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Pastures vulnerability and adaptation strategies to climate change impacts in the Alps

Deliverable C.5

Report on vulnerability analysis

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ACTION C.5: Vulnerability analysis
Deliverable: Report on vulnerability analysis

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Contents

List of figures

green (i.e. biomass available for grazing) and light green (i.e. sparse biomass, not available for grazing).

Figure S2. Estimated durations (20-year mean values) of snow-cover periods (SC, grey bars) and vegetation growing seasons (dark green bars) with two grassland models for baseline and climate change scenarios under business-as-usual management in both parks for the low productivity (LP) macro-type. The vegetation growth season was divided into dark green (i.e. biomass available for grazing) and light green (i.e. sparse biomass, not available for grazing).

Figure S3. Daily (20-year mean) simulation 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 medium productivity (MP) macro-type.

Figure S4. Daily (20-year mean) simulation 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 low productivity (LP) macro-type.

Figure S5. Daily (20-year mean) simulation of aboveground biomass (kg DM m^2) in the high productivity pasture (HP) at PNE using DayCent, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

Figure S6. Daily (20-year mean) simulation of aboveground biomass (kg DM m^2) in the high productivity pasture (HP) at PNE using PaSim, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

Figure S7. Daily (20-year mean) simulation of aboveground biomass (kg DM m^2) in the high productivity pasture (HP) at PNGP using DayCent, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

Figure S8. Daily (20-year mean) simulation of aboveground biomass (kg DM m^{-2}) in the high productivity pasture (HP) at PNGP using PaSim, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

Figure S9. Changes in the second (BP2b) aboveground biomass peak (kg DM m^{-2}) between business-as-usual management under baseline climate (black histogram) and all alternatives management options under RCP4.5 (cyan and blue histograms) and RCP8.5 (clear and dark orange histograms) for the high productivity pasture (HP) in both parks as provided by DayCent and PaSim. Vertical bars are standard deviations.

Figure S10. Heatmap visualisation of the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated in the high productivity pasture (HP) using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to current climate and management in the Parc National des Écrins (PNE) and Parco Nazionale Gran Paradiso (PNGP).

Figure S11. Heatmap visualisation of the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated in the medium productivity pasture (MP) using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to current climate and management in the Parc National des Écrins (PNE) and Parco Nazionale Gran Paradiso (PNGP).

Figure S12. Heatmap visualisation of the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated in the low productivity pasture (LP) using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to current climate and management in the Parc National des Écrins (PNE) and Parco Nazionale Gran Paradiso (PNGP).

Executive Summary

This report has been elaborated in the framework of Action C.5 ("Vulnerability analysis"), which focuses on the assessment of the vulnerability of pastures in the Western Alpine range. This deliverable integrates the methodologies and results deriving from the modelling activities carried out with DayCent and PaSim (detailed in the deliverable C.4 "Models calibrated and validated"), and developed here, together with the socio-economic model, to assess the vulnerability of pastoral communities in two study areas (Parc National des Ecrins and Parco Nazionale Gran Paradiso) and their adaptive capacity.

1 How to read the document

The document consists of five main sections (plus introduction, references and supplementary material). Each section contains a complete description of a set of operations or processes or links to additional internal documents where the topic is developed in more detail.

The sections are organised as follows:

"Introduction" (Section 3), in which the topic is introduced with ground on the relevant body of literature. "Process-based modelling: impacts and adaptations" (Section 4), in which the model-based impacts are presented under scenarios of climate change, without and with options of pastoral management adaptation. "Socio-economic modelling" (Section 5), which assesses the vulnerability of both parks through a socio-economic analytical framework developed after a participatory process that focused on a wide range of aspects and factors affecting the local pastoral system. "Concluding statements" (Section 6) summarises the conclusions and the implications of these findings. "References" (Section 7), in which the supporting literature is reported. "Supplementary material" (Section 8), in which the supporting literature is reported

2 List of acronyms

AGB	Aboveground biomass
BaU	Business-as-usual management
BP1a	Biomass peak date (period 1)
BP1b	Biomass peak (period 1)
BP2a	Biomass peak date (period 2)
BP2b	Biomass peak (period 2)
C	Carbon

CERPAM	Centre d'Etudes et de Réalisations Pastorales Alpes-Méditerranée
CH_4	Methane
CMCC-CCLM4	Euro-Mediterranean Center on Climate Change- Climate Limited-area Modelling Community (version 4)
CNRM-ALADIN	Centre National de Recherches Météorologiques-Aire Limitée Adaptation dynamique Développement InterNational
CO_2	Carbon dioxide
DayCent	Daily CENTURY model
FCM	Fuzzy Cognitive Mapping
GDadv	Grazing period advanced by 14 days
GPP	Gross primary production
GS	Growing season length (number of days between the GSs and GSe)
GSe	Growing season end
GSs	Growing season start
HP	High productive pasture macro-type
ICTP-RGCM4	International Center for Theoretical Physics - Regional and Global Climate Modeling Program (version 4)
LD	Livestock density (livestock units ha^{-1})
LD-20%	Livestock density decrease (-20%)
LD+20%	Livestock density increase (+20%)
LP	Low productive pasture macro-type
MP	Mid productive pasture macro-type
N	Nitrogen
N_2O	Nitrous oxide

NDVI	Normalised difference vegetation index
NEE	Net ecosystem exchange of C
NPP	Net primary production
PaSim	Pasture Simulation model
PNE	Parc National des Ecrins
PNGP	Parco Nazionale Gran Paradiso
ppmv	Parts per million by volume
RCM	Regional circulation model
RCP	Representative concentration pathway
RECO	Ecosystem respiration
SC	Snow cover length (number of days between SCs and SCe)
SCe	Snow cover end: first of 10 consecutive days of the year with snow cover ≤5 cm
SCs	Snow cover start: first of 10 consecutive days of the year with snow cover ≥5 cm
SWC	Soil water content

3 Introduction

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 century, along with an important reduction of precipitation in the summer season (Gobiet et al., 2014). These changes likely alter grassland productivity and quality (Dibari et al., 2016), harm cold-tolerant high-altitude grassland communities (Gottfried et al., 2012) and lead to a decline of the areas suitable for some vegetation types (Dibari et al., 2013). Moreover, land abandonment and rural depopulation phenomena determine relevant changes in mountain ecosystems and depletion of plant species richness (Orlandi et al., 2016). Appropriate management can preserve grassland biodiversity, maintain ecosystem services and counteract climate change impacts (Nori and Gemini, 2011; Felber 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 adoption of ad hoc policies (e.g. European Agricultural Policy; EC, 2013).

In recent decades, alpine forage-livestock systems have undergone profound socio-economic changes associated with the effects of climate change, which is recognised as one of the main drivers affecting mountain grasslands and their management (Herzog and Seidl, 2018; Dibari et al., 2020). 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, in two representative areas of the western alpine territory: the Écrins (France) and the Gran Paradiso (Italy) national parks (PNE and PNGP, respectively). As part of their long-term observation work, both the PNE and the PNGP contribute to the study and monitoring of climate change-related phenomena, taking information collected at different meteorological stations and supplementing it with analyses of vegetation changes through aerial and satellite images, glacier measurement and monitoring, and interdisciplinary programmes focused on high-altitude lakes, mountain pastures and indicator species (Bonet et al., 2016). In this context, modelling the performance of pastoral systems is of great help since it allows the definition of management strategies that maximize pastoral production while minimizing 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. In particular, satellite-derived normalised difference vegetation index (NDVI) trajectories (deliverable C.2 "Pastures typologies survey and mapping") were extracted for the modelling work.

The involvement of local pastoralists was the basis for the design and assessment of the analytical framework concerning the climate-change adaptation. 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 adaptation options for pastoral management identified by stakeholders.

We applied two calibrated biogeochemical models, DayCent and PaSim (Deliverable C.4 "Models calibrated and validated"), to low-, mid- and high-altitude pastures representative of high, mid- and low-productivity situations (HP, MP and LP, respectively) in the two parks

(PNE and PNGP). 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. N_2O) and C fluxes (e.g. NEE) in a variety of managed ecosystems. PaSim is a grassland-specific ecosystem model composed of detailed sub-models for vegetation, animals, microclimate, soil biology, soil physics and management to simulate grassland productivity and C-N fluxes.

Simulated pastoral outputs were obtained by forcing DayCent and PaSim with daily downscaled weather data, which were selected to map a broad range of climate outcomes for impact modelling (Deliverable C.3 "List of environmental and socio-economic indicators"). Climate scenarios from three Regional Climate Models (RCMs) from Med-CORDEX - CNRM-ALADIN (0.11° × 0.11°), ICTP-RGCM4 (0.44° × 0.44°), and CMCC-CCLM4 (0.44° × 0.44°) - with radiative forcing for the medium RCP4.5 and the high RCP8.5 (Representative Concentration Pathways 4.5 and 8.5), were used for the reference period 1981-2010 (near past with 400 ppmv) and for two future time-slices: 2011-2040 (near future with 450 and 470 ppmv CO_2) and 2041-2070 (mid future with 540 and 670 ppmv CO_2). Three daily datasets were thus derived reproducing the mean change in climate conditions for each single site in RCP4.5 and 8.5 for 2031-2040 (near past), 2041-2070 (near future) and 2071-2100 (far future) time-slices.

The modelling work was carried out in two simulation suites: suite 1 with projected climate change scenarios (impact projections) and suite 2 with modified management under projected climate change scenarios (adaptation assessment). With the adaptation assessment (suite 2), we show simulated outputs using the two grassland models fed with the following the adaptation practices under climate-change forcing resulting from A participatory process: the livestock density in the pasture increased or decreased by 20% (LD-20% and LD+20%, respectively), and the grazing period advanced by 14 days (GDadv).

As a basis for the design and assessment of the analytical framework, the participatory process was conducted since 2018 with group of *c.* 20 local stakeholders in each park including farmers, technicians, and representatives of the two parks and local chambers of agriculture. Stakeholders were invited to participate in a board to discuss and debate the local pastoral systems and the challenges and opportunities related to climate changes in the western alpine region. The selection of stakeholders was facilitated by the existence of the "Sentinel Mountain Pastures" working group and its network (Deléglise et al., 2019). The participatory process involved a number of meetings, interviews and informal discussions that ran parallel to the data collection and territorial analysis (Targetti et al., 2019).

We present and discuss in detail only the results obtained in the first macro-type (high productivity) for which a full modelling analysis is available. The results obtained in the medium and low productivity macro-types, for which details are provided in the Supplementary material, are also partly presented. Simulation results are presented separately by study-area by using time-series graphs to illustrate the dynamics of selected variables (aboveground biomass, soil water content, C fluxes and CH_4 and N_2O emissions), as well as two-dimensional colour data visualisations (heatmap graphs).

4 Process-based modelling: impacts and adaptations

For both parks, we assessed the sensitivity of the two grassland models to (suite 1) climate change (RCP4.5 and RCP8.5 for the near and far future) with business-as-usual (BaU) management and to (suite 2) management scenarios (14-day grazing advance and ±20% grazing intensity). Mean multi-year responses are presented below for a selection of production (aboveground biomass), biophysical (soil water content) and biogeochemical (C-N fluxes) outputs.

4.1. Growing season

Under the climate-change scenarios with both models, the estimated duration of the snow season decreases in the two areas due to earlier spring melt and later snowpack accumulation. This condition leads to an earlier start and later end of the growing season (GS) in both parks, especially in the far future (2041-2070) (Figure 1). Specifically, using DayCent, the start of the growing season (GSs) was anticipated by an average of 11 and 28 days in the PNE and 12 and 39 days in the PNGP, for the 2011-2040 and 2041-2070. The end of the growing season (GSe) was delayed by an average of 8 and 17 days in the PNE and 17 days in the PNGP for the period 2041-2070. In contrast, no changes in GSe were observed in the PNGP for the period 2011-2040. Using PaSim, the GSs was advanced by an average of 14 and 31 days in the PNE and 7 and 19 days in the PNGP for the periods 2011-2040 and 2041-2070. The GSe was delayed by an average of 5 and 23 days for the periods 2011-2040 and 2041-2070 in the PNE and 36 days in the PNGP for both time slices.

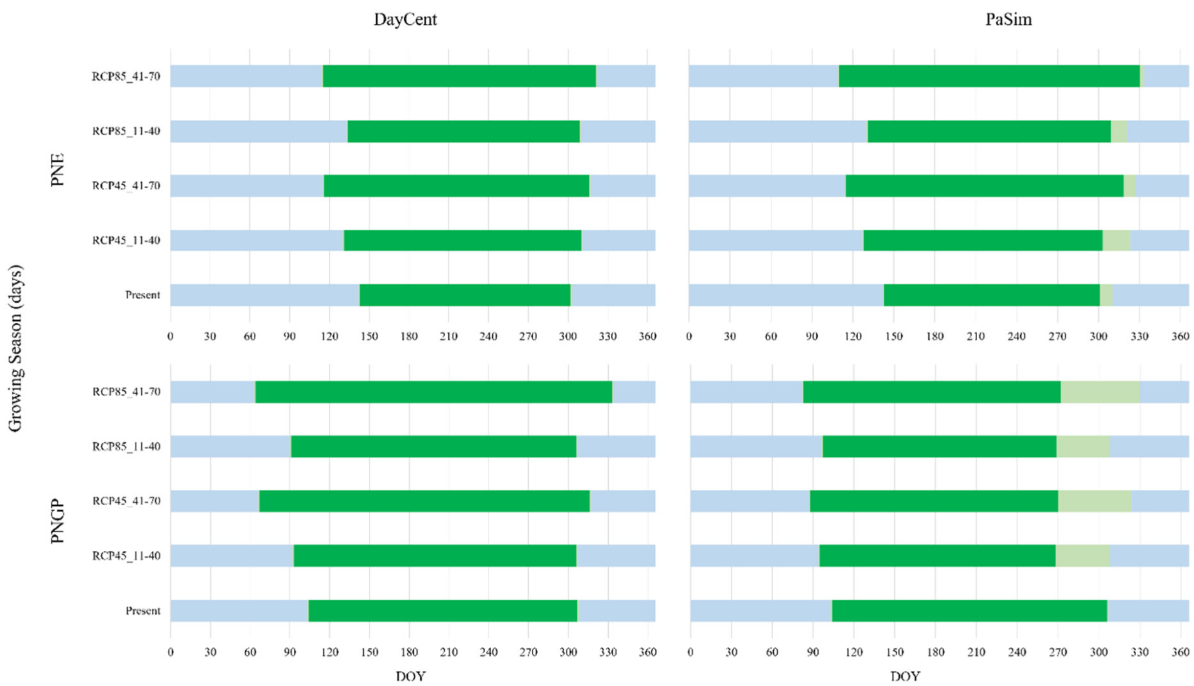

Figure 1. Estimated durations (20-year mean values) of snow-cover periods (SC, grey bars) and vegetation growing seasons (dark green bars) with two grassland models for baseline and climate change scenarios under business-as-usual management in both parks for the high

productivity (HP) macro-type. The vegetation growth season was divided into dark green (i.e. biomass available for grazing) and light green (i.e. sparse biomass, not available for grazing).

