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1 **Uncertainties in the adaptation of alpine pastures to climate change**

2 **based on remote sensing products and modelling**

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19 20 **Highlights**

- 21 • Alpine pastures are vulnerable to climate change.
- 22 • Remote sensing and modelling support vulnerability analysis in the western Alps.
- 23 • Earlier grazing, not changes in cattle density, copes with increased vulnerability.
- 24 • Summer water stresses and warming may lower C sequestration by pastures.

27 **Abstract**

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

46

47 *Keywords:* alpine pastures, climate-change adaptation, modelling, remote sensing

48

49 **1. Introduction**

50 Mountain pastures are important livelihood systems in the European Alps, with a
51 multifunctional form of land use encompassing agriculture, outdoor recreation, and tourism as well
52 as conservation needs (Wanner et al., 2021). Rich in terms of biodiversity (Kurtogullari et al., 2020)
53 and cultural heritage (Jourdain-Annequin and Duclos, 2006), alpine pastures fulfil economic, social
54 and environmental functions at the same time (Bengtsson et al., 2019). They provide low-cost
55 fodder for grazing livestock during the summer period and - where traditional transhumance
56 systems are present – represent a complementary resource for Mediterranean pastoral systems
57 (Caballero et al., 2009). Shaped by pastoral activities, alpine pastures have undergone multiple
58 transformations over the centuries, mainly driven by the fragile balance between maximising
59 agricultural productivity and the limits imposed by the temporal and spatial dynamics of the climate
60 and forests-grasslands interactions (Kurz, 2013). However, alpine pastoralism manifests its
61 fragility in the face of the changes induced by recent global warming. Climate changes and their
62 impacts are visible in the alpine region, which has experienced a temperature increase of almost 2
63 °C over the last century, along with an important reduction of precipitation in the summer season
64 (Gobiet et al., 2014). Specifically, droughts have been one of the main manifestations of climate
65 variability. Corresponding to periods of abnormally low precipitation, they alter grassland
66 productivity and quality (Nettier et al., 2010; Dibari et al., 2016) by offsetting the positive effect
67 of summer heatwaves on canopy greenness (Corona-Lozada et al., 2019), as seen in the European
68 Alps following a series of droughts (Calanca, 2007). The response of European mountain plant
69 assemblages to increasing temperatures (thermophilisation) also suggests a progressive decline of
70 cold-tolerant high-altitude grassland communities (Gottfried et al., 2012) and landscape
71 modifications with warming-induced upward range shifts (Engler et al., 2011). This may lead to
72 both a decrease in areas suitable for pasture and a reduction in pasture diversity driven by low-

73 quality vegetation types in the Alpine chain (Dibari et al., 2020), together with changes in grazing
74 practices (Dibari et al., 2021). This is critical because most impacts on grassland ecosystems can
75 be related to overgrazing and changes in the timing of livestock transhumance, with high stocking
76 densities in particular causing a range of negative impacts on plant and animal communities, as
77 observed in central France (Dumont et al., 2009) and in the Italian Maritime Alps (Negro et al.,
78 2011).

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

91 This posture forms the basis of the design and implementation of this study started in 2017 in
92 two representative areas of the western alpine territory: the *Écrins* (France) and *Gran Paradiso*
93 (Italy) national parks (PNE and PNGP, respectively). In the pasturelands of the two parks, ground-
94 based and remotely sensed observation systems, as well as model-based simulations were used to
95 identify efficient management strategies able to support pastoral management and the sustainability
96 of pastoral systems. Modelling adaptation strategies was supported by a participatory-based

97 process bringing together different local stakeholders in the two case study areas. The target of the
98 modelling concerned the performance of pastoral systems and in particular the definition of
99 production while minimising environmental impacts. Remote sensing supports such modelling by
100 offering information on the spatial and temporal variation of important canopy state variables
101 which would be difficult to obtain otherwise. The involvement of local pastoralists was the basis
102 for the design and assessment of the analytical framework concerning the climate-change
103 adaptation strategies.

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

108

109 **2. Materials and Methods**

110 *2.1. Study areas*

111 In its wide-ranging perspective, the study considered three macro-types of pastoral vegetation
112 (high, medium and low productivity) located at different altitudes (low, medium and high) in two
113 national parks of the western Alps, on either side of the French-Italian border (Stendardi et al.,
114 2022, Filippa et al., 2022) (Fig. 1).

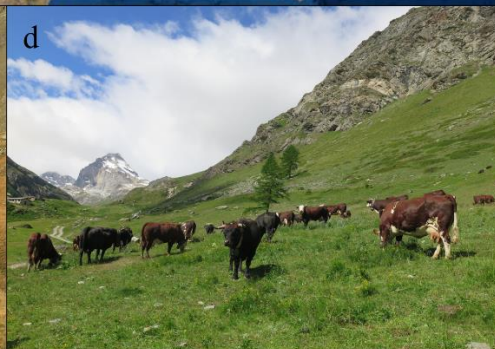
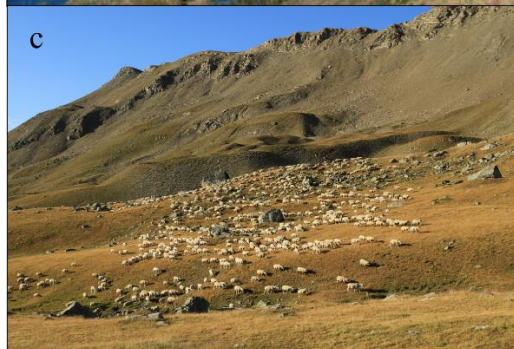
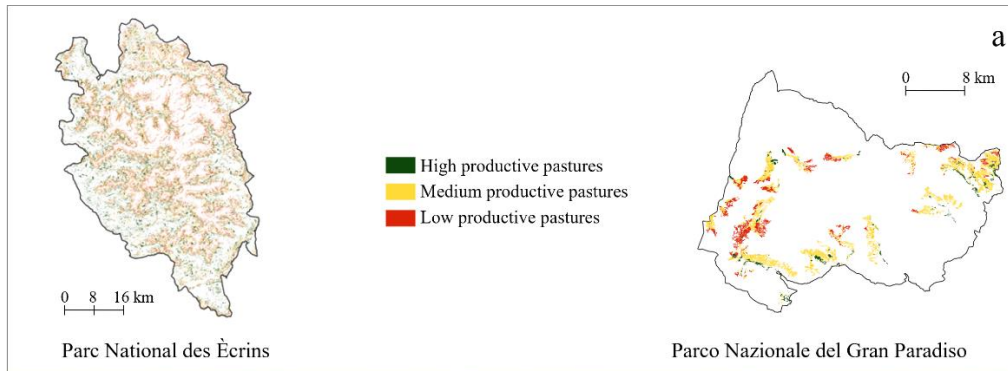
115 Established in 1973, the *Parc National des Écrins* (PNE) covers an area of ~91800 ha
116 (approximately in the range 44° 03'-45° 05' N and 06° 05'-06° 35' E) in the two French
117 departments of Hautes-Alpes (region Provence-Alpes-Côte d'Azur) and Isère (region Auvergne-
118 Rhône-Alpes). It includes *c.* 70,000 ha of summer pastureland (~30% of the park area), which is
119 grazed by about 115,000 sheep (75% of the total stocking rate), 5,800 cows and >1,000 of goats
120 and horses. Transhumance (which is declining across Europe) is still relevant in the study area,

121 with ~1/3 of the total sheep stocking rate in summer pasture being involved in transhumance (Brien,
122 2018).

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

130 The surface of both parks is represented by mountainous environments, located from low valleys
131 to very high mountains, with the highest peaks of 4,102 m a.s.l. (Barre des Écrins) and 4,061 m
132 a.s.l. (Gran Paradiso Mountain) for the PNE and PNGP, respectively. The territories of the two
133 protected areas are characterised by forests, from broadleaf in the lower parts to coniferous in the
134 higher parts, and by mountain and alpine grasslands and pastures. The climate is generally alpine,
135 but with different microclimatic conditions due to high variability in topographical features
136 (elevation, aspect and slope). In addition, there are different lithological formations. All these
137 complex and variable conditions produce a large typology of different plant communities
138 characterised by a great richness of vegetation.

139



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

146
 147 The territories of the two parks lie within the areas of three vegetation macro-typologies (Table
 148 1), which group the main plant communities that can be found in the subalpine and alpine pastures
 149 of the French Southern Alps (Jouglet, 1999), the Vanoise and Aosta Valley (Bornard et al., 2007)
 150 and Piedmont in Italy (Cavallero et al., 2007). These typologies have been harmonised in 13
 151 categories of common pastures that were further grouped in three productivity macro-types
 152 (Stendardi et al., 2022).

