gradient). While the use of modelling approaches and remote-sensing products in vulnerability studies is not new *per se*, the integration of these tools within alpine pastoral communities has a point of originality, as the analysis carried out can help to solve multidisciplinary challenges such as which areas are vulnerable and how they compare under harsh climatic conditions. The findings of this study indicate an increase in the length of the growing season by 15–40 days, leading to expected changes in the timing and amount of biomass production and a likely decrease in biomass regrowth during the summer season due to prolonged drought conditions. The greatest uncertainties were found in the GHG balance and mitigation capacity of alpine pastures, where contrasting patterns were observed between the impact models used (ranging from -350 to $+100$ g C m^{-2} yr^{-1} for NEE), mainly due to the different flux simulation approaches. Similarly, earlier grazing dates appeared to be the most suitable adaptation strategy, especially when combined with increasing livestock density, while decreasing livestock density did not show any significant change.

The elaboration of adaptation measures, carried out in this study with local herding and farming communities, provides a basis for appropriate agricultural policy and land management measures adapted to ongoing climate change. However, although different modelling approaches are able to capture distinct aspects of the adaptive process, they tend to be applied in relative isolation, without producing unified representations. The corollary of this is that the usefulness of future projections of climate-change impacts by grassland models, such as those represented here, is strongly influenced by the quality of the climate model data used to run them and the field data used to calibrate them. Social impact assessment studies are now needed to examine how production/biophysical/biogeochemical impacts, i.e. the effects of climatic anomalies on alpine pasture performances, propagate through the socio-economic and political system. Such an integrated approach, which would include the potential for adaptation and adjustment to climate pressure, would reflect the reality of pastoral communities much better than the modelling used and raises fruitful research questions on the vulnerability of alpine territories and their adaptive capacity.

Author contributions

Conceptualization, Brilli Lorenzo, Bellocchi Gianni; **methodology**, Brilli Lorenzo, Bellocchi Gianni, Filippa Gianluca, Galvagno Marta, Cremonese Edoardo; **software**, Brilli Lorenzo, Moriondo Marco, Filippa Gianluca, Galvagno Marta, Cremonese Edoardo, Martin Raphael; **validation**, Brilli Lorenzo, Martin Raphael; **formal analysis**, Brilli Lorenzo, Bellocchi Gianni, Moriondo Marco, Filippa Gianluca, Martin Raphael; **investigation**, Brilli Lorenzo, Bellocchi Gianni, Martin Raphael; **resources**, Argenti Giovanni, Bassignana Maurizio, Bindi Marco, Dibari Camilla; **data curation**, Brilli Lorenzo, Moriondo Marco, Filippa Gianluca, Galvagno Marta, Cremonese Edoardo, Martin Raphael; **writing—original draft preparation**, Brilli Lorenzo, Bellocchi Gianni; **writing—review and editing**, Argenti Giovanni, Bassignana Maurizio, Bonet, Richard, Choler Philippe, Della Vedova Muriel, Dibari Camilla, Leolini Luisa, Piccot Anais, Stendardi Laura, Targetti Stefano,

visualization, Brilli Lorenzo, Bellocchi Gianni; **supervision**, Brilli Lorenzo, Bellocchi Gianni; **project administration**, Bellocchi Gianni, Dibari Camilla, Argenti Giovanni, Bassignana Maurizio, Bindi Marco; funding **acquisition**, Argenti Giovanni, Bassignana Maurizio, Bellocchi Gianni, Bindi Marco, Dibari Camilla.

All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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