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

4.2. Soil water content (0.30 m topsoil)

Under the climate-change scenarios, both models indicated an earlier decline of soil water content (SWC), near or below the permanent wilting point, especially during the warm season in both parks (Figure 2). The highly process-based model (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 (Deliverable C.3 "List of environmental and socio-economic indicators") to amplify seasonal differences (i.e. an excess of 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, while grassland growth can continue later in the year (Figure 2).

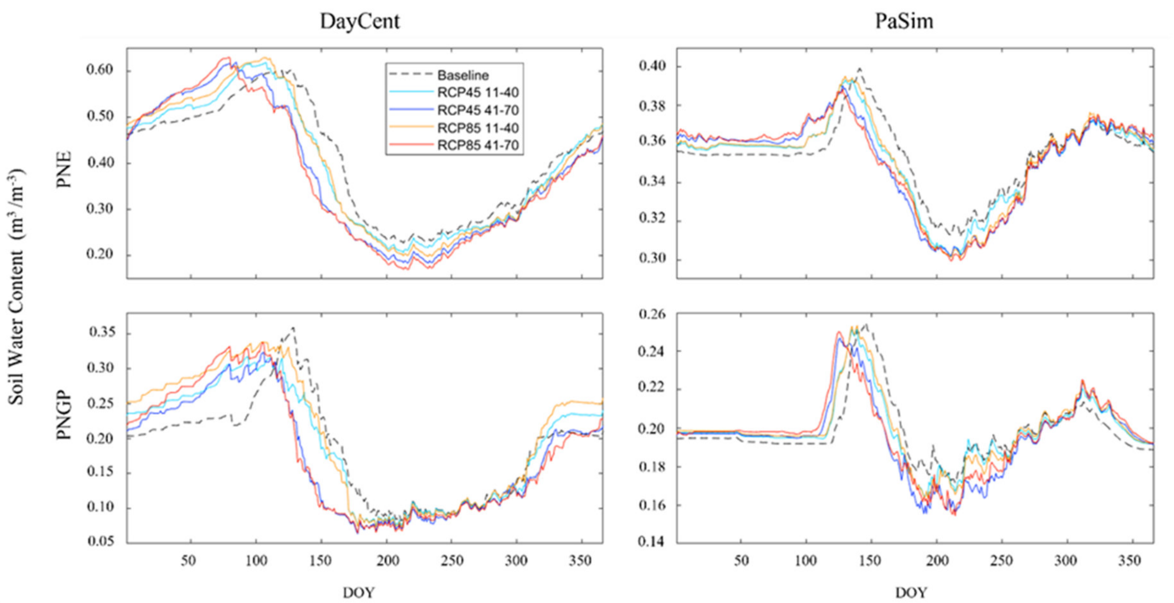

Figure 2. Daily (20-year mean) simulation of 0.30-m soil water content (SWC) with two grassland models (DayCent, PaSim), for baseline and climate change scenarios under business-as-usual management in both parks for the high productivity (HP) macro-type.

The MP and LP macro-types showed similar SWC patterns 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 (Figure S3 and Figure S4). In the MP macro-type, the SWC simulated by DayCent varied in a range of ~0.20-0.65 $m^3\ m^{-3}$ in the PNE and ~0.05-0.40 $m^3\ m^{-3}$ in the PNGP, while with PaSim, the SWC ranged from ~0.30-0.45 $m^3\ m^{-3}$ in the PNE and ~0.12-0.24 $m^3\ m^{-3}$ in the PNGP (Figure S5). In the LP macro-type, the SWC simulated by DayCent ranged from ~0.20-0.65 $m^3\ m^{-3}$ 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 (Figure S4).

4.3. Aboveground biomass

Figure 3 shows the aboveground biomass (AGB) production patterns under baseline management in both parks for the HP macro-type, as obtained with the two grassland models, while the AGB patterns obtained with all the alternative management options can be found in the Supplementary material (Figures S5-S8). The main differences in AGB patterns among alternative management and climate scenarios were evaluated based on changes in peak dates (BP1a and BP2a) and corresponding AGB values (BP1b and BP2b), which strongly influence the decisions of stakeholders and farmers in assessing the most suitable periods for grazing.

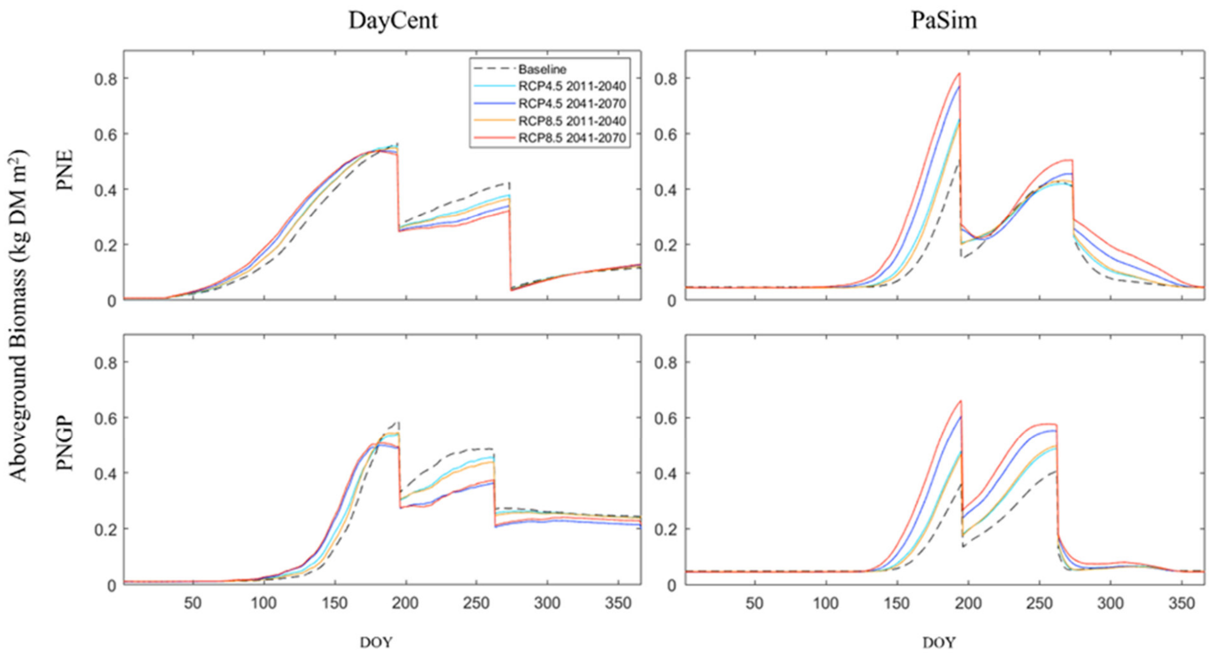

Figure 3. Daily simulation (20-year mean) of aboveground biomass (AGB) with two grassland models, for baseline and climate change scenarios under business-as-usual management in both parks for the high productivity (HP) macro-type.

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 S1). In contrast, the peak biomass simulated by PaSim was mainly driven by the effect of grazing, showing only a slight lead under the future scenarios (i.e. by 2-3 days) for both PNE (194±4 standard deviation) and PNGP (196±5 standard deviation, Table S2).

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 to 15 days in the PNE and contrasting patterns (from -3 to +2 days) in the PNGP (Table S1). 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 only a slight delay (1-5 days) in the PNGP and PNE, respectively (Table S2).

In the baseline scenarios, the biomass production of the first peak (BP1b) is similar with both models in the PNE (~0.43±0.11 kg DM m^{-2}, on average), while in the PNGP it is ~38% lower with PaSim compared to DayCent (~0.61±0.17 kg DM m^{-2}). The models tend to overestimate the experimentally determined biomass peaks (0.53 kg DM m^{-2} or lower, after IAR data), which reflect the biomass data derived from satellite measurements and on which the model was calibrated (deliverable C.4 "Models calibrated and validated"), with peaks from the 2018-2020 >0.6 kg DM m^{-2}. Considering the standard deviation of 0.17 kg DM m^{-2}, the lower values of the confidence intervals are close to the measured values. 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}). The 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 when approaching the warmer scenarios, while DayCent reported a decrease in biomass production of ~20% in both study-areas (Table S1 and Table S2). These results mainly reflect the calibration against observational patterns (Deliverable C.4 "Models calibrated and validated"), with the PaSim production profile indicating faster plant growth in spring, with a distinct peak biomass, and rapid summer regrowth. This behaviour is much more evident in the climate-change scenarios, resulting in differences in AGB that are about 38-45% higher at peak with PaSim than with DayCent (Figure 3), explained by the absence of sensible water deficits in PaSim (Figure 2).

For the MP and LP macro-types, the biomass peaks (BP1b and BP2b) partly reflect the trends found in the HP macro-type (Tables S3-S6). Specifically, while PaSim reported an increase in biomass peak value of 50-100% with warmer scenarios in all macro-types for both parks, DayCent indicated a decrease by 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 under business-as-usual (BaU) was compared to the peak biomass of alternative management practices (i.e. BaU + adaptation management options) under future scenarios. To simplify reading, only the first biomass peak in both parks is reported here (Figure 4), while the dynamics of the second peak (Figure S9) and those of the medium and low productivity macro-types (Tables S3, S4, S5 and S6) are reported in the Supplementary material.

Using DayCent, in the PNE under RCP4.5 (blue), on average, the highest values of AGB at the first biomass peak compared to BaU (0.52±0.06 kg DM m^{-2}) were with LD+20% both under current (+18.3%) and advanced (+13.5%) dates (Figure 4). Only a slight increase was observed using the other strategies (+1 to +7.7%). Under RCP8.5 (orange), BP1b shows a similar pattern as that observed under RCP4.5, with higher values adopting the LD+20% under both current (+16.3%) and advanced (+13.4%) dates, and a slight mean increase using the other strategies (+3.8 to +6.7%). In the PNGP, under RCP4.5, a decrease in BP1b values compared to the 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 (Figure 4b), the BP1b showed a similar pattern and magnitude to that 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 the BaU (0.50±0.17 kg DM m^{-2}) were observed, on average, when maintaining the same grazing dates with all management options (+43%) while a smaller increase was observed when advancing the grazing dates (+11.7%). Under RCP8.5, BP1b shows a similar pattern to that observed under RCP4.5, with higher values when adopting both the current (+46%) and advanced (+16.7%) grazing dates. In the PNGP, under RCP4.5, BP1b values compared to BaU (0.37±0.11 kg DM m^{-2}) were observed, on average, both by maintaining the same grazing dates with all the management options (+47.3%) and by advancing the grazing dates (+23.9%). Under RCP8.5, BP1b showed the same pattern as under RCP4.5, with higher values under 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 less clear patterns in the PNGP.

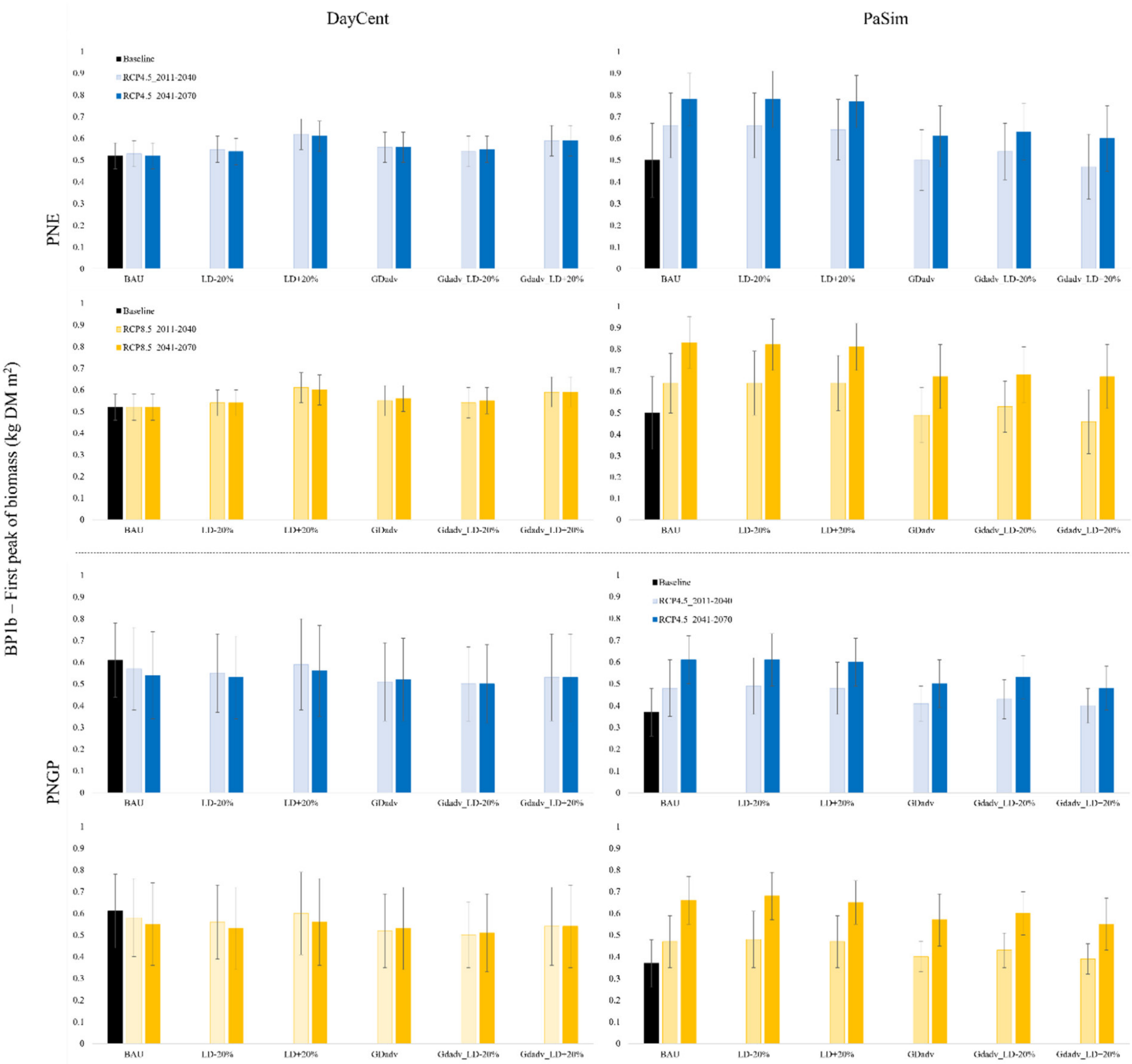

Figure 4. Changes in the first (BP1b) peak aboveground biomass (kg DM m⁻²) between business-as-usual management under baseline climate (black histogram) and all alternatives management options under RCP4.5 (cyan and blue histograms) and RCP8.5 (clear and dark orange histograms) for high productivity pasture (HP) in both parks as provided by DayCent and PaSim. Vertical bars are standard deviations.