153
 154 Table 1. Description of three pastoral macro-types (HP: high productivity; MP: medium
 155 productivity; LP: low productivity) in the two study areas (PNE: *Parc National des Écrins*; PNGP:
 156 *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

157 ¹ A-I - Alpine intermediate: sparse vegetation on medium to moderate slopes, windy ridges and bumps in the alpine
158 level (main species: *Carex curvula*, *Trifolium alpinum*, *Avenula versicolor*); SA-II - *Nardus* swards: on lowlands and
159 slopes in the subalpine or alpine level, vegetation of medium height (0.2-0.3 m), not very dense, dominated by *Nardus*
160 *stricta* (main species: *Nardus stricta*, *Carex sempervirens*, *Trifolium alpinum*, *Festuca rubra*); A-II – nival: sparse
161 vegetation in snow combes and moderate slopes in alpine and nival environment (main species: *Alchemilla*
162 *pentaphyllea*, *Salix herbacea*, *Carex foetida*, *Plantago alpina*); S-II - subalpine intermediate: vegetation in flatlands
163 and low slopes of the subalpine level with medium-rich soil, 0.3 to 0.5 m high, dense grassy patches dominated by fine
164 to medium-leaved *Gramineae* (main species: *Festuca rubra*, *Agrostis capillaris*, *Phleum alpinum*, *Alchemilla*
165 *xanthochlora*); S-III - *Patzkea paniculata* swards: on medium sunny slopes in the subalpine level, vegetation very tall
166 (over 0.5 m), very dense, dominated by *Gramineae* with long, thick leaves, especially *Patzkea paniculata* (main
167 species: *Patzkea paniculata*, *Festuca rubra*, *Carex sempervirens*).
168

169 2.2. Data collection

170 The Normalised Difference Vegetation Index (NDVI) is a standard way to determine vegetation
171 cover and productivity. High NDVI values (approximately >0.7-0.8) indicate healthy vegetation,
172 dense and productive canopies, while low NDVI values indicate land with little or no vegetation
173 or stressed canopies. Satellite-derived NDVI data for the period 2018-2020 were retrieved for the
174 two study areas by processing the Sentinel-2 imagery. The images (10-m spatial resolution,
175 level2A) were atmospherically and topographically corrected with the Sen2Cor processor
176 (<https://step.esa.int/main/snap-supported-plugins/sen2cor>). The images were filtered on a per-pixel
177 basis with the scene classification (SCL) map, retaining only top quality, and cloud- and shadow-
178 free pixels. The downloading and processing of the data were performed on Google Earth Engine
179 (<https://earthengine.google.com>) with a dedicated Python (<https://www.python.org>) script

180 (Hufkens, 2017). Seasonal NDVI trajectories were used to retrieve growing season start and end
181 based on a fixed threshold method (20% seasonal amplitude) similar to what proposed by Shen et
182 al., (2015a). These dates were then compared to those retrieved from the snow cover seasonal
183 pattern (table 1) and found to be in good agreement. Aboveground biomass (AGB) and leaf area
184 index (LAI) were measured in both areas following standardised protocols (Filippa et al., 2015).
185 An empirical model was fitted between AGB/LAI observations and the corresponding S2-derived
186 NDVI, and the resulting equations (Supplementary material, section 1) were then used to convert
187 S2-NDVI data in AGB and LAI data for the three productivity macro-types of each study area.

188

189 2.3. *Climate-change scenarios*

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

195 Climate data from three Regional Climate Models (RCMs) from Med-CORDEX (Ruti et al.,
196 2016) - CNRM-ALADIN ($0.11^\circ \times 0.11^\circ$), ICTP-RGCM4 ($0.44^\circ \times 0.44^\circ$), and CMCC-CCLM4
197 ($0.44^\circ \times 0.44^\circ$) for the reference period 1981-2010 (near past) and for two future time-slices 2011-
198 2040 (near future) and 2041-2070 (mid future). For near past period ambient CO₂ concentration
199 was fixed to 400 ppm. For future periods, Representative Concentration Pathways 4.5 and 8.5
200 (RCP4.5, RCP4.5) were selected, with ambient CO₂ concentration at 450 (RCP4.5) and 470 ppm
201 (RCP8.5) for near future and 540 and 670 ppm for mid future.

202 The delta-change approach was applied as a downscaling procedure, where the observed daily
203 weather data available for each given site were modified using as forcing factors the outcomes

204 obtained from the RCM simulations. These were calculated as the mean absolute monthly
205 differences between the RCM baseline (1981-2010) and the future RCM periods selected for
206 simulations (2041-2070, 2071-2100) for minimum and maximum air temperatures and the
207 percentage variation in monthly cumulated rainfall, wind speed and solar radiation. These
208 differences were then added, month by month, to the observed daily meteorological data from PNE
209 and PNGP to derive future weather data that were used to feed model simulations for future periods.
210 The three daily datasets deriving from RCMs downscaling were finally merged into a single dataset
211 reproducing the mean change in climate conditions for each study area in RCP4.5 and 8.5 for 2031-
212 2040, 2041-2070 and 2071-2100 time-slices.

213

214 2.4. *Participatory approach*

215 To understand the impact of climatic events and changes in grazing practices, and to preserve
216 (or restore) the sustainable management of these areas, the "Sentinel Alpine Pastures" programme
217 focuses on how to adapt to different phenomena as part of a long-term approach to the complex
218 dynamics of climate change, to anticipate adaptive strategies (Dobremez et al., 2014). These
219 sources of information thus represent a unique opportunity to environmentally characterise these
220 pastoral areas by using advanced techniques such as remote sensing and process-based simulation
221 modelling. As a basis for the design and assessment of the analytical framework, a participatory
222 process was conducted since 2018 with groups of *c.* 100 local stakeholders in each park including
223 farmers, technicians, representatives of the two parks and officials from local institutions. The
224 participatory process involved meetings, interviews and informal discussions that took place in
225 parallel with data collection and territorial analysis (Targetti et al., 2019). Participation addressed
226 three main topics: i) current pastoral practices, related barriers and incentives, and key drivers of
227 socio-economic change; ii) effective adaptation measures already implemented in the western

228 Alps; and iii) which measures should be prioritised (Piccot et al., 2022). In this study, we assessed
229 the effect of prioritised adaptation options from a modelling perspective as it emerged from the
230 participatory approach, recognising the limited set of modelling assumptions contained in the
231 adaptation requests, which represent a fraction of plausible adaptations and a step towards
232 transformative changes (Holman et al., 2019).

233

234 2.5. *Grassland modelling*

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

246 Here, the soil-vegetation generic model DayCent (Parton et al., 1994, 1998) and the grassland-
247 specific model PaSim (Riedo et al., 1998) were chosen to simulate alpine pastures. Both provide a
248 mechanistic view of the multiple processes and interactions occurring in grassland systems and are
249 able to simulate grassland productivity and C and N fluxes under alternative management options.
250 DayCent is the daily time-step adaptation of the biogeochemical model CENTURY (Parton et al.,
251 1994), which simulates plant growth, soil C dynamics, N leaching, gaseous emissions (e.g. nitrous

252 oxide) and C fluxes (e.g. net ecosystem exchange) in a variety of managed ecosystems. PaSim is a
253 grassland-specific ecosystem model consisting of detailed sub-models for vegetation, animals,
254 microclimate, soil biology, soil physics and management to simulate grassland productivity and C-
255 N fluxes.

256

257 2.6. *Simulation design*

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

262 Model calibration (suite 1) was carried out over the years 2018 to 2020 in the two parks, setting
263 management practices (grazing intensity and periods) as defined in Table 2 (one or two short
264 periods with short-term, intensive management), on a set of parameters (Table S1 and Table S2) to
265 which model sensitivity was determined in previous studies for both DayCent (e.g. Fitton et al.,
266 2014; Nécipalová et al., 2015) and PaSim (e.g. Ben Touhami et al., 2013; Ma et al., 2015; Pulina et
267 al., 2018; Sándor et al., 2018). The agreement between simulated and observed dry matter (DM)
268 was assessed by inspection of time-series graphs (fluctuations of output variables over time), and
269 numerically, through two commonly used performance metrics of model evaluation (Richter et al.,
270 2012): root mean square error (best, $0 \leq \text{RMSE} < +\infty$ g DM m⁻², worst) and coefficient of
271 determination (worst, $0 \leq R^2 \leq 1$, best).

272 Table 2. Management of three pastoral macro-types (HP: high productivity; MP: medium productivity; LP: low productivity) in the two
 273 study areas (PNE: *Parc National des Écrins*; PNGP: *Parco Nazionale Gran Paradiso*). Grazing 1 and Grazing 2 refer to the first and
 274 second (if present) grazing periods expressed as days of the years, respectively, over the investigated macro-types. Livestock Standard
 275 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 1 st						Grazing 2 th					
		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	-	-	-	-	-	-

276

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

280 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 ₂ O emissions from the N cycle)
	Net primary production	NPP		
	Ecosystem respiration	RECO		
	Gross primary production	GPP		
	Methane	CH ₄		
	Nitrogen dioxide	N ₂ O	kg N m ⁻² yr ⁻¹	
Soil water content	SWC	m ³ m ⁻³	Soil water content	

281

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

287 Simulation results are presented separately per study area, comparing DayCent and PaSim
288 outputs with satellite-derived AGB data (suite 1). Time-series graphs are presented to illustrate the
289 dynamics of selected variables (AGB, SWC, C fluxes and CH₄ and N₂O emissions) for suites 2 and
290 3, as well as two-dimensional colour data visualisations (heatmap graphs).

291

292 **3. Results**

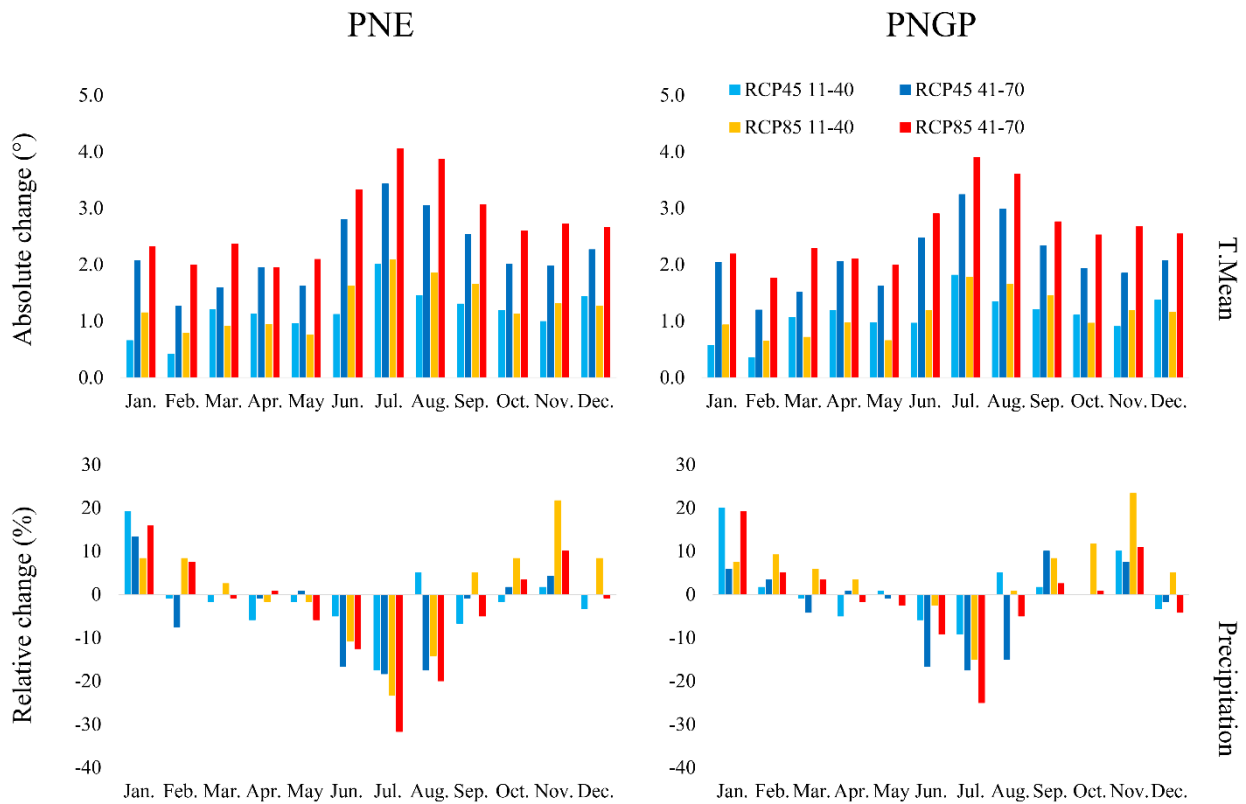
293 For greater clarity in the presentation of results and discussion, we present in detail only the
294 results obtained in the high productivity macro-type for which a full modelling analysis is available.
295 We also briefly present the results obtained in the medium and low productivity macro-types,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

297

298 *3.1. Climate analysis*

299 The monthly distribution of air temperatures in the two study areas (Fig. 2), averaged from the
300 outputs of the ICTP-REGCM4, CMCC-CCLM4 and CNRM-ALADIN climate models, showed an
301 overall increase in temperature towards the far future, similar for both parks, with a distinct
302 seasonal trend, with the highest increases in summer (+4 °C at PNE and +3.7 °C at PNGP under
303 the warmest scenario) and the lowest in autumn-winter (+2.5 °C at PNE and +2.3 °C at PNGP
304 under the warmest scenario). Analysis of simulated monthly rainfall data (Fig. 2) showed increases
305 in autumn-winter (November-February) relative to the baseline in both scenarios and sites (PNE:

306 +3.3% and +9.9%; PNGP: +5.4 % and +9.5 %, for RCP4.5 and RCP8.5, respectively), while
 307 spring-summer exhibited a strong decrease in rainfall, more pronounced in the PNE (-11.7% and -
 308 18.8%, for RCP4.5 and RCP8.5, respectively) than in the PNGP (-10 % in both scenarios). In both
 309 parks, no clear trend was observed, nor was a clear pattern evident when analysing the differences
 310 between time-slices, as there was no trend of increasing/decreasing monthly precipitation in the
 311 progression from the near to the far future.



312
 313 Figure 2. Absolute change (°C) in monthly mean air temperature (top graphs) and relative change
 314 (%) of monthly cumulated rainfall (bottom graphs) generated in the two study areas with the RCM
 315 ensemble (ICTP-REGCM4, CMCC-CCLM4 and CNRM-ALADIN) for two climate scenarios
 316 (RCP4.5, RCP8.5) and two future periods - 2011-2040 and 2041-2070 - over the baseline period
 317 1981-2010.

318

319 3.2. *Suite 1 of simulations: model evaluation against observed data*

320 The resulting sets of parameter values allowed the outputs of the two impact models to be
321 compared for each study area. Plant parameters served to accommodate changes in the sward
322 structures driven by local environmental conditions and management. Although no formal
323 sensitivity analysis was conducted for the model parameters, the calibration applied separately to
324 each study area allowed us to explore the variability of parameter values between the two parks.
325 An indication from the calibration work is that, for both models, the parameter values can be
326 considerably different across alternative conditions (Table S1 and Table S2). For instance, the
327 different vegetation patterns in the two parks are reflected in the PaSim parameter “maximum
328 specific leaf area”, whose lower values tend to be associated with the PNGP (e.g. for the high-
329 productivity pastoral vegetation macro-type, the value decreased from $\sim 37 \text{ m}^2 \text{ kg}^{-1}$ in the PNE to
330 $\sim 22 \text{ m}^2 \text{ kg}^{-1}$ in the PNGP). Photosynthetic rates estimated with PaSim (Table S1) were lower in the
331 PNGP during the reproductive stage ($pmco2rep \sim 25 \mu\text{mol C m}^{-2} \text{ s}^{-1}$ against $\sim 32 \mu\text{mol C m}^{-2} \text{ s}^{-1}$ in
332 the PNE) and higher during the vegetative stage ($pmco2veg \sim 16 \mu\text{mol C m}^{-2} \text{ s}^{-1}$ against $\sim 13 \mu\text{mol}$
333 $\text{C m}^{-2} \text{ s}^{-1}$ in the PNE). With DayCent, air temperature thresholds (optimal and maximum), the
334 number of soil layers influencing water and nutrient availability, and the allocation of C to different
335 plant organs influenced plant growth and C fluxes. Specifically, for the high-productivity pastoral
336 vegetation macro-type, the coefficient for calculating potential monthly aboveground biomass
337 production as a function of solar radiation outside the atmosphere lowers from 4.1 in the PNGP to
338 $\sim 1.0 \text{ m}^2 \text{ kg}^{-1}$ in the PNE, while the thresholds for optimal air temperatures were slightly higher in
339 the PNGP than in the PNE (Table S2).