For the MP and LP macro-types, PaSim suggested a generalised increase in biomass production that was particularly large (>50%) in the PNE than in the PNGP in 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 an increase in productivity of 10-20% was found in the PNE when approaching the warmest scenario at the current grazing date and at different livestock densities (i.e. BaU, LD-20% and LD+20%). 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 S1). Conversely, the peak biomass simulated by PaSim was mainly driven by the effect of grazing, showing only a slight lead under the future scenarios (i.e. by 2-3 days) for both PNE (194±4 standard deviation) and PNGP (196±5 standard deviation, Table S2).

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 to 15 days in the PNE and contrasting patterns (from -3 to +2 days) in the PNGP (Table S1). 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 only a slight delay (1-5 days) in the PNGP and PNE, respectively (Table S2).

In the baseline scenarios, the biomass production of the first peak (BP1b) is similar with both models in the PNE (~0.5 kg DM m^{-2}), while in the PNGP it is ~38% lower with PaSim compared to DayCent (~0.6 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}). The 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 when approaching the warmer scenarios, while DayCent reported a decrease in biomass production of ~20% in both study-areas (Table S1 and Table S2). These results mainly reflect the calibration against observational patterns (Deliverable C.4 "Models calibrated and validated"), with the PaSim production profile indicating faster plant growth in spring, with a distinct peak biomass, and rapid summer regrowth. This behaviour is much more evident in the climate-change scenarios, resulting in differences in AGB that are about 38-45% higher at peak with PaSim than with DayCent (Figure 3), likely due to the absence of sensible water deficits in PaSim (Figure 2).

For the MP and LP macro-types (Tables S3-S6), the biomass peaks (BP1b and BP2b) partly reflect the trends found in the HP macro-type. Specifically, while PaSim reported an increase in biomass peak value of 50-100% with warmer scenarios in all macro-types for both parks, DayCent indicated a decrease by 3-20% with the sole exception of the LP macro-type in the PNE, where biomass production increased of ~25%.

4.4. Carbon-nitrogen fluxes

Under current climate and management conditions, PaSim shows limited non-CO_2 emissions, 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 potential for C sequestration (NEE) varies 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 1).

Table 1. C-N emissions (NEE: net ecosystem 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 S7).

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

The absolute values of C-N fluxes (Figure S10) indicate that both models agree in representing the magnitude of these fluxes, with the differences being explained by the inherent features of the two model structures (i.e. animal respiration, enteric fermentation). Heatmaps of % differences between the current conditions (i.e. baseline climate and BaU management) and the combinations of alternative climate and management scenarios allow an assessment of the impact of altered climate and management changes on gas emissions in the two parks (Figure 5).

As for the NEE, in particular, 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 2041-2070 time-frame), reducing LD and advancing grazing dates, thus reflecting the baseline AGB pattern (Figure 3) 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 approaching extreme climate conditions, which is greater when LDis reduced. An increase in C uptake of up to 30% was observed both under at the current grazing date and at the advanced grazing date when the LDis increased.

Concerning CH_4 emissions, the PaSim heatmap indicates higher emissions (~>20%) as LDincreases. While this pattern is clearly observed in the PNE, the results in the PNGP are more contrasting, as advancing the grazing date also leads to an increase in CH_4 emissions, even when LDis reduced. Projected climate conditions do not appear to influence the pattern of emissions, which are mainly driven by management. In contrast, CH_4 emissions estimated by DayCent are driven by climate 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 management of the two parks, where an increase in LDleads to higher emissions (up to ~40%), while a decrease in LDreduces emissions to ~50%. DayCent shows instead contrasting patterns between the two parks. Specifically, N_2O emissions in the PNE are mainly driven by management, where increasing LDleads to increased emissions (up to ~30%), while in the PNGP, N_2O emissions are mainly driven by 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, the NEE simulated by PaSim for the LP macro-type showed contrasting patterns. The simulated NEE in the PNE (195±193 g C m^{-2} yr^{-1}) decreased as the warmer scenarios were approached (107±181 g C m^{-2} yr^{-1}), while the simulated NEE in the PNGP (151±72 g C m^{-2} yr^{-1}) increased as the warmer scenarios were approached (163±97g C m^{-2} yr^{-1}), indicating that both parks may be sources of C (Figure S11 and Figure S12). For the MP macro-types, the NEE decreased in both parks as the 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}) (Figure S11 and Figure S12). In contrast, under the baseline climate scenario, the NEE simulated by DayCent 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, identifying these types as C sinks. As the warmer scenarios are approached, NEE tended to decrease in 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 (Figure S11 and Figure S12).

The patterns of simulated CH_4 and N_2O emissions for the LP and MP macro-types were in agreement with 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 (Figure S9 and Figure S10).

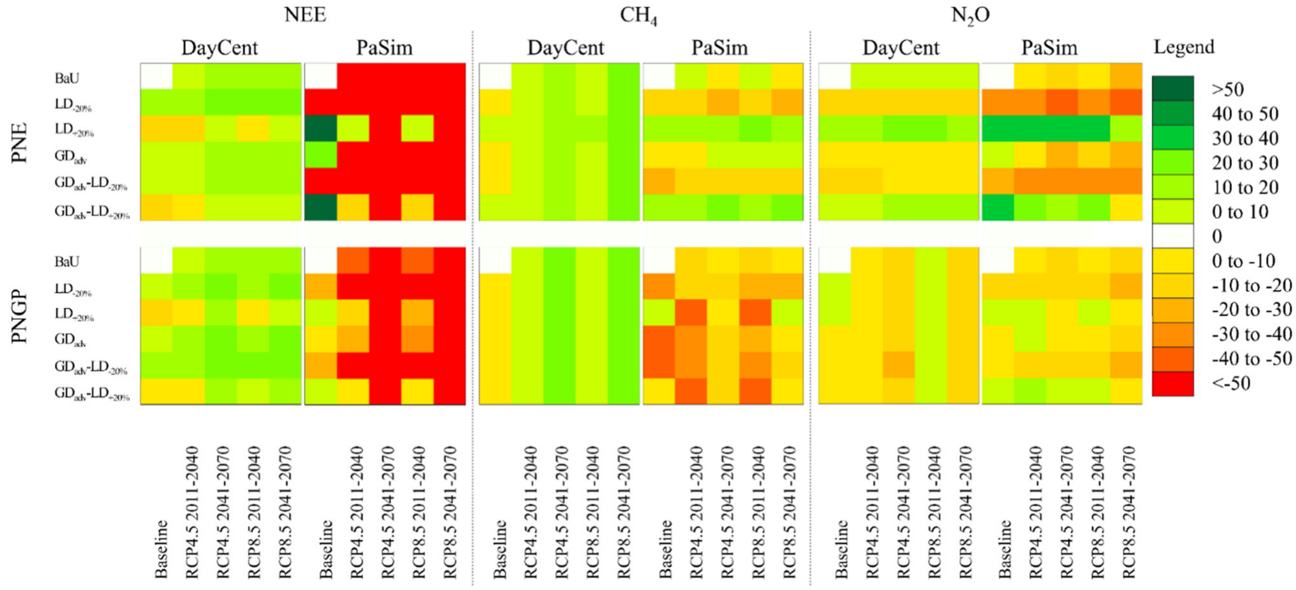

Figure 5. Heatmap visualisation of the relative differences (%) between the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to 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 (Figure S7).

5 Socio-economic modelling: the Fuzzy Cognitive Mapping

For both parks, the socio-economic modelling approach was based on the Fuzzy Cognitive Mapping (FCM) technique, aimed at assessing the vulnerability of pastoral systems in the two case-study regions. The objective of the socio-economic model was to highlight the climate variables that were more critical for farmers in connection with the range of different stress factors currently present. The expected result was an improved understanding of the adaptation of local pastoral systems to climate-related changes (Gray et al., 2015). In other words, the climate change and impact variables evidenced by the biophysical modelling were included in the socio-economic modelling according to the outputs of a participative process that considered the pastoral system as a whole. Thus, a range of variables was considered, such as other aspects perceived as relevant by farmers (e.g. CAP incentives and wolf predation). With respect to the high productivity (HP) macro-type, a specific difficulty emerged inherent to differences between the results of grassland modelling and farmers' representations. Indeed, while it is common for participation policies or communication strategies to focus on a single species (e.g. a flagship or umbrella species) in order to gain stakeholder support (Kogut and Ritov , 2005; Small et al., 2007), farmers have a more functional view of biodiversity as a whole (Pellegrin et al., 2018; Fischer and Young, 2007; Soini and Aakkula, 2007). Thus, we could not use a day-by-day calculation of biomass amount to work with breeders. We chose to consider as proxies two variables that are well understood by farmers: 'high elevation grasslands' and 'reduced quality of high elevation grasslands'.

5.1. Description of the socio-economic modelling approach

The socio-economic analytical framework was developed following a participatory-based process that targeted a wide range of aspects and factors affecting the local pastoral system. The analytical framework concerned three dimensions of analysis to assess the range of potential impacts of climate change on the local pastoral system and identify the most relevant factors capable of enhancing (or reducing) its adaptive capacity (Fraser et al., 2011; Metzger et al., 2006):

1) the impacts of climate change on local agro-ecosystem resources (Bellocchi et al., 2020);

2) a stakeholder-based assessment of socio-economic sensitivity directly or indirectly linked to these changes; and

3) an exploration of the "proactive" adaptations that the local pastoral system could mobilise.

The latter was based on a FCM focusing on local farmers' perception of the cause-effect links and mechanisms behind the vulnerability of the pastoral system to climate change, and in particular the potential changes affecting the use of upland pastures.

The participatory-based process was carried out between 2017 and 2022 with a group of local stakeholders in each case-study area, including farmers and farmers' associations, technicians and representatives of local institutions (deliverable E2 "Report on what emerged from consultation workshops" for further details).

The participatory process involved three workshops, several interviews and informal discussions that were carried out in parallel with data collection, analysis and information processing in each case-study area (Figure 6). The aim of the process was to build an analytical network including the most relevant factors affecting local pastoral systems as identified by stakeholders.

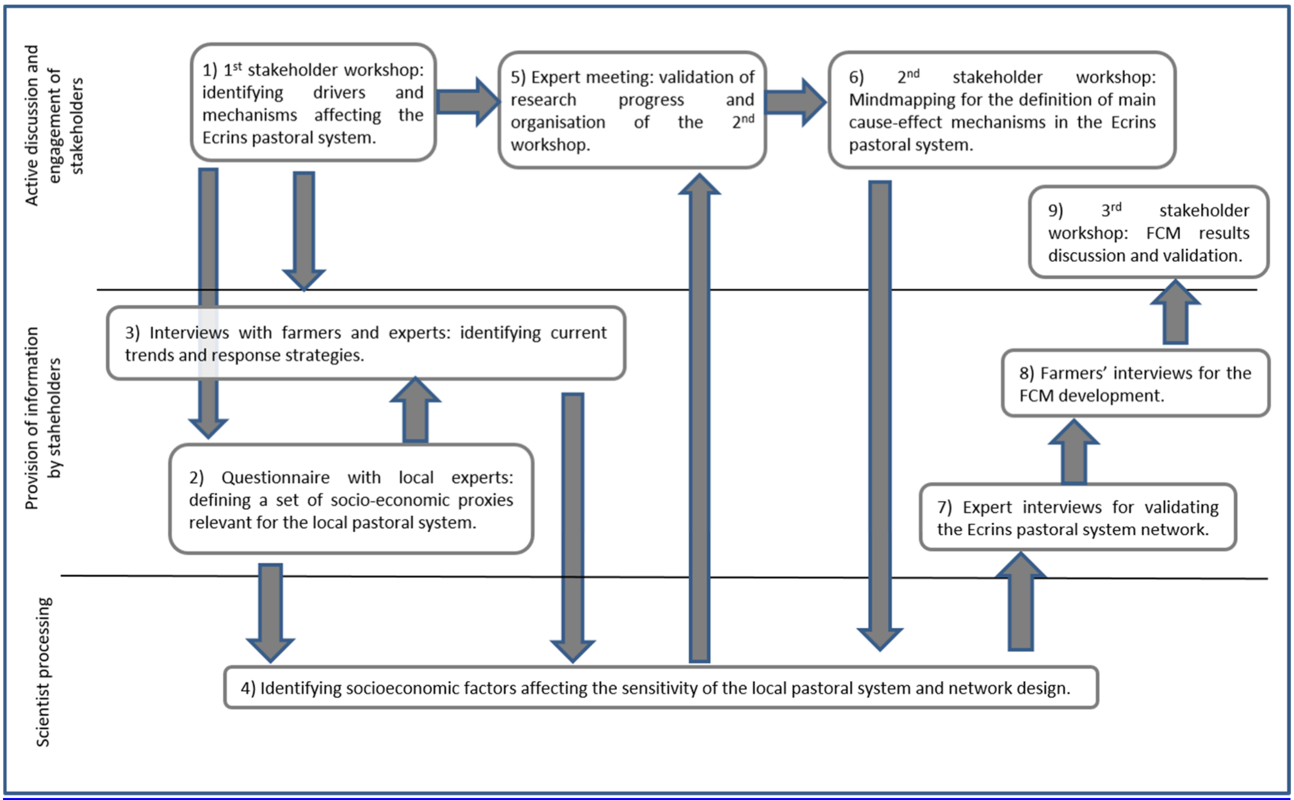

Figure 6. Combined participatory and data collection/processing procedure employed for the development of the analytical network of the Ecrins pastoral system. The stakeholder board was involved in three distinct workshops, meetings, survey and individual interview

sessions. The process fed into parallel processing steps led by researchers to build analytical maps and feed into subsequent participatory activities (adapted from Targetti et al., 2021).