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

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

346

347 *3.3. Suite 2 and 3 of simulations: impacts of future scenarios and adaptation strategies*

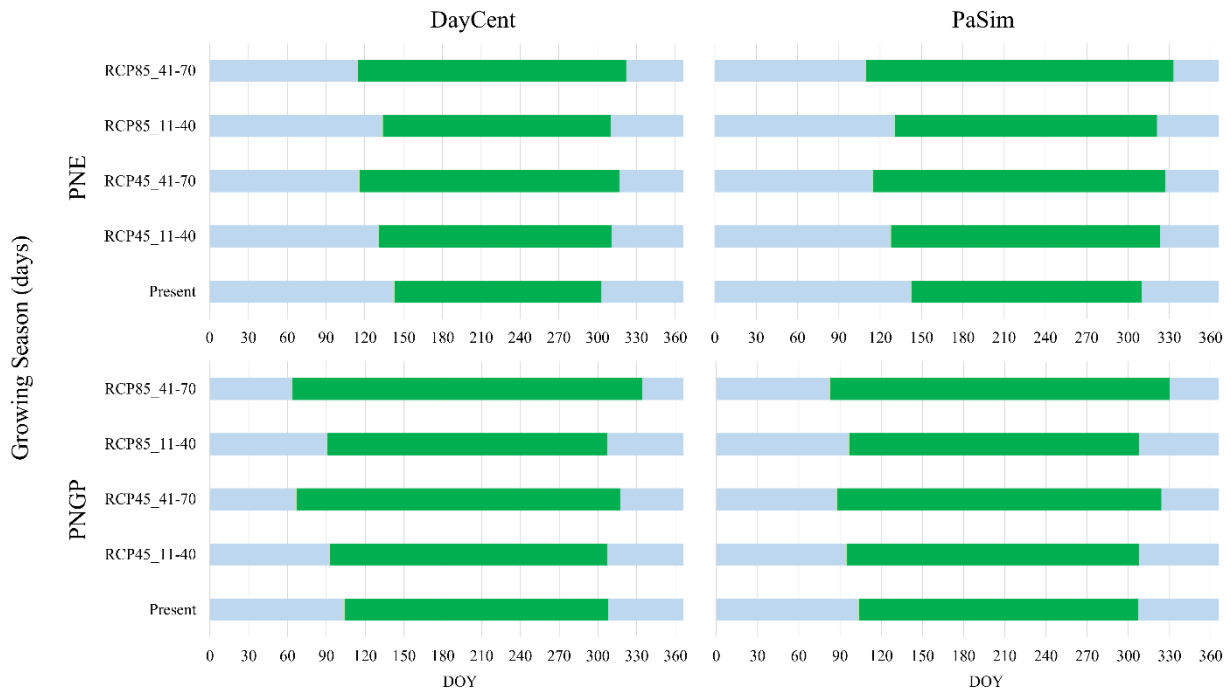
348 For both parks, we assessed the sensitivity of the two grassland models to (suite 2) climate
349 change (RCP4.5 and RCP8.5 for the near and far future) with business-as-usual (BaU) management
350 and to (suite 3) management scenarios (GDadv and LD±20%). Multi-year mean responses for
351 selected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

353

354 *3.4. Growing season*

355 Under the climate-change scenarios, with both grassland models, the estimated length of the
356 snow season decreases in both areas due to earlier spring snowmelt and later autumn/winter
357 snowpack accumulation. This condition leads to an earlier onset and later end of the growing season
358 (GS) in both parks, especially in the far future (i.e. 2041-2070) (Fig. 3). Specifically, using
359 DayCent, the start of the growing season (GSs) was on average 11 and 28 days earlier in the PNE,
360 and 12 and 39 days earlier in the PNGP, for the 2011-2040 and 2041-2070. The end of the growing
361 season (GSe) was delayed on average 8 and 17 days in the PNE, and 17 days in the PNGP for 2041-
362 2070. In contrast, no changes in GSe were observed in PNGP for the period 2011-2040.

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



368

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

373

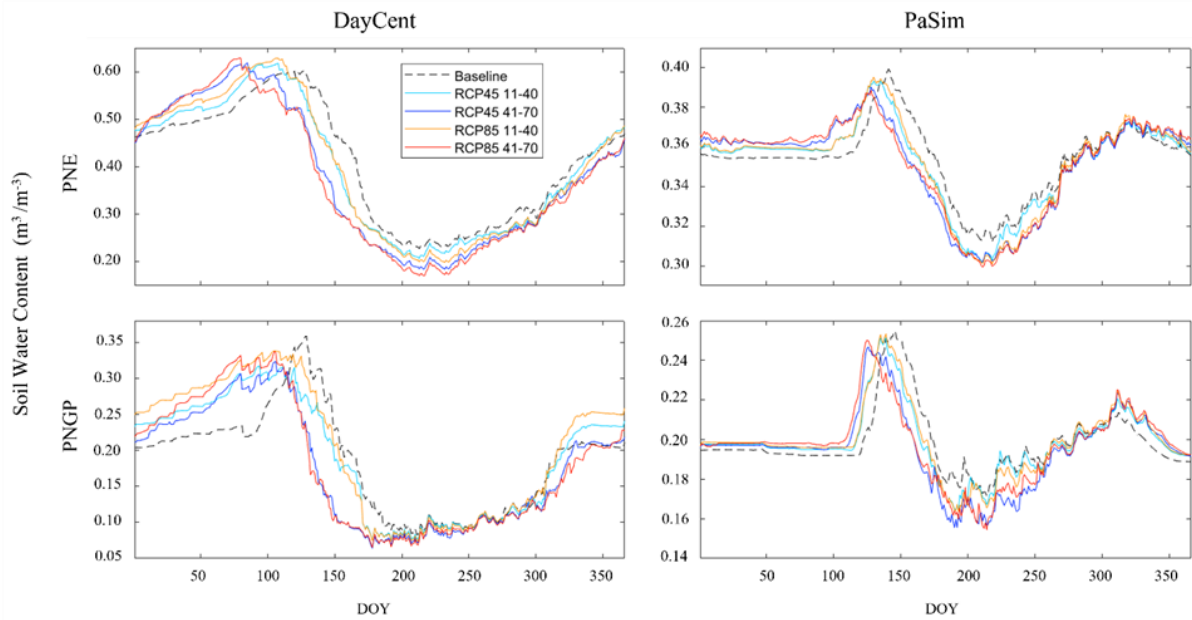
374 The MP and LP macro-types showed similar growing season patterns to those observed in the
 375 HP macro-type, with GSs advanced and GSe delayed towards the end of the century, with the
 376 largest impacts using RCP8.5. For all three macro-types, DayCent reported a mean GS extension
 377 ranging between 15 and 40 days in the PNE, and between 12 to 45 days in the PNGP for the periods
 378 2011-2040 and 2041-2070, respectively. Using PaSim, the increase in GS ranged between 17 and
 379 44 days in the PNE, and between 23 and 35 days in the PNGP for the periods 2011-2040 and 2041-
 380 2070, respectively (Fig. S3 and Fig. S4). Overall, both models suggested a longer growing season
 381 of 2 to 5 weeks when approaching the warmest scenarios.

382

383 3.5. Soil water content (0.30 m topsoil)

384 Under the climate-change scenarios, both models indicated an earlier decline in SWC, near or
385 below the permanent wilting point (Table 1), especially during the warm season in both parks (Fig.
386 4). PaSim showed less pronounced oscillations in SWC ($\sim 0.30\text{-}0.40\text{ m}^3\text{ m}^{-3}$ in the PNE and $\sim 0.15\text{-}$
387 $0.25\text{ m}^3\text{ m}^{-3}$ in the PNGP), while DayCent interpreted the increased water supply projected by
388 climate modelling in winter (Fig. 2) to amplify seasonal differences (i.e. an excess SWC in winter
389 followed by a deficit in summer), with $\sim 0.15\text{-}0.60\text{ m}^3\text{ m}^{-3}$ in the PNE and $\sim 0.05\text{-}0.35\text{ m}^3\text{ m}^{-3}$ in the
390 PNGP (i.e. even below the permanent wilting point). Despite the differences between the two
391 models, for both parks the simulated patterns suggest that with drier summer conditions, grassland
392 growth may be limited by water in summer (Fig. 4).

393



394

395 Figure 4. Simulated annual pattern (20-year mean values) of 0.30-m soil water content (SWC) with
396 two grassland models (DayCent, PaSim), for baseline and climate-change scenarios under

397 business-as-usual management in both parks for the high productivity (HP) macro-type. The annual
398 pattern was reported at daily time-step (DOY: day of the year).

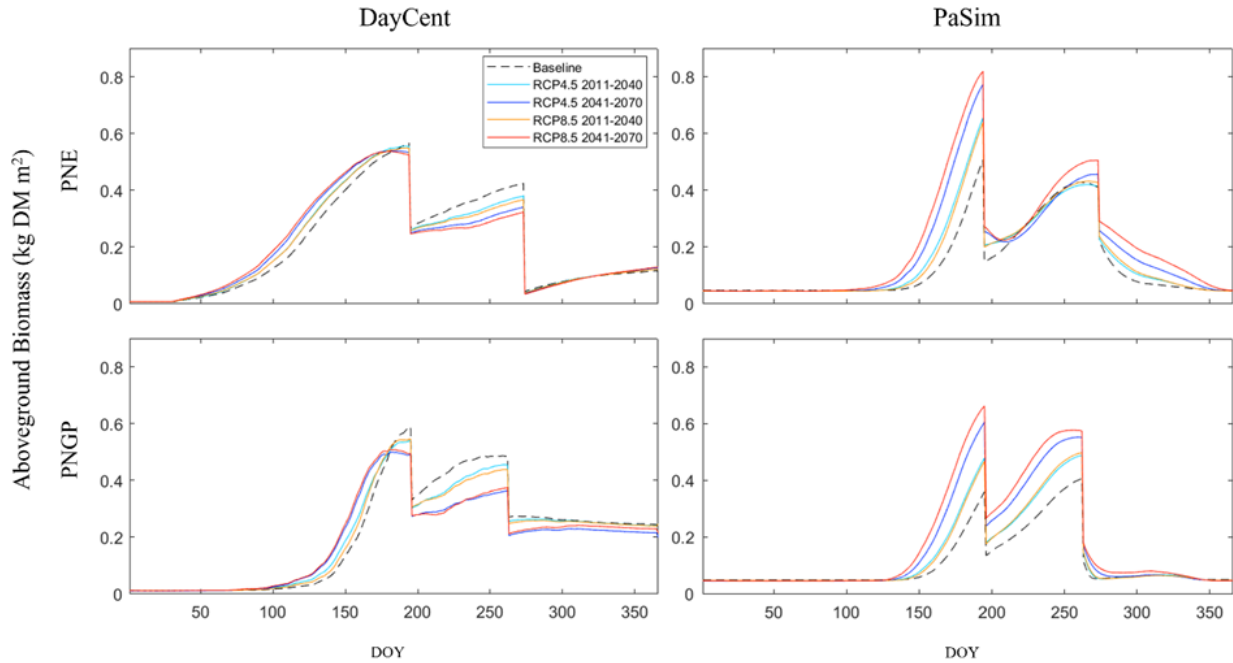
399
400 The MP and LP macro-types showed SWC patterns similar to those observed for the HP macro-
401 type, with a reduction in SWC when approaching warmer scenarios and less pronounced SWC
402 oscillations in PaSim compared to DayCent (Fig. S5 and Fig. S6). In the MP macro-type, the SWC
403 simulated by DayCent ranged over $\sim 0.20\text{-}0.65 \text{ m}^3 \text{ m}^{-3}$ in the PNE and $\sim 0.05\text{-}0.40 \text{ m}^3 \text{ m}^{-3}$ in the
404 PNGP, whereas with PaSim, the SWC was in the range $\sim 0.30\text{-}0.45 \text{ m}^3 \text{ m}^{-3}$ in the PNE and $\sim 0.12\text{-}$
405 $0.24 \text{ m}^3 \text{ m}^{-3}$ in the PNGP (Fig. S5). In the LP macro-type, the SWC simulated by DayCent ranged
406 from $\sim 0.20\text{-}0.65 \text{ m}^3 \text{ m}^{-3}$ in the PNE and $\sim 0.05\text{-}0.40 \text{ m}^3 \text{ m}^{-3}$ in the PNGP, while with PaSim, the
407 SWC was in the range $\sim 0.32\text{-}0.48 \text{ m}^3 \text{ m}^{-3}$ in the PNE and $\sim 0.12\text{-}0.22 \text{ m}^3 \text{ m}^{-3}$ in the PNGP (Fig. S6).

408

409 3.6. *Aboveground biomass*

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

417



418
 419 Figure 5. Simulated annual pattern (20-year mean values) of aboveground biomass (AGB) with
 420 two grassland models, for baseline and climate-change scenarios under business-as-usual
 421 management in both parks for the high productivity (HP) macro-type. The annual pattern was
 422 reported at daily time-step (DOY: day of the year).

423
 424 Under the baseline climate scenarios, DayCent reported the first biomass peak (BP1a) on day
 425 189 (± 9 standard deviation) and 190 (± 8 standard deviation) for the PNE and PNGP, respectively.
 426 Under future climate scenarios, the model indicated an advance of BP1a of 7-10 days for the PNE
 427 and 3-7 days for the PNGP (Table S4). In contrast, the biomass peak simulated by PaSim was
 428 mainly driven by the effect of grazing, showing only a slight advance under the future scenarios
 429 (i.e. 2-3 days) for both PNE (194 ± 4) and PNGP (196 ± 5 , Table S5).

430 For the second biomass peak (BP2a), DayCent indicated that biomass peaks were at day 267
 431 (± 14 standard deviation) in the PNE and day 244 (± 13 standard deviations) in the PNGP under the
 432 baseline scenarios, while future scenarios suggested advanced biomass peaks of 3 to 15 days in the

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

437 In the baseline scenarios, the biomass production of the first peak (BP1b) is similar with both
438 models in the PNE ($\sim 0.52 \pm 0.06$ kg DM m⁻²), while in the PNGP it is $\sim 38\%$ lower with PaSim
439 compared to DayCent ($\sim 0.61 \pm 0.17$ kg DM m⁻²). For the second peak (BP2b), the biomass value
440 provided by DayCent (0.44 ± 0.06 kg DM m⁻²) was close to that provided by PaSim (0.43 ± 0.08 kg
441 DM m⁻²) in the PNE, while at the PNGP the biomass simulated by DayCent (0.52 ± 0.14 kg DM m⁻²)
442 was higher compared to that provided by PaSim (0.41 ± 0.06 kg DM m⁻²). Future patterns for
443 BP2b partly mirror those of BP1b, with PaSim providing an increase in biomass production of
444 $\sim 18\%$ in the PNE and $\sim 41\%$ in the PNGP as the warmer scenarios are approached, while DayCent
445 reported a decrease in biomass production of $\sim 20\%$ in both study areas (Table S4 and Table S5).
446 These results mainly reflect calibration against observational patterns (Fig. S2), with the PaSim
447 production profile indicating faster plant growth in spring, with a distinct peak biomass, and rapid
448 regrowth in summer. This behaviour is much more evident in the climate-change scenarios,
449 resulting in differences in AGB that are about 38-45% higher at the peak with PaSim than with
450 DayCent (Fig. 5), likely due to the absence of sensible water deficits simulated by PaSim (Fig. 4).

451 For the MP and LP macro-types (Tables S6-S9), the biomass peaks (BP1b and BP2b) partly
452 reflect the trends found in the HP macro-type. Specifically, while PaSim reported an increase in
453 peak biomass value of 50-100% with warmer scenarios in all macro-types for both parks, DayCent
454 indicated a decrease of 3-20% with the sole exception of the LP macro-type in the PNE, where
455 biomass production increased of $\sim 25\%$. For the impact of adaptation strategies, the value of peak
456 biomass obtained with alternative management practices (i.e. BaU + adaptation management