The analytical networks developed in the two case-study areas served as the basis for developing the FCM. A questionnaire was then developed to elicit weights and relations between the different factors as outlined in the network. The questionnaire aimed to assess farmers' perception related to a range of adaptation strategies under the combined effect of the stressors indicated during the participatory process (e.g. climate changes, predation, agricultural policy). The questionnaire was tested internally, finalised and employed for interviews with local farmers. Nine farmers from the Parc des Ecrins and five from the Parco Nazionale Gran Paradiso agreed to participate in the interviews, which took place in November-December 2020 in the PNE and in March-April 2022 in the PNGP.

5.2. Results

The difference between the two case-study areas is evidenced by the weights assigned to the different factors in the analytical networks (Table 2).

Four factors appeared to be the most connected and characterised by considerably higher cumulative relevance in the PNE network: agricultural policy subsidies, wolf predation, hiring of expert shepherds and reduced herbage quality. This result highlights the relevance of factors that influence farmers' decisions in the process of adaptation to climate and global changes. Nonetheless, a range of different connections in our FCM drove two of these factors. More specifically, agricultural policy was mainly a driver influencing other factors in the analytical network. Similarly, predation was considered an important causal factor, although it was characterised by a significant number of relations directly influencing it. As expected, "Abandonment of upland pastures" was characterised by a relevant number of factors influencing it. Indeed, it was directly related to farmers' management decisions, and it was the factor on which stakeholders had the highest interest. In the PNGP, the most relevant factors were: 'Upland grasslands', 'Production', 'Revenue' and 'Bottom valley meadows'. Thus, aspects more traditionally related to farm production were considered relevant. On the other hand, aspects linked to pasture productivity such as forage quality and biomass were present in the PNE. In the PNGP, abandonment was not a factor included. However, the most important factor ('upland grasslands') refers directly to the relevance attributed to the utilisation of summer pastures and can thus be considered a factor/concept with the opposite idea of pasture abandonment. Factors related to predation, climate variability, quality of life and training were present and thus considered relevant in both case-study areas.

Table 2. Pastoral systems' network: the centrality values indicate the sum of the weights assigned to the connections that influence it (i.e. connections towards the factor) and the sum of the weights of the influence of the factor on the other factors in the network (i.e. connections from the factor towards the other factors).

PNGP		PNE	
Factors	**Centrality score**	**Factors**	**Centrality score**
Upland grasslands	14.47	CAP subsidies	8.88
Relevance of farm productivity	12.01	Predation	8.73
Revenue	11.15	Experienced shepherd hiring	8.30
Bottom valley meadows	10.00	Upland grassland quality reduction	8.20

Tourism	8.00	Search for alternative forage resources	6.17
Farm organisation and life quality	7.96	Investments	6.15
Predation	7.87	Abandonment	5.98
Professional identity	6.53	Meat price	5.40
Alpages ouverts	6.52	Improved grassland management	5.35
Hay buying	6.19	Hay buying	5.28
Climate variability	5.85	Upland grassland biomass reduction	4.55
Improved infrastructure	5.83	Improved infrastructures	4.48
Local society	5.64	CERPAM	4.35
Pastoral training and 'education'	5.38	Wolfdogs	3.98
Diversification	5,24	Work charge	3.70
Traditional farmer	5,21	Livestock pests	3.65
New farmer	5.05	Climate variability	3.30

Regarding the vulnerability scenarios in the two case-study areas, the simulation of the FCM matrix clearly confirmed that Common Agricultural Policy subsidies are a relevant factor for maintaining pastoral activity in both case-study areas and that, conversely, predation is a relevant driver of pastoral abandonment (Figure 7). However, in both areas, the weight of the CAP on the whole system is more important than the weight of predation. Indeed, the progressive increase of CAP subsidies results in a slight reduction of abandonment in the PNE and an increase of pasture relevance in the PNGP, even with high predation rates.

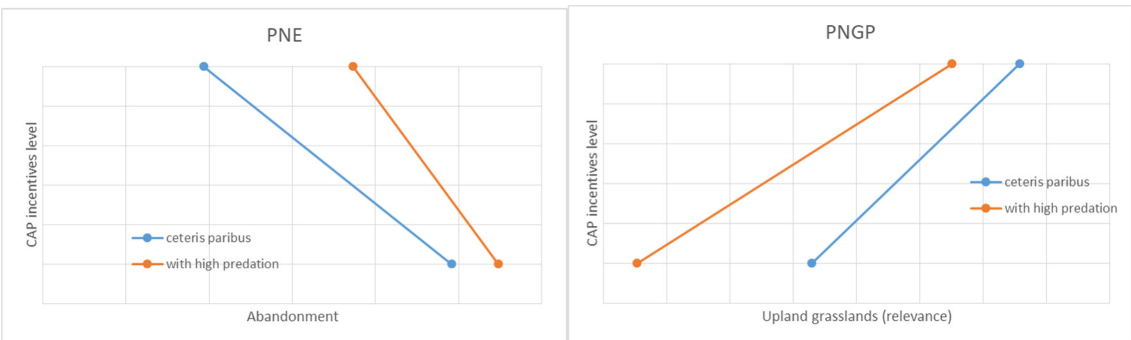

Figure 7. FCM matrix simulation of the abandonment trend resulting from different levels of CAP incentives and the predation effect.

Concerning herbage biomass production on summer pastures, it was considered as one of the relevant factor to be included in the network in the PNE only. However, changes in the vulnerability of the pastoral system related to herbage biomass in the PNE were marginal. A much larger effect resulted from the impact of herbage quality in the PNE and climate variability in both case study areas.

Regarding herbage quality, the major impacts in the PNE are expected to be on abandonment and - linked to this – on increasing intensification trends and the need to buy hay in case of reduced herbage quality (Figure 8). However, the workload of the farmer should also decrease due to the reduced need for organisation and administrative burdens connected to the use of summer pastures (e.g. transport organisations, CAP documents, livestock management, predation issues). In the PNE, an adjustment in the technical support from CERPAM (*Centre d'Etudes et de Réalisations Pastorales Alpes-Méditerranée*) and the availability of trained shepherds resulted as an effective strategy to cope with abandonment. Nevertheless, the reduction of herbage quality will imply a certain level of hay purchase and increasing intensification trends, even with a stronger impact of the shepherds and CERPAM.

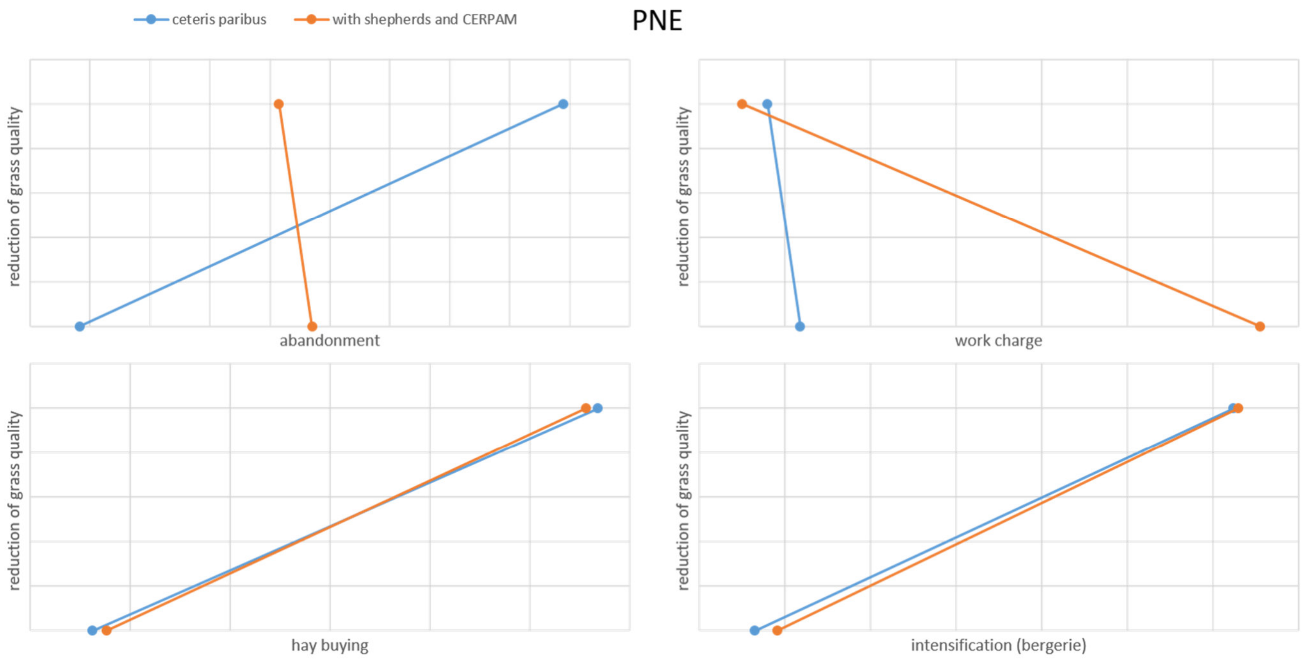

Figure 8. Simulation of the FCM matrix for NCB related to the grass quality reduction scenarios.

As evidenced in Figure 9, climate variability is the climate-related factor that is perceived as a major threat by farmers. In both case-study areas, scenarios involving higher interannual variability have relevant effects on increased abandonment, intensification trends and the need for hay. Contrary to the effects of herbage quality, climate variability also had negative impacts on workload (in the PNE) and an organisation and quality of life (in the PNGP). That impact is at odds with the reduction of summer pasture utilisation. Indeed, a shift towards more intensive systems should favour a reduction of workload. However, the impacts of climate variability were related to difficulties in organising the summer season. Unpredictable climate conditions that can change suddenly had strong consequences on e.g. livestock management and planning of hay needs. These impacts had relevant effects on the daily organisation of the farm and the workload or organisation and quality of life quality of the farmers.

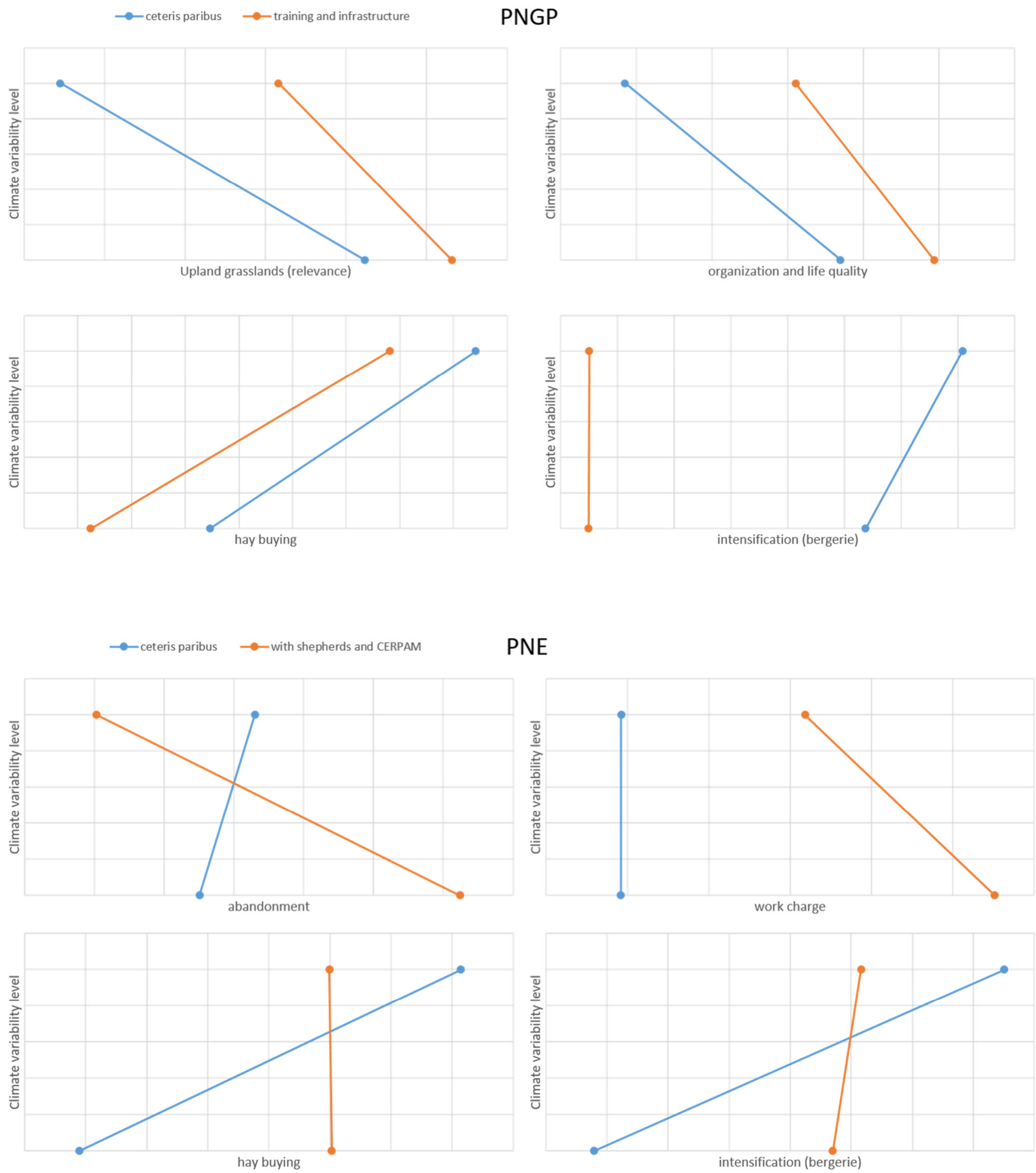

Figure 9. Simulation of the FCM matrix for PNGP and PNE related to climate variability.