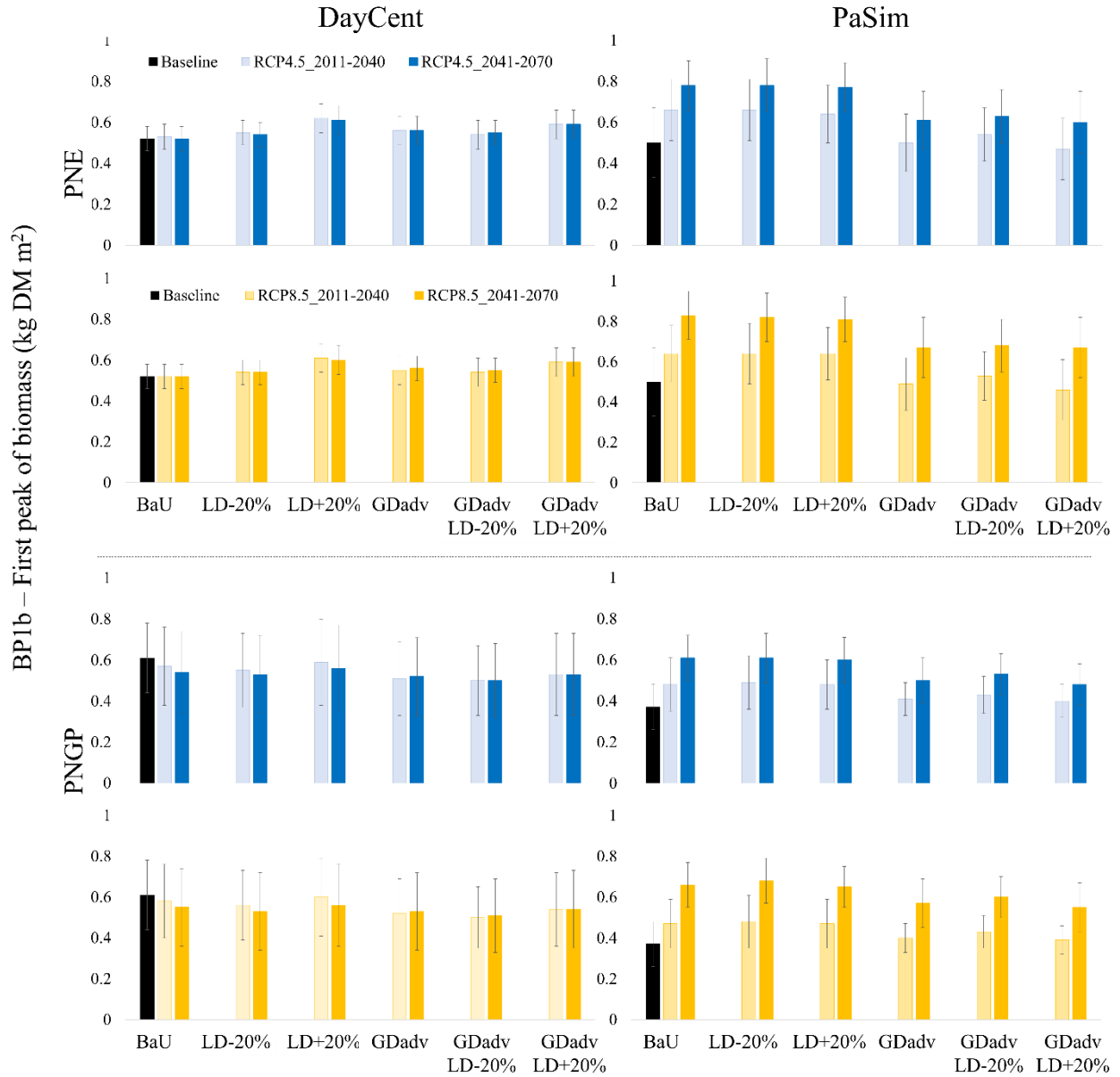
457 options) was compared with the peak biomass of business-as-usual (BaU) management under
458 projected scenarios. To simplify the reading, only the first biomass peak of the HP macro-type in
459 both parks is reported here (Fig. 6), while the dynamics of the second peak (Fig. S11) and those of
460 the MP and LP macro-types are reported in the Supplementary material (Tables S6, S7, S8 and
461 S9).

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

474 Using PaSim, all management options showed an increase in peak biomass under all climate
475 scenarios and time-slices. Specifically, in the PNE under RCP4.5, higher BP1b values compared
476 to BaU (0.50 ± 0.17 kg DM m⁻²) were observed, on average, when the same grazing dates were
477 maintained with all management options (+43%) while a smaller increase was observed when
478 grazing dates were advanced (+11.7%). Under RCP8.5, BP1b shows a similar pattern to that
479 observed under RCP4.5, with higher values occurring when both current (+46%) and advanced
480 (+16.7%) grazing dates are adopted. In the PNGP, under RCP4.5, BP1b values compared to BaU

481 (0.37±0.11 kg DM m⁻²) were observed, on average, both maintaining the same grazing dates with
482 all management options (+47.3%) and advancing grazing dates (+23.9%). Under RCP8.5, BP1b
483 showed the same pattern as under RCP4.5, with higher values at both current (+53.6%) and
484 advanced (+32.4%) grazing dates. Overall, DayCent showed less variability in peak biomass
485 production in the PNE than in the PNGP, with increasing variability as we approach the far future
486 (2041-2070) with the warmest scenario (i.e. RCP8.5) in both parks. In contrast, PaSim indicated
487 greater variability in peak biomass production in the PNE than in the PNGP, with decreasing
488 variability towards the far future with the warmest scenario in the PNE and contrasting patterns in
489 the PNGP.

490



491
 492 Figure 6. Changes in the first (BP1b) peak aboveground biomass (kg DM m^{-2}) between business-
 493 as-usual management (BaU) under baseline climate (black histogram) and all alternative
 494 management options under RCP4.5 (cyan and blue histograms) and RCP8.5 (clear and dark orange
 495 histograms) for high productivity pasture (HP) in both parks as provided by DayCent and PaSim.
 496 Vertical bars are standard deviations.

497

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

506

507 *3.7. Carbon-nitrogen fluxes*

508 Under current climate and management conditions, PaSim shows limited non-CO₂ emissions in
 509 both parks, i.e. 1.9 and 1.6 g C m⁻² yr⁻¹ for CH₄ and 1 and 3 g N m⁻² yr⁻¹ for N₂O emissions, while
 510 the C exchanges (NEE) vary from a limited sink in the PNE (-41 g C m⁻² yr⁻¹) to a limited source
 511 in the PNGP (+96 g C m⁻² yr⁻¹). DayCent represents a higher sinking pattern (-350 and -308 g C m⁻²
 512 yr⁻¹) and lower CH₄ emissions (2.5E-04 and 1.2E-04 g C m⁻² yr⁻¹) in both parks, while N₂O
 513 emissions (0.5 and 3.8 g N m⁻² yr⁻¹) are in agreement with PaSim (Table 4).

514

515 Table 4. C-N emissions (NEE: net ecosystem CO₂ exchange; CH₄: methane; N₂O: nitrous oxide)
 516 from the two study areas (baseline climate), estimated (20-year mean ± standard deviation) using
 517 two grassland models. The estimated components of the C budget (GPP: gross primary production;
 518 NPP: net primary production; RECO: ecosystem respiration) can be found in Supplementary
 519 material (Table S10).

Site	Model	NEE	CH ₄	N ₂ O
		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

520

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

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

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

536 As for CH₄ emissions, the PaSim heatmap indicates that emissions are higher (~>20%) as
537 livestock density increases. While this pattern is clearly observed in the PNE, the results in the
538 PNGP are more contrasted, as the earlier grazing date also leads to increased CH₄ emissions, even
539 when livestock density is reduced. Projected climate conditions do not appear to influence the
540 pattern of emissions, which are mainly driven by management. In contrast, the CH₄ emissions