6 Concluding statements

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 varying 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 solve multidisciplinary challenges such as which areas are more or less vulnerable and how they compare under harsh climatic conditions. After assessing the baseline (near-past) climate and future climate change assumptions in the areas concerned, impact studies were carried out to identify the direct effect of climate anomalies on alpine pastures by investigating their sensitivity to climate scenarios and management options with respect to production, biophysical and biogeochemical outputs. The elaboration of adaptation measures with local herding and farming communities provides a basis for appropriate measures of agricultural policy and land management adapted to ongoing climate changes. However, while different modelling approaches can capture distinct aspects of the adaptive process, they have done so in relative isolation, without producing improved unified representations. The corollary of this is that the usefulness of future projections of climate change impacts from grassland models, such as those represented here, is greatly 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 have examined how production/biophysical/biogeochemical impacts, i.e. the effects of climatic anomalies on the performance of alpine pastures, propagate through the socio-economic and political system. This kind of integrated approach, which includes the potential for adaptation and adjustment to climate pressure, reflects 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.

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8 Supplementary material

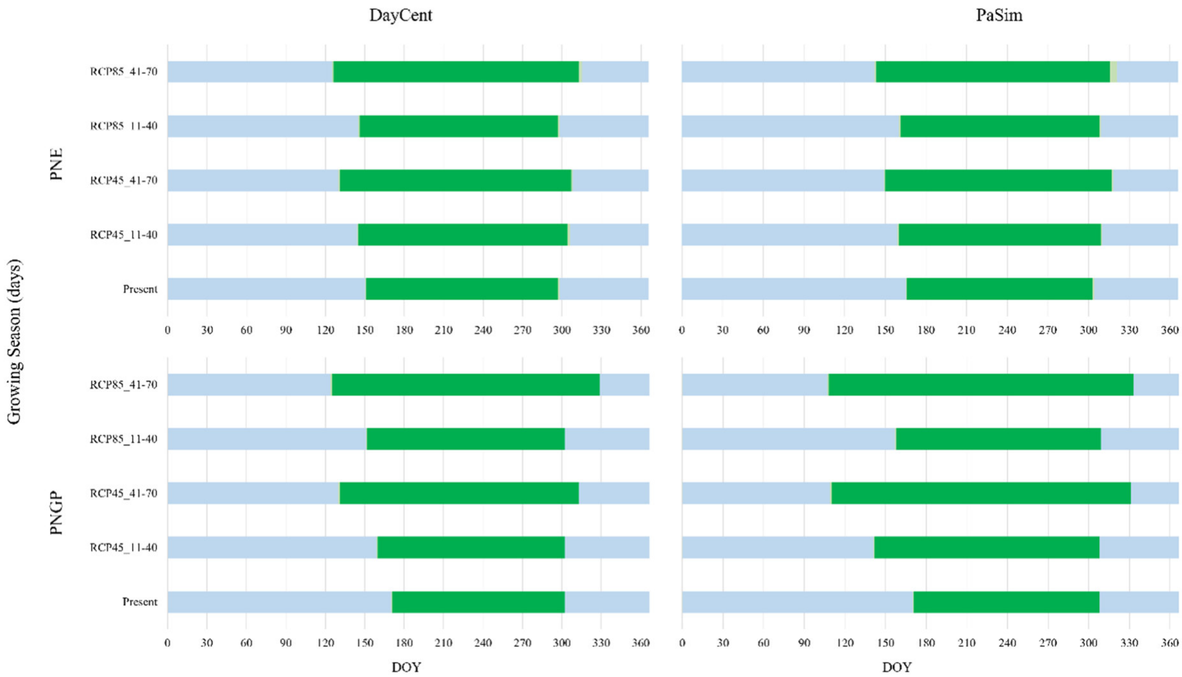

Figure S1. Estimated durations (20-year mean values) of snow-cover periods (SC, grey bars) and vegetation growing seasons (dark green bars) with two grassland models for baseline and climate change scenarios under business-as-usual management in both parks for the medium productivity (MP) macro-type. The vegetation growth season was divided into dark green (i.e. biomass available for grazing) and light green (i.e. sparse biomass, not available for grazing).

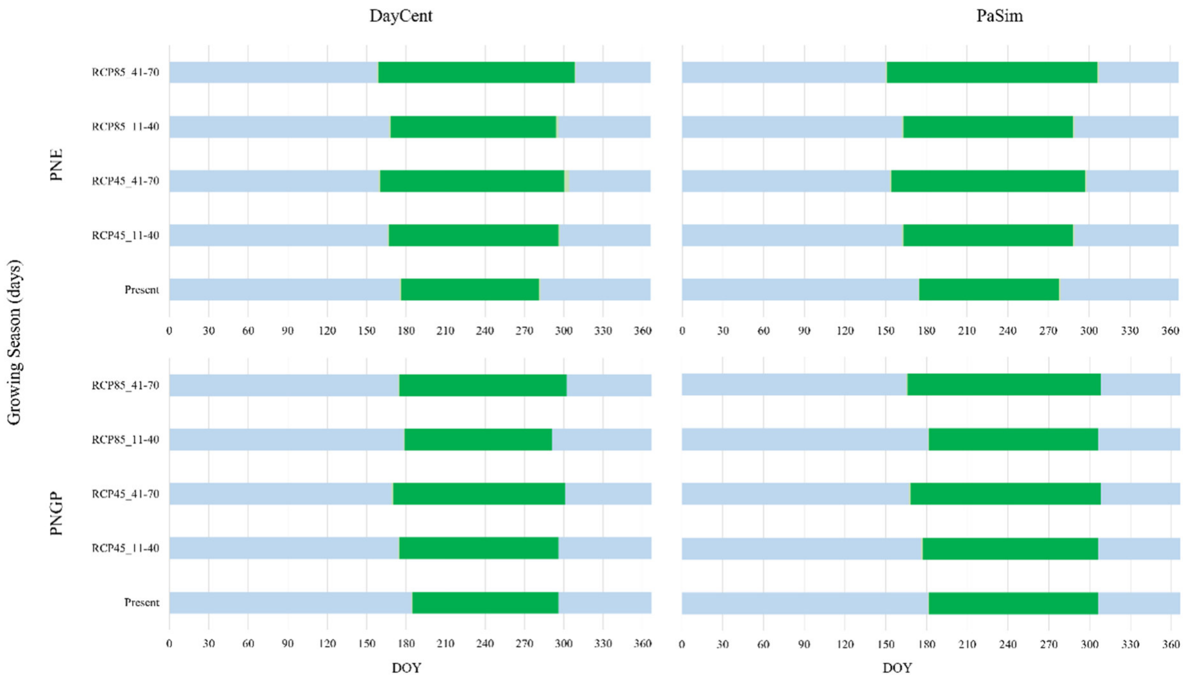

Figure S2. Estimated durations (20-year mean values) of snow-cover periods (SC, grey bars) and vegetation growing seasons (dark green bars) with two grassland models for baseline and climate change scenarios under business-as-usual management in both parks for the low productivity (LP) macro-type. The vegetation growth season was divided into dark green (i.e. biomass available for grazing) and light green (i.e. sparse biomass, not available for grazing).

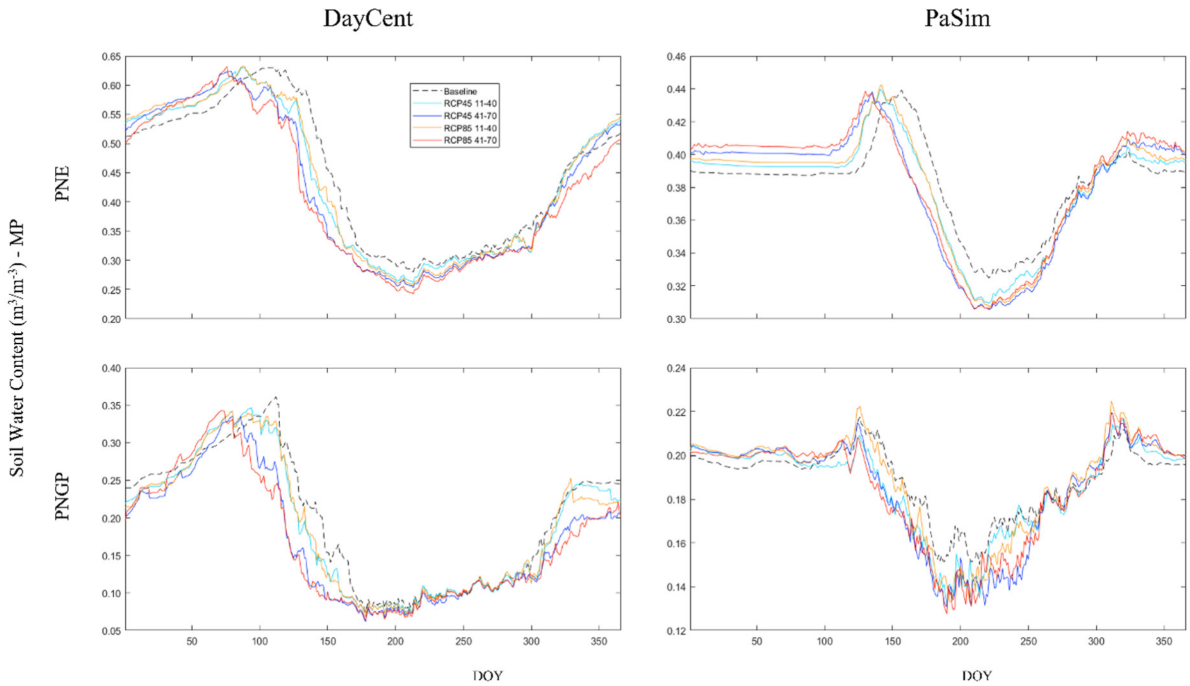

Figure S3. Daily (20-year mean) simulation of 0.30-m soil water content (SWC) with two grassland models (DayCent, PaSim), for baseline and climate change scenarios under business-as-usual management in both parks for the medium productivity (MP) macro-type.

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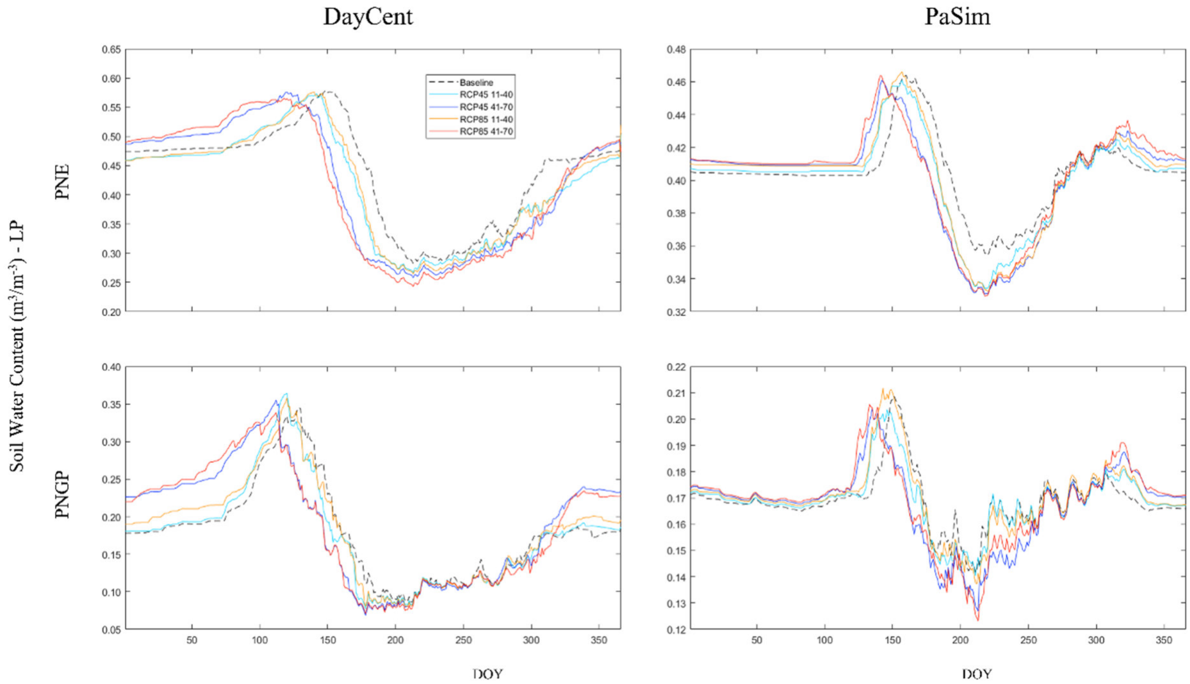

Figure S4. Daily (20-year mean) simulation of 0.30-m soil water content (SWC) with two grassland models (DayCent, PaSim), for baseline and climate change scenarios under business-as-usual management in both parks for the low productivity (LP) macro-type.

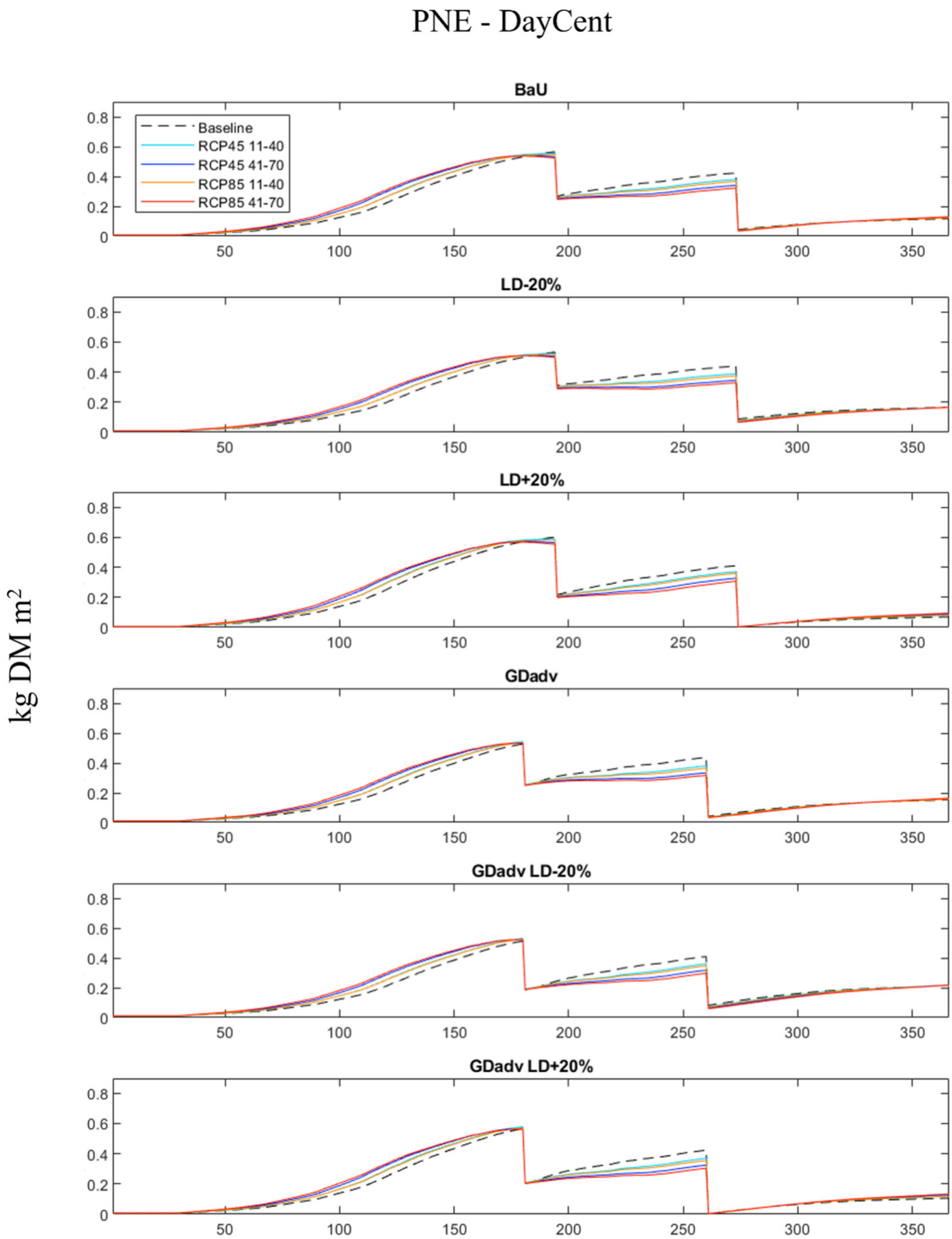

Figure S5. Daily (20-year mean) simulation of aboveground biomass (kg DM m²) in the high productivity pasture (HP) at PNE using DayCent, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

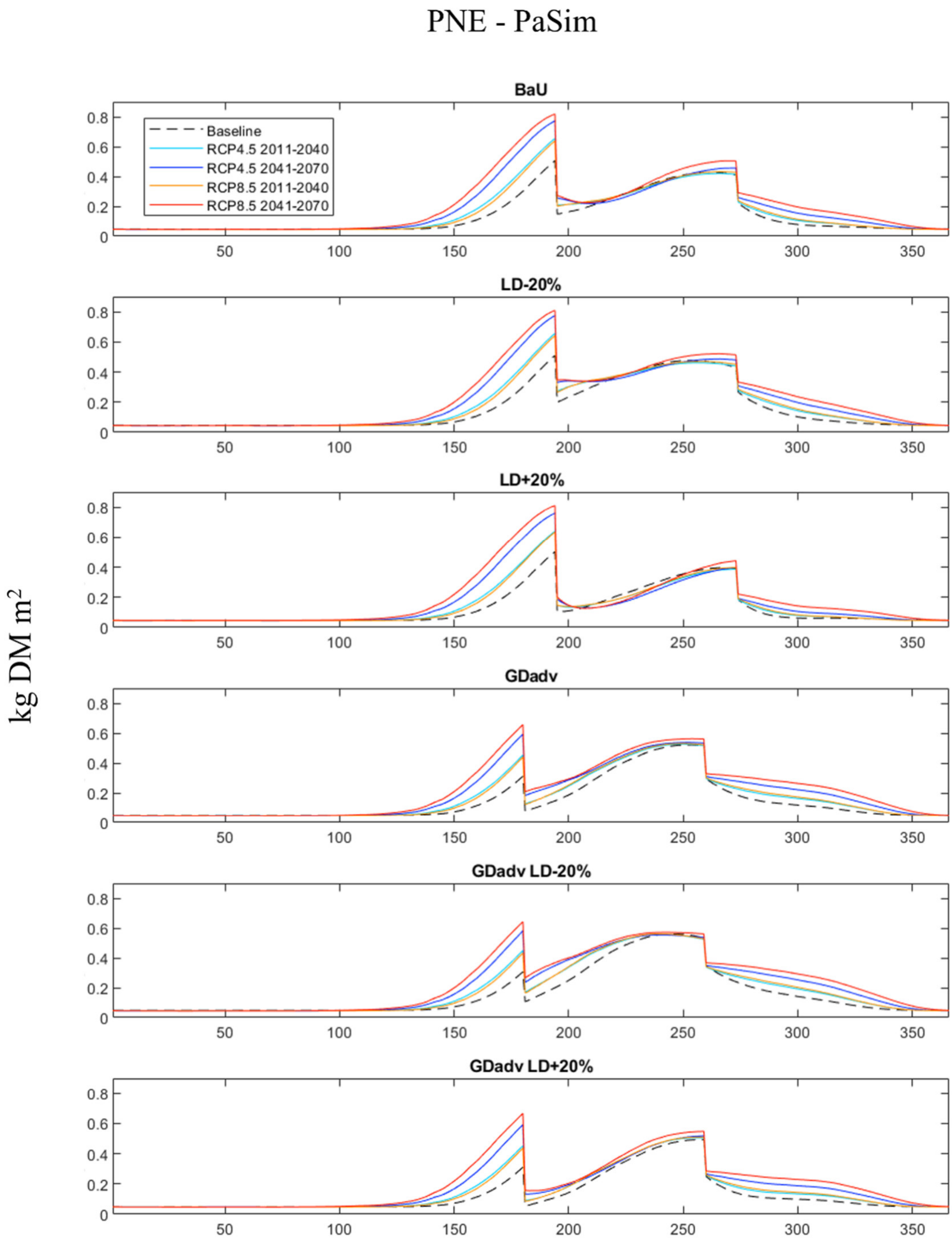

Figure S6. Daily (20-year mean) simulation of aboveground biomass (kg DM m²) in the high productivity pasture (HP) at PNE using PaSim, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

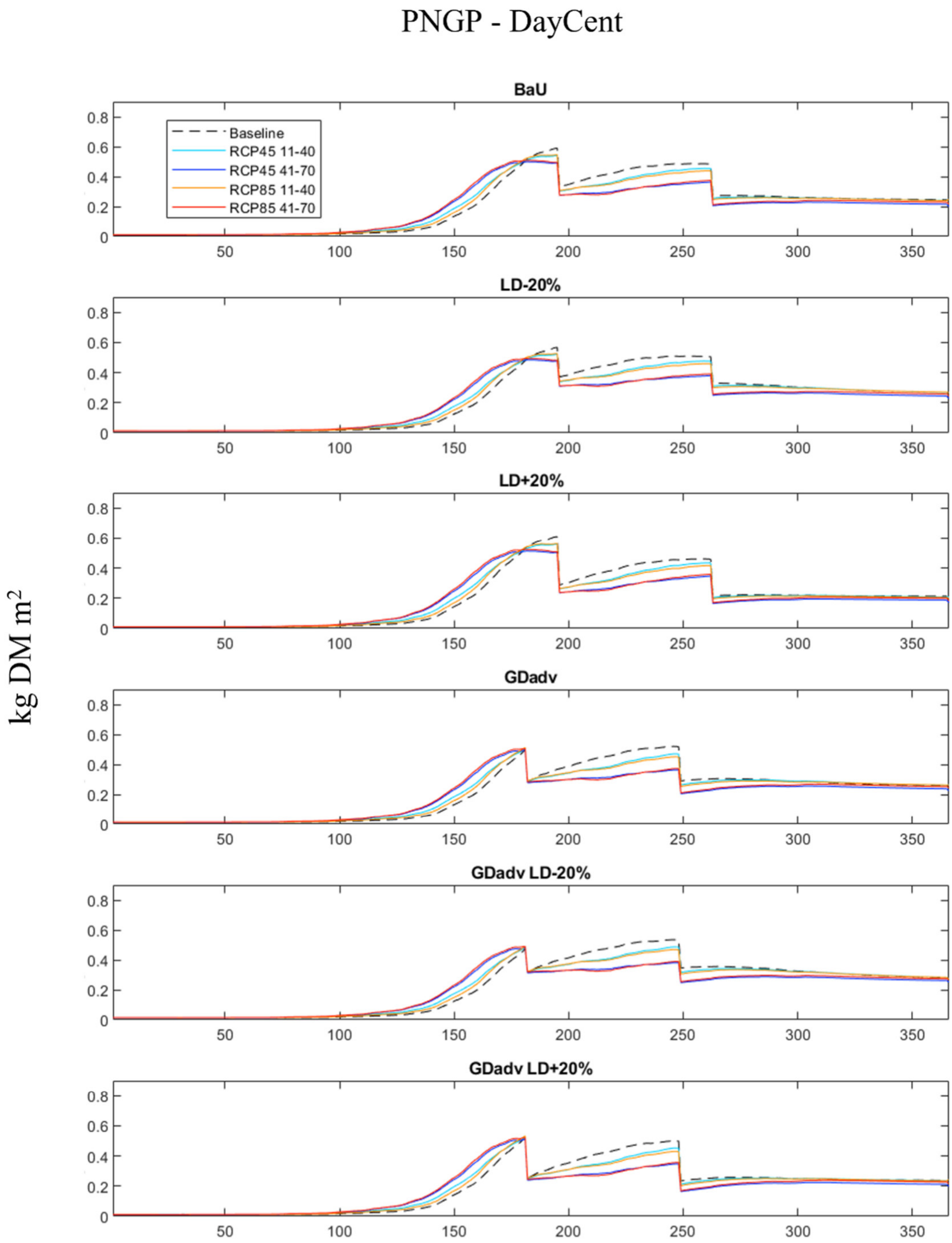

Figure S7. Daily (20-year mean) simulation of aboveground biomass (kg DM m²) in the high productivity pasture (HP) at PNGP using DayCent, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

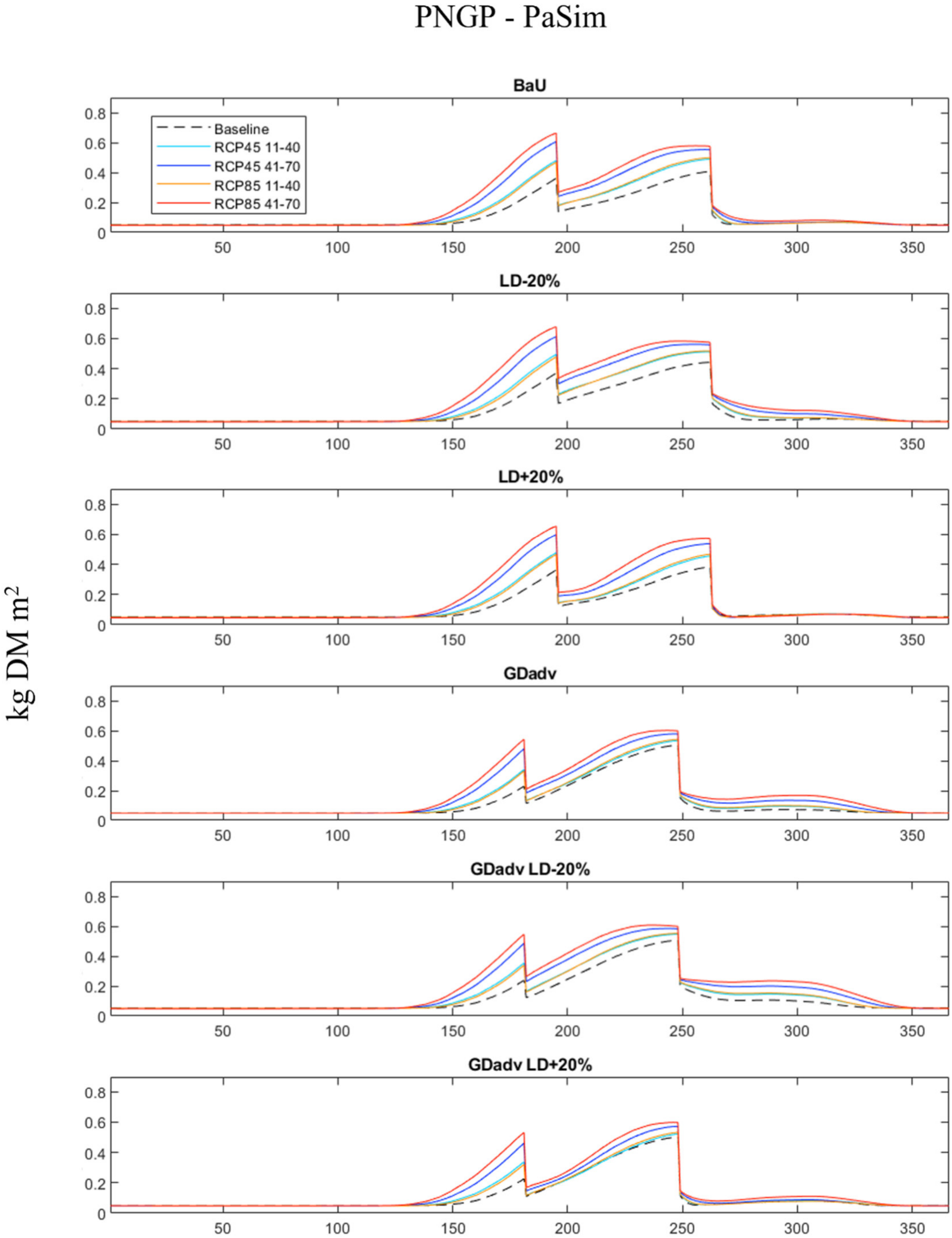

Figure S8. Daily (20-year mean) simulation of aboveground biomass (kg DM m^{-2}) in the high productivity pasture (HP) at PNGP using PaSim, for business as usual (BaU) and five alternative management options under baseline (black dotted line) and climate-change scenarios.