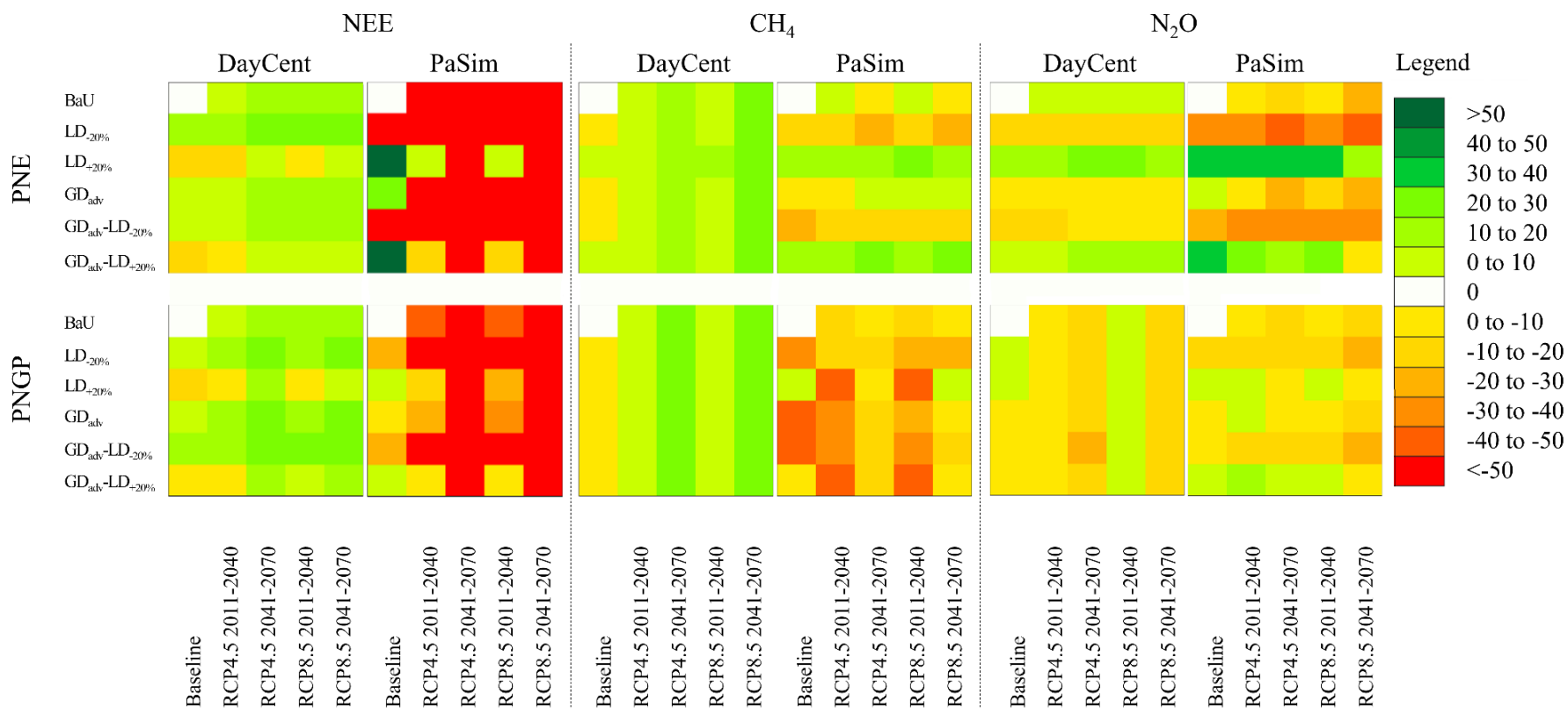
541 estimated by DayCent are conditional on climatic conditions, with the highest emission values (up
542 to ~30%) occurring towards the end of the century (i.e. in the period 2041-2070).

543 Finally, the N₂O emissions estimated by PaSim were mainly driven by the type of management
544 adopted in the two parks, where an increase in livestock density leads to higher emissions (up to
545 ~40%), while a decrease in livestock density reduces emissions to ~50%. Unlike PaSim, DayCent
546 shows contrasting patterns between the two parks. Specifically, N₂O emissions in the PNE are
547 mainly driven by management, where increasing livestock density leads to increased emissions (up
548 to ~30%), while in the PNGP, N₂O emissions are mainly driven by the climate scenarios, with the
549 highest emissions (up to ~40%) for the period 2041-2070 under both RCPs (4.5 and 8.5).

550 Under the baseline scenario, PaSim-simulated NEE for the LP macro-type showed contrasting
551 patterns. Simulated NEE in the PNE (195 ± 193 g C m⁻² yr⁻¹) decreased as the warmest scenarios
552 were approached (107 ± 181 g C m⁻² yr⁻¹), while simulated NEE in the PNGP (151 ± 72 g C m⁻² yr⁻¹)
553 increased as the warmest scenarios were approached (163 ± 97 g C m⁻² yr⁻¹), making both parks
554 sources of C (Fig. S14 and Fig. S15). For the MP macro-types, NEE decreased in both parks as
555 warming scenarios approached, with the PNE still being a source of C (448 ± 388 g C m⁻² yr⁻¹) while
556 the PNGP turned into a sink of C (-91 ± 81 g C m⁻² yr⁻¹) (Fig. S14 and Fig. S15). In contrast, under
557 the baseline climate scenario, DayCent- simulated NEE in both MP (-126 ± 36 and -163 ± 135 g C
558 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.
559 Under the warmest scenarios, NEE tended to decrease for all macro-types in both parks, with the
560 sole exception of the LP macro-type in the PNE, where it showed a significant increase (+90%) in
561 C uptake (Fig. S13 and Fig. S14).

562 The patterns of simulated CH₄ and N₂O emissions for the LP and MP macro-types matched
563 those reported for the HP macro-type, where the estimates provided by DayCent were mainly

564 driven by climatic conditions whilst those of PaSim were mainly related to the different
565 management types (Fig. S13 and Fig. S14).



566

567 Figure 7. Heatmap visualisation of the relative differences (%) between the three main greenhouse gas emissions (NEE: net ecosystem
 568 exchange; CH₄: methane; N₂O: nitrous oxide), estimated using two grassland models (DayCent, PaSim), for alternative management
 569 and climate-change scenarios compared to the current climate and management in the *Parc National des Écrins* (PNE) and *Parco*
 570 *Nazionale Gran Paradiso* (PNGP). Absolute values are given in the supplementary material (Fig. S10).

571 **4. Discussion**

572 *4.1. Uncertainty in climate-change impact assessments*

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

590 Also in the case of vegetation response to CO₂ enrichment, there are large uncertainties in the
591 (complex) climate model projections and underlying scenarios. The extent of our imperfect
592 knowledge of the processes (and their interactions) embedded in models (epistemic uncertainties)
593 is reflected in climate modelling, where it mainly concerns atmospheric and biosphere physics,
594 ocean-atmosphere coupling, embedded empirical relationships, parameterisation and spatial

595 resolution. At smaller scales, impact models (such as the grassland models used here) may suffer
596 from the omission or lack of consideration of long-term climate-related processes (e.g. plant
597 acclimation; Sándor et al., 2018) and their interactions (model structure), as well as changes in
598 parameter values due to new climate conditions (which may require re-parameterisation of the
599 model, e.g. Ben Touhami et al., 2015). Estimates of future conditions should be presented for
600 review by stakeholders, who can then assess the different levels of uncertainty in the multiple
601 elements and estimate their own relevant projections based on their own area of expertise. In
602 climate-change impact studies, a range of emission scenarios are used to feed climate models and,
603 in turn, impact models. Uncertainty accumulates and propagates throughout the process of climate-
604 change projection and impact assessment, which is carried out by developing fine-scale climate
605 data from coarse-scale climate models and feeding the resulting local-scale scenarios into impact
606 models to determine impacts and assess possible adaptations (Bellocchi et al., 2015). Emission
607 scenarios are neither forecasts nor policy recommendations (Moss et al., 2010) but are selected to
608 map a broad range of climate outcomes for further research and assessment, including impact-
609 modelling studies. In particular, policies contrary to those established to discuss extreme situations
610 (Cao et al., 2022) should not lead to a misuse of RCP8.5 as a no-climate-policy baseline (Pilke and
611 Ritchie, 2021).

612 Our work demonstrates the value gained by conducting a process to assess the ability of a
613 modelling framework and remotely sensed products to represent past (observational) and future
614 (projected) conditions (two-time frames), based on the outputs of two climate scenarios (radiative
615 forcing), three climate models (climate forcing) and two grassland models (impacts and
616 adaptations). For the latter, the study identified grassland models sufficiently contrasted in their
617 ability to represent processes controlling the dynamics of energy, water and C-N cycles. This
618 choice was made in order to better assess changes in model estimates as a result of changing

619 assumptions and to identify the most significant ones that reflect reality. In addition, this approach
620 helps to identify the range of variability over which model outputs may vary. In the selection phase,
621 two models were identified in which processes are represented at different levels of detail. While
622 PaSim is a complex (grassland-specific) model, simulating C-N and water cycles in detail (with a
623 module dedicated to livestock impact and livestock-atmosphere feedbacks), DayCent is a more
624 empirical (generic) model, with relatively simple relationships between driving variables and
625 fluxes. The two models differ in the representation of soil properties, vegetation type, agricultural
626 practices and environmental forcing, as well as in the initialisation of C pools. The common feature
627 of both models is that they were both designed to be applied considering the grassland community
628 as a crop with parameters describing the morphological and physiological characteristics of the
629 vegetation set at values that should represent the mean traits of the community. Consequently, their
630 ability to characterise interactions in multi-species grasslands is limited, beyond simple mixtures
631 of legumes and grasses (Van Oijen et al., 2020).