Table S1. Peak aboveground biomass (kg DM m^{-2}) and date (doy: day of year) as estimated in the high productivity pasture (HP) by DayCent in both parks (20-year mean) under baseline and projected climatic conditions for business-as-usual (BaU) and five alternative management options. LD-20%: reduction of livestock density by 20%; LD+20%: increase of livestock density by 20%; GDadv: advancement of grazing dates (14 days); GDadv_LD-20%: combination of LD-20% and GDadv; GDadv_LD+20%: combination of LD+20% and GDadv.

Management	**Scenario**	**DayCent**							
		High productivity pasture (HP)							
		PNE				**PNGP**			
		DOY		**kg DM m^{-2}**		**DOY**		**kg DM m^{-2}**	
		Peak_1	**Peak_2**	**Peak_1**	**Peak_2**	**Peak_1**	**Peak_2**	**Peak_1**	**Peak_2**
BAU	Baseline	189±9	267±14	0.52±0.06	0.44±0.06	190±8	244±13	0.61±0.17	0.52±0.14
	RCP4.5_11-40	182±12	264±19	0.53±0.06	0.39±0.05	187±11	245±19	0.57±0.19	0.48±0.16
	RCP4.5_41-70	178±12	256±26	0.52±0.06	0.36±0.04	183±13	241±22	0.54±0.20	0.39±0.13
	RCP8.5_11-40	182±12	257±24	0.52±0.06	0.38±0.05	187±10	245±20	0.58±0.18	0.46±0.16
	RCP8.5_41-70	177±13	252±29	0.52±0.06	0.34±0.04	183±12	247±17	0.55±0.19	0.40±0.13
LD-20%	RCP4.5_11-40	182±12	265±16	0.55±0.06	0.39±0.06	187±11	244±19	0.55±0.18	0.50±0.18
	RCP4.5_41-70	178±12	256±26	0.54±0.06	0.36±0.04	183±12	240±29	0.53±0.19	0.41±0.14
	RCP8.5_11-40	182±12	258±24	0.54±0.06	0.38±0.06	187±10	245±20	0.56±0.17	0.49±0.17
	RCP8.5_41-70	177±13	252±29	0.54±0.06	0.34±0.04	183±12	243±27	0.53±0.19	0.42±0.13
LD+20%	RCP4.5_11-40	181±12	269±11	0.62±0.07	0.37±0.05	187±11	247±17	0.59±0.21	0.45±0.15
	RCP4.5_41-70	177±13	267±14	0.61±0.07	0.33±0.06	183±13	250±14	0.56±0.21	0.37±0.13
	RCP8.5_11-40	180±12	269±11	0.61±0.07	0.36±0.06	186±10	246±17	0.60±0.19	0.44±0.15
	RCP8.5_41-70	176±13	265±19	0.60±0.07	0.31±0.06	182±13	252±13	0.56±0.20	0.38±0.12
GDadv	RCP4.5_11-40	175±8	249±19	0.56±0.07	0.39±0.06	179±8	242±20	0.51±0.18	0.49±0.17
	RCP4.5_41-70	173±8	246±22	0.56±0.07	0.34±0.05	174±8	235±25	0.52±0.19	0.40±0.14
	RCP8.5_11-40	174±8	245±22	0.55±0.07	0.37±0.06	180±7	242±21	0.52±0.17	0.47±0.16
	RCP8.5_41-70	172±9	244±23	0.56±0.06	0.33±0.05	174±8	238±24	0.53±0.19	0.40±0.13
Gdadv_LD-20%	RCP4.5_11-40	175±8	257±8	0.54±0.07	0.36±0.06	181±10	241±21	0.50±0.17	0.51±0.17
	RCP4.5_41-70	173±8	254±25	0.55±0.06	0.32±0.06	174±7	232±26	0.50±0.18	0.42±0.14
	RCP8.5_11-40	174±8	253±13	0.54±0.07	0.35±0.06	181±9	238±21	0.50±0.15	0.50±0.17

	RCP8.5_41-70	172±9	252±26	0.55±0.06	0.30±0.05	175±7	237±23	0.51±0.18	0.42±0.13
Gdadv_LD+20%	RCP4.5_11-40	175±8	254±13	0.59±0.07	0.37±0.06	178±9	243±20	0.53±0.20	0.47±0.16
	RCP4.5_41-70	172±8	249±19	0.59±0.07	0.33±0.05	173±8	238±22	0.53±0.20	0.37±0.13
	RCP8.5_11-40	174±8	252±15	0.59±0.07	0.36±0.06	179±6	242±21	0.54±0.18	0.45±0.16
	RCP8.5_41-70	172±9	249±19	0.59±0.07	0.31±0.05	173±9	239±23	0.54±0.19	0.38±0.12

Table S2. Peak aboveground biomass (kg DM m^{-2}) and date (doy: day of year) as estimated in the high productivity pasture (HP) by PaSim in both parks (20-year mean) under baseline and projected climatic conditions for business-as-usual (BaU) and five alternative management options. LD-20%: reduction of livestock density by 20%; LD+20%: increase of livestock density by 20%; GDadv: advancement of grazing dates (14 days); GDadv_LD-20%: combination of LD-20% and GDadv; GDadv_LD+20%: combination of LD+20% and GDadv.

Management	Scenario	PaSim							
		High productivity pasture (HP)							
		PNE				PNGP			
		DOY		kg DM m^{-2}		DOY		kg DM m^{-2}	
		Peak_1	Peak_2	Peak_1	Peak_2	Peak_1	Peak_2	Peak_1	Peak_2
BAU	Baseline	194±3	263±7	0.50±0.17	0.43±0.08	196±5	261±2	0.37±0.11	0.41±0.06
	RCP4.5_11-40	194±1	264±8	0.66±0.15	0.43±0.09	195±0	261±2	0.48±0.13	0.49±0.05
	RCP4.5_41-70	193±3	268±7	0.78±0.12	0.46±0.06	195±0	258±5	0.61±0.11	0.56±0.03
	RCP8.5_11-40	194±0	264±8	0.64±0.14	0.44±0.07	195±0	261±2	0.47±0.12	0.50±0.05
	RCP8.5_41-70	191±5	268±6	0.83±0.12	0.51±0.05	194±1	255±6	0.66±0.11	0.58±0.03
LD-20%	RCP4.5_11-40	195±5	254±9	0.51±0.18	0.48±0.07	196±5	260±2	0.37±0.12	0.44±0.05
	RCP4.5_41-70	194±4	255±12	0.66±0.15	0.48±0.06	195±0	259±4	0.49±0.13	0.51±0.04
	RCP8.5_11-40	193±3	261±11	0.78±0.13	0.50±0.04	195±0	255±6	0.61±0.12	0.57±0.03
	RCP8.5_41-70	194±4	256±12	0.64±0.15	0.49±0.05	195±0	256±4	0.48±0.13	0.52±0.04
LD+20%	RCP4.5_11-40	191±5	262±8	0.82±0.12	0.53±0.04	194±1	250±7	0.68±0.11	0.59±0.02
	RCP4.5_41-70	194±0	266±6	0.50±0.16	0.4±0.07	196±5	261±1	0.37±0.11	0.38±0.07
	RCP8.5_11-40	194±1	269±5	0.64±0.14	0.39±0.08	195±0	261±2	0.48±0.12	0.46±0.05
	RCP8.5_41-70	193±3	271±4	0.77±0.12	0.40±0.11	195±0	260±2	0.60±0.11	0.54±0.04
GDadv	RCP4.5_11-40	194±0	269±5	0.64±0.13	0.40±0.08	195±0	261±2	0.47±0.12	0.47±0.05
	RCP4.5_41-70	191±5	271±4	0.81±0.11	0.44±0.10	195±1	258±5	0.65±0.10	0.57±0.03
	RCP8.5_11-40	204±17	252±6	0.37±0.13	0.53±0.07	211±11	247±1	0.35±0.05	0.50±0.05
	RCP8.5_41-70	195±18	248±7	0.50±0.14	0.54±0.06	201±17	248±1	0.41±0.08	0.53±0.04
Gdadv_LD-20%	RCP4.5_11-40	188±15	249±8	0.61±0.14	0.55±0.05	191±16	244±5	0.50±0.11	0.58±0.03
	RCP4.5_41-70	195±18	248±7	0.49±0.13	0.54±0.06	201±17	247±2	0.40±0.07	0.54±0.04
	RCP8.5_11-40	186±14	250±4	0.67±0.15	0.57±0.05	191±16	241±6	0.57±0.12	0.61±0.03

	RCP8.5_41-70	209±13	246±8	0.43±0.13	0.57±0.07	213±8	247±2	0.36±0.06	0.51±0.05
Gdadv_LD+20%	RCP4.5_11-40	200±18	240±10	0.54±0.13	0.57±0.07	207±15	246±4	0.43±0.09	0.55±0.04
	RCP4.5_41-70	193±17	241±11	0.63±0.13	0.57±0.05	199±17	241±6	0.53±0.10	0.59±0.03
	RCP8.5_11-40	202±17	240±11	0.53±0.12	0.58±0.06	209±13	245±4	0.43±0.08	0.56±0.04
	RCP8.5_41-70	191±17	241±11	0.68±0.13	0.59±0.05	195±17	237±7	0.60±0.10	0.62±0.03

Table S3. Peak aboveground biomass (kg DM m^{-2}) and date (doy: day of year) as estimated in the medium productivity pasture (MP) by DayCent in both parks (20-year mean) under baseline and projected climatic conditions for business-as-usual (BaU) and five alternative management options. LD-20%: reduction of livestock density by 20%; LD+20%: increase of livestock density by 20%; GDadv: advancement of grazing dates (14 days); GDadv_LD-20%: combination of LD-20% and GDadv; GDadv_LD+20%: combination of LD+20% and GDadv.

Management	**Scenario**	**DayCent**							
		Medium productivity pasture (MP)							
		PNE				**PNGP**			
		DOY		**kg DM m^{-2}**		**DOY**		**kg DM m^{-2}**	
		Peak_1	**Peak_2**	**Peak_1**	**Peak_2**	**Peak_1**	**Peak_2**	**Peak_1**	**Peak_2**
BAU	Baseline	206±12	- - -	0.35±0.05	- - -	183±14	219±34	0.59±0.18	0.51±0.2
	RCP4.5_11-40	196±10	- - -	0.35±0.04	- - -	171±11	218±27	0.58±0.18	0.42±0.16
	RCP4.5_41-70	189±13	- - -	0.34±0.04	- - -	163±11	219±36	0.56±0.15	0.35±0.13
	RCP8.5_11-40	198±10	- - -	0.34±0.04	- - -	174±14	219±29	0.56±0.19	0.42±0.15
	RCP8.5_41-70	185±15	- - -	0.34±0.04	- - -	164±11	219±36	0.56±0.15	0.34±0.12
LD-20%	RCP4.5_11-40	206±11	- - -	0.34±0.04	- - -	183±14	222±35	0.58±0.17	0.5±0.19
	RCP4.5_41-70	199±9	- - -	0.34±0.04	- - -	171±11	218±27	0.57±0.17	0.42±0.15
	RCP8.5_11-40	191±12	- - -	0.33±0.03	- - -	163±11	219±36	0.55±0.15	0.35±0.13
	RCP8.5_41-70	200±9	- - -	0.33±0.04	- - -	174±14	218±27	0.56±0.18	0.41±0.14
LD+20%	RCP4.5_11-40	188±12	- - -	0.33±0.03	- - -	164±11	224±38	0.56±0.15	0.34±0.12
	RCP4.5_41-70	204±8	- - -	0.38±0.05	- - -	183±14	211±10	0.6±0.18	0.51±0.2
	RCP8.5_11-40	195±11	- - -	0.37±0.05	- - -	171±11	218±27	0.59±0.18	0.42±0.16
	RCP8.5_41-70	187±15	- - -	0.36±0.04	- - -	163±11	219±36	0.56±0.15	0.35±0.13
GDadv	RCP4.5_11-40	195±11	- - -	0.37±0.05	- - -	174±14	219±29	0.57±0.19	0.42±0.15
	RCP4.5_41-70	184±15	- - -	0.36±0.04	- - -	164±11	219±36	0.57±0.15	0.34±0.12
	RCP8.5_11-40	199±15	- - -	0.34±0.04	- - -	183±14	222±39	0.58±0.17	0.5±0.18
	RCP8.5_41-70	194±12	- - -	0.34±0.05	- - -	171±11	213±27	0.58±0.17	0.42±0.15
Gdadv_LD-20%	RCP4.5_11-40	186±11	- - -	0.34±0.04	- - -	163±11	218±36	0.55±0.15	0.35±0.13
	RCP4.5_41-70	195±12	- - -	0.34±0.05	- - -	174±14	213±27	0.56±0.18	0.41±0.14
	RCP8.5_11-40	182±12	- - -	0.34±0.04	- - -	164±11	223±38	0.56±0.15	0.34±0.12

	RCP8.5_41-70	207±25	- - -	0.32±0.04	- - -	183±14	222±39	0.57±0.17	0.49±0.18
Gdadv_LD+20%	RCP4.5_11-40	199±19	- - -	0.33±0.04	- - -	171±11	216±27	0.57±0.17	0.41±0.15
	RCP4.5_41-70	189±15	- - -	0.32±0.04	- - -	163±11	222±37	0.55±0.15	0.35±0.12
	RCP8.5_11-40	199±19	- - -	0.32±0.04	- - -	175±14	213±27	0.55±0.18	0.41±0.14
	RCP8.5_41-70	186±9	- - -	0.33±0.04	- - -	164±11	223±38	0.56±0.15	0.34±0.12

Table S4. Peak aboveground biomass (kg DM m-2) and date (doy: day of year) as estimated in the medium productivity pasture (MP) by PaSim in both parks (20-year mean) under baseline and projected climatic conditions for business-as-usual (BaU) and five alternative management options. LD-20%: reduction of livestock density by 20%; LD+20%: increase of livestock density by 20%; GDadv: advancement of grazing dates (14 days); GDadv_LD-20%: combination of LD-20% and GDadv; GDadv_LD+20%: combination of LD+20% and GDadv.