632

633 4.2. *Analysis of climate-change impacts and adaptation strategies*

634 The two impact models adopted agreed in the representation of impacts such as the timing and
635 extent of the growing season and C-N fluxes, whilst divergences were observed for other outputs
636 (e.g. biomass production and peak production). The longer growing season simulated by both
637 models was mainly driven by the extension of the potential growing season in spring, whilst it was
638 limited during autumn-winter, reflecting long-term observations in large alpine regions
639 (Barichivich et al., 2013; Ernakovich et. al., 2014; Chen and Yang, 2020). The agreement in the
640 GS outputs suggests the ability of the models to reproduce the changing seasonality of
641 photosynthesis in vegetation, including the beginning and end of the growing season. Although
642 both models were widely applied in various contexts (e.g. Calanca et al., 2007; Abdalla et al., 2010;

643 Vital et al., 2013; Ma et al., 2015; Ben Touhami and Bellocchi, 2015; Pulina et al., 2018; Fitton et
644 al., 2019; Fucks et al., 2019, 2020; Melo-Damian et al., 2021), this is one of the few studies
645 reproducing the dynamics in alpine pastoral environments, whose multifaceted structure of territory
646 and vegetation coupled with extreme weather conditions is difficult to parameterise due to limited
647 ground-based data for initialisation, calibration and assessment, the complex response of the
648 vegetation growth and information on critical thresholds (e.g. air temperatures, water needs,
649 radiation use efficiency) for mixed plant communities. As evidence of this, the mean plant growth
650 trend simulated with both models (20-year means, Fig. 5) does not seem to reflect the observed
651 pattern of very slow or no growth during the snow season, followed by a rapid increase in biomass
652 accumulation as the snow melts. Generally, after the onset of growth in May or early June, plants
653 grow rapidly, and daily dry matter accumulation can reach a maximum within a few weeks.
654 Grassland models in their current state are not designed to properly represent such a progression
655 of biomass accumulation with the rapid attainment of the first biomass peak. If this behaviour was
656 roughly captured with the calibration work (over three years of AGB data; Fig. S2), and
657 discrepancies appeared less evident with PaSim. Also, the lack of overlap between snow-cover
658 periods and vegetation growing seasons was due to limitations inherent to the modelling of
659 complex ecosystems. Specifically, biogeochemical models are often unable to discriminate the
660 presence of snow and biomass at the same time on a given surface unit, but instead work separately
661 on it. Thus, to avoid speculation on the residual amount of snow cover and, therefore, period
662 overlap, the two components were showed separately. Considering that biophysical data show a
663 large degree of variability, and that discrepancies between model estimates and actual data are
664 common despite calibration efforts, research avenues can be opened from this assessment to
665 improve simulation models for such harsh environments as high altitude mountains, where snow
666 beds melt late and plants grow rapidly, but the rapid growth period is short during the middle of

667 the growing season, and this pattern evolves with changing climate (e.g. Wang et al., 2020). The
668 extension of data series is indeed critical, as while calibrated models provide an adequate
669 description of the available data, they may not capture known trends over long time horizons
670 (Bellocchi et al., 2010).

671 Regarding C-N fluxes, the two grassland models agreed to some extent across study areas and
672 pasture macro-types, with differences in magnitude and patterns likely associated with the inherent
673 structure of each specific C and N sub-model (e.g. Cavalli et al., 2019). The higher C uptake
674 estimated by DayCent compared to PaSim (Figs. S12, S13 and S14) reflects the fact that PaSim
675 estimates the animal contribution to ecosystem respiration, which is not accounted for in DayCent's
676 C budget. Similarly, DayCent estimated limited CH₄ emissions since (unlike PaSim) it does not
677 account for fermentative digestion in its C-N sub-model. The magnitude of N₂O emissions was
678 instead similar between the two models for each study area and macro-type. Overall, the analysis
679 also revealed that GHG dynamics were mainly driven by weather variables in DayCent and by
680 livestock management in PaSim. In this way, PaSim estimates of CH₄, and CO₂ emissions may
681 better reflect observational studies that underpin the impact of management on the annual C cycle
682 of grassland systems (as well as cropping systems), in addition to the variability of local
683 environmental drivers (Pinares-Patiño et al., 2007; Ceschia et al., 2010; Zeeman et al., 2010, 2019).
684 In particular, the importance of quantifying direct CO₂ emissions from grazing animals is
685 emphasised (e.g. Pinares-Patiño et al., 2007). In the absence of observational data to compare with
686 the simulation results, we refer to the literature on the C sequestration capacity of grasslands, which
687 reports contrasting results similar to those of Table 4, which do not exclude that mountain
688 grasslands may oscillate between being sinks and moderate sources (e.g. Zeeman et al., 2010).

689 Although the two grassland models generally agree in their impact projections, they often differ
690 in essential details, for instance with regard to future peak pasture production. Among the reasons

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

708 However, there may also be biases in the simulation of SWC, with grassland models that may
709 not be accurate enough to estimate these dynamics. This is often associated with an unrealistically
710 low amplitude of the annual cycle (fluctuation damping, after Wu et al., 2002) of the soil water
711 content curve compared to field measurements (Sándor et al., 2017). It is known that the quality of
712 soil water content simulations can seriously affect model outputs. In case of poor estimation of soil
713 water content, model calibration may result in biased parameter values. Several factors, such as
714 permanent wilting point, root distribution and maximum transpiration rate, are in fact related to the

715 rate of water infiltration into the soil during precipitation events and snowmelt periods (Philip,
716 1993), which would require detailed datasets for an accurate description. Because of the known
717 role of soil water content in determining evapotranspiration rates, stomatal conductance and other
718 processes, this issue has obvious implications for sites and seasons where water shortage is a typical
719 feature. The response of the models to water-limited conditions is thus questionable, which means
720 that the applicability of the models in semi-arid or arid pastoral systems may not always be
721 supported. This is to some extent related to the ability of roots to extract water from the soil (Volaire
722 and Lelièvre, 2001). The usefulness of soil water content estimation is not as straightforward as for
723 other variables and it is clear the development of improved models is fundamentally necessary for
724 soil hydrology, to rectify structural errors in models and to avoid systematic errors associated with
725 some of the model parameters. These may involve further study of runoff, diffusion and percolation
726 processes, while accounting for features such as ponding water formation, and snowmelt and
727 groundwater movement (Hidy et al., 2016).

728

729 4.3. *Effect of adaptation measures*

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

737 The earlier grazing date better matched the future biomass peaks simulated by DayCent, also
738 agreeing with observations in alpine regions (i.e. Xu et al., 2016) and thus resulting in a more

739 efficient use of pastures. Although this pattern paved the way for increasing the number of grazing
740 events during the growing season, reduced biomass regrowth due to dry summer conditions
741 inhibited the possibility of further grazing. Reduced soil water availability and increased number
742 of days of heat stress can lead to stomatal closure and inhibit biomass production in summer, which
743 must be taken into account in addition to the increase in plant photosynthetic rates with increasing
744 CO₂ concentration in the atmosphere, not to mention the possible degradation of grasslands due to
745 severe summer drought episodes (Moreau and Lorgeou, 2007). For that, any excess water in winter
746 can be used to reduce the water deficit when the soil is drier than the field capacity. While this
747 would hint at the possibility of using irrigation even at high altitudes to extend the number of
748 grazing events, the balance between costs (e.g. of energy and irrigation systems) and benefits (e.g.
749 increased end product) would need to be thoroughly investigated. In contrast, in the scenario
750 depicted by PaSim, which would be too liberal in the sense that it simulates optimal growing
751 conditions in midsummer (i.e. without an expectation of summer water stress), this adaptation
752 strategy would not be necessary.

753 The model results indicate higher biomass production when LD is increased (although changes
754 in livestock density do not particularly modify production levels). This result is likely due to a
755 higher N availability to plants provided by a higher amount of N excreted in faeces and urine which,
756 together with a simulated non-linear effect of grazing on production, led to a faster and higher
757 biomass regrowth rate. While both models consider N from excretion and the effect of grazing on
758 production, detrimental effects on biomass production due to the impact of soil compaction when
759 animal density increases were not considered. However, higher animal numbers may increase soil
760 compaction, resulting in poor water retention and altered (slower) mineralisation processes that
761 may reduce biomass regrowth and forage quality (Li et al., 2017). In this perspective, the response
762 of biomass growth to changes in LD could be partly overestimated or affected by a certain level of

763 uncertainty in both models. Despite these limitations, we can conclude that the alpine region is set
764 to become warmer and wetter, and that yields in these areas are highly dependent on both water
765 availability and the type of management adopted. The projected climate scenarios and adaptation
766 options considered are not expected to substantially worsen the GHG balance, although a caveat is
767 that C sequestration by pasturelands may be reduced in a warmer climate. However, there is a need
768 to further develop and evaluate grassland models for key processes and outputs, such as CO₂ and
769 non-CO₂ emissions, as well as to systematically and more accurately characterise the extent and
770 timing of human intervention in a range of grazing areas covering broader climatic gradients.

771

772 **5. Concluding remarks**

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

787 especially when combined with increasing livestock density, while decreasing livestock density
788 did not show any significant change.

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

803

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815

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