Management	Scenario	PaSim							
		Medium productivity pasture (MP)							
		PNE				PNGP			
		DOY		kg DM m-2		DOY		kg DM m-2	
		Peak_1	Peak_2	Peak_1	Peak_2	Peak_1	Peak_2	Peak_1	Peak_2
BAU	Baseline	229±30.99	- - -	0.19±0.07	- - -	212±5	221±5	0.33±0.04	0.34±0.04
	RCP4.5_11-40	217±16.67	- - -	0.24±0.09	- - -	211±6	222±5	0.35±0.06	0.35±0.06
	RCP4.5_41-70	213±6.58	- - -	0.30±0.09	- - -	213±3	225±5	0.4±0.03	0.41±0.02
	RCP8.5_11-40	213±8.38	- - -	0.24±0.07	- - -	213±5	222±5	0.36±0.05	0.36±0.05
	RCP8.5_41-70	212±0	- - -	0.35±0.11	- - -	211±7	226±4	0.45±0.03	0.46±0.03
LD-20%	RCP4.5_11-40	227±27.77	- - -	0.19±0.06	- - -	213±4	221±5	0.33±0.04	0.33±0.04
	RCP4.5_41-70	219±18.68	- - -	0.24±0.08	- - -	212±4	222±5	0.35±0.06	0.35±0.05
	RCP8.5_11-40	213±6.58	- - -	0.30±0.10	- - -	213±3	224±5	0.41±0.03	0.42±0.03
	RCP8.5_41-70	216±13.37	- - -	0.24±0.07	- - -	213±4	222±5	0.36±0.04	0.36±0.04
LD+20%	RCP4.5_11-40	213±5.92	- - -	0.33±0.10	- - -	211±6	226±4	0.46±0.04	0.47±0.04
	RCP4.5_41-70	224±28.97	- - -	0.20±0.07	- - -	212±5	221±5	0.33±0.04	0.34±0.04
	RCP8.5_11-40	213±8.71	- - -	0.24±0.08	- - -	210±7	221±5	0.36±0.05	0.36±0.04
	RCP8.5_41-70	212±0	- - -	0.31±0.09	- - -	212±6	225±5	0.4±0.04	0.41±0.03
GDadv	RCP4.5_11-40	213±8.38	- - -	0.24±0.08	- - -	213±4	222±5	0.35±0.06	0.36±0.05
	RCP4.5_41-70	212±0	- - -	0.36±0.11	- - -	211±7	226±4	0.45±0.03	0.46±0.03
	RCP8.5_11-40	253±35.42	- - -	0.17±0.05	- - -	211±4	219±13	0.34±0.05	0.14±0.02
	RCP8.5_41-70	221±32.76	- - -	0.20±0.07	- - -	210±7	216±0	0.36±0.05	0.15±0.02
Gdadv_LD-20%	RCP4.5_11-40	211±25	- - -	0.25±0.09	- - -	212±3	216±0	0.41±0.02	0.17±0.01
	RCP4.5_41-70	223±32	- - -	0.20±0.06	- - -	212±4	216±0	0.36±0.05	0.15±0.02
	RCP8.5_11-40	207±21	- - -	0.28±0.10	- - -	210±6	222±16	0.45±0.03	0.2±0.02

	RCP8.5_41-70	253±31	- - -	0.17±0.05	- - -	212±4	216±0	0.33±0.04	0.17±0.02
Gdadv_LD+20%	RCP4.5_11-40	235±31	- - -	0.20±0.07	- - -	213±3	216±0	0.35±0.04	0.18±0.02
	RCP4.5_41-70	211±23	- - -	0.25±0.09	- - -	212±3	221±15	0.41±0.04	0.22±0.02
	RCP8.5_11-40	231±30	- - -	0.21±0.06	- - -	212±4	216±0	0.37±0.03	0.19±0.02
	RCP8.5_41-70	211±23	- - -	0.28±0.09	- - -	211±5	230±22	0.46±0.03	0.25±0.02

Table S5. Peak aboveground biomass (kg DM m^{-2}) and date (doy: day of year) as estimated in the low productivity pasture (LP) by DayCent in both parks (20-year mean) under baseline and projected climatic conditions for business-as-usual (BaU) and five alternative management options. LD-20%: reduction of livestock density by 20%; LD+20%: increase of livestock density by 20%; GDadv: advancement of grazing dates (14 days); GDadv_LD-20%: combination of LD-20% and GDadv; GDadv_LD+20%: combination of LD+20% and GDadv.

Management	Scenario	DayCent							
		Low productivity pasture (LP)							
		PNE				PNGP			
		DOY		kg DM m^{-2}		DOY		kg DM m^{-2}	
		Peak_1	Peak_2	Peak_1	Peak_2	Peak_1	Peak_2	Peak_1	Peak_2
BAU	Baseline	221±13	- - -	0.07±0.02	- - -	188±12	223±26	0.22±0.07	0.21±0.08
	RCP4.5_11-40	219±9	- - -	0.08±0.02	- - -	181±15	246±41	0.22±0.07	0.18±0.08
	RCP4.5_41-70	218±7	- - -	0.09±0.01	- - -	170±11	253±53	0.20±0.06	0.15±0.04
	RCP8.5_11-40	218±7	- - -	0.08±0.02	- - -	182±14	242±43	0.21±0.06	0.18±0.07
	RCP8.5_41-70	218±7	- - -	0.09±0.01	- - -	170±11	253±53	0.20±0.06	0.15±0.04
LD-20%	RCP4.5_11-40	230±20	- - -	0.08±0.01	- - -	181±15	246±41	0.22±0.07	0.19±0.07
	RCP4.5_41-70	224±16	- - -	0.09±0.01	- - -	170±11	251±50	0.20±0.06	0.15±0.04
	RCP8.5_11-40	228±19	- - -	0.08±0.01	- - -	182±14	244±42	0.21±0.06	0.18±0.07
	RCP8.5_41-70	224±17	- - -	0.09±0.01	- - -	170±11	256±51	0.20±0.06	0.15±0.04
LD+20%	RCP4.5_11-40	217±0	- - -	0.08±0.02	- - -	180±14	242±43	0.22±0.07	0.18±0.08
	RCP4.5_41-70	217±1	- - -	0.09±0.02	- - -	170±11	250±54	0.20±0.06	0.15±0.04
	RCP8.5_11-40	217±0	- - -	0.08±0.02	- - -	182±14	242±43	0.21±0.06	0.18±0.07
	RCP8.5_41-70	216±1	- - -	0.09±0.01	- - -	170±11	249±54	0.20±0.06	0.15±0.04
GDadv	RCP4.5_11-40	245±25	- - -	0.07±0.01	- - -	180±14	259±36	0.22±0.07	0.16±0.05
	RCP4.5_41-70	241±27	- - -	0.08±0.01	- - -	170±11	276±41	0.20±0.06	0.14±0.04
	RCP8.5_11-40	246±24	- - -	0.07±0.01	- - -	182±13	257±39	0.21±0.07	0.16±0.05
	RCP8.5_41-70	242±27	- - -	0.08±0.01	- - -	170±11	283±39	0.20±0.06	0.13±0.04
Gdadv_LD-20%	RCP4.5_11-40	260±1	- - -	0.08±0.01	- - -	180±14	251±35	0.22±0.07	0.17±0.05
	RCP4.5_41-70	258±10	- - -	0.08±0.01	- - -	170±11	271±44	0.2±0.06	0.14±0.04
	RCP8.5_11-40	258±9	- - -	0.08±0.01	- - -	182±13	257±39	0.21±0.07	0.17±0.05

	RCP8.5_41-70	252±19	- - -	0.08±0.01	- - -	170±11	277±43	0.20±0.06	0.14±0.04
Gdadv_LD+20%	RCP4.5_11-40	230±28	- - -	0.07±0.01	- - -	180±14	267±30	0.22±0.07	0.15±0.05
	RCP4.5_41-70	223±27	- - -	0.07±0.01	- - -	170±11	281±36	0.20±0.06	0.13±0.04
	RCP8.5_11-40	226±28	- - -	0.07±0.01	- - -	182±13	264±32	0.21±0.07	0.15±0.05
	RCP8.5_41-70	221±27	- - -	0.07±0.01	- - -	170±11	287±34	0.20±0.06	0.13±0.03

Table S6. Peak aboveground biomass (kg DM m^{-2}) and date (doy: day of year) as estimated in the low productivity pasture (LP) by PaSim in both parks (20-year mean) under baseline and projected climatic conditions for business-as-usual (BaU) and five alternative management options. LD-20%: reduction of livestock density by 20%; LD+20%: increase of livestock density by 20%; GDadv: advancement of grazing dates (14 days); GDadv_LD-20%: combination of LD-20% and GDadv; GDadv_LD+20%: combination of LD+20% and GDadv.

Management	**Scenario**	**PaSim**							
		Low productivity pasture (LP)							
		PNE				**PNGP**			
		DOY		**kg DM m^{-2}**		**DOY**		**kg DM m^{-2}**	
		Peak_1	**Peak_2**	**Peak_1**	**Peak_2**	**Peak_1**	**Peak_2**	**Peak_1**	**Peak_2**
BAU	Baseline	261±10	- - -	0.19±0.08	- - -	202±37	242±23	0.11±0.02	0.12±0.02
	RCP4.5_11-40	262±8	- - -	0.23±0.09	- - -	212±4	227±8	0.14±0.02	0.12±0.01
	RCP4.5_41-70	264±9	- - -	0.31±0.09	- - -	212±3	219±3	0.17±0.03	0.13±0.02
	RCP8.5_11-40	264±8	- - -	0.24±0.09	- - -	209±13	229±11	0.14±0.03	0.12±0.01
	RCP8.5_41-70	266±11	- - -	0.38±0.08	- - -	212±3	221±5	0.19±0.04	0.15±0.03
LD-20%	RCP4.5_11-40	262±9	- - -	0.20±0.08	- - -	204±37	237±21	0.11±0.02	0.12±0.02
	RCP4.5_41-70	262±9	- - -	0.24±0.09	- - -	212±4	227±8	0.14±0.02	0.13±0.01
	RCP8.5_11-40	264±9	- - -	0.32±0.09	- - -	212±3	220±5	0.16±0.03	0.14±0.02
	RCP8.5_41-70	263±8	- - -	0.25±0.09	- - -	209±13	230±11	0.14±0.03	0.13±0.02
LD+20%	RCP4.5_11-40	266±11	- - -	0.39±0.08	- - -	212±2	221±5	0.18±0.04	0.16±0.03
	RCP4.5_41-70	259±15	- - -	0.19±0.08	- - -	202±37	241±23	0.11±0.02	0.12±0.02
	RCP8.5_11-40	261±8	- - -	0.22±0.09	- - -	212±3	227±8	0.14±0.02	0.12±0.01
	RCP8.5_41-70	262±12	- - -	0.3±0.09	- - -	213±2	218±3	0.16±0.03	0.12±0.02
GDadv	RCP4.5_11-40	263±8	- - -	0.23±0.10	- - -	209±13	228±11	0.14±0.03	0.12±0.01
	RCP4.5_41-70	266±11	- - -	0.38±0.09	- - -	212±3	220±5	0.19±0.04	0.14±0.03
	RCP8.5_11-40	262±9	- - -	0.19±0.09	- - -	205±38	239±20	0.11±0.01	0.13±0.02
	RCP8.5_41-70	264±8	- - -	0.23±0.08	- - -	210±7	230±11	0.13±0.02	0.14±0.03
Gdadv_LD-20%	RCP4.5_11-40	266±10	- - -	0.31±0.10	- - -	207±8	224±8	0.14±0.02	0.14±0.02
	RCP4.5_41-70	264±8	- - -	0.24±0.10	- - -	202±37	231±11	0.13±0.02	0.14±0.03
	RCP8.5_11-40	267±11	- - -	0.38±0.08	- - -	203±7	224±8	0.16±0.03	0.15±0.03

	RCP8.5_41-70	262±9	- - -	0.20±0.08	- - -	204±38	239±20	0.11±0.01	0.13±0.02
Gdadv_LD+20%	RCP4.5_11-40	263±9	- - -	0.24±0.09	- - -	210±7	230±11	0.13±0.02	0.14±0.03
	RCP4.5_41-70	265±9	- - -	0.32±0.09	- - -	207±8	224±8	0.15±0.02	0.14±0.02
	RCP8.5_11-40	264±7	- - -	0.24±0.10	- - -	199±39	233±12	0.13±0.02	0.14±0.03
	RCP8.5_41-70	266±11	- - -	0.39±0.08	- - -	204±7	225±8	0.16±0.02	0.15±0.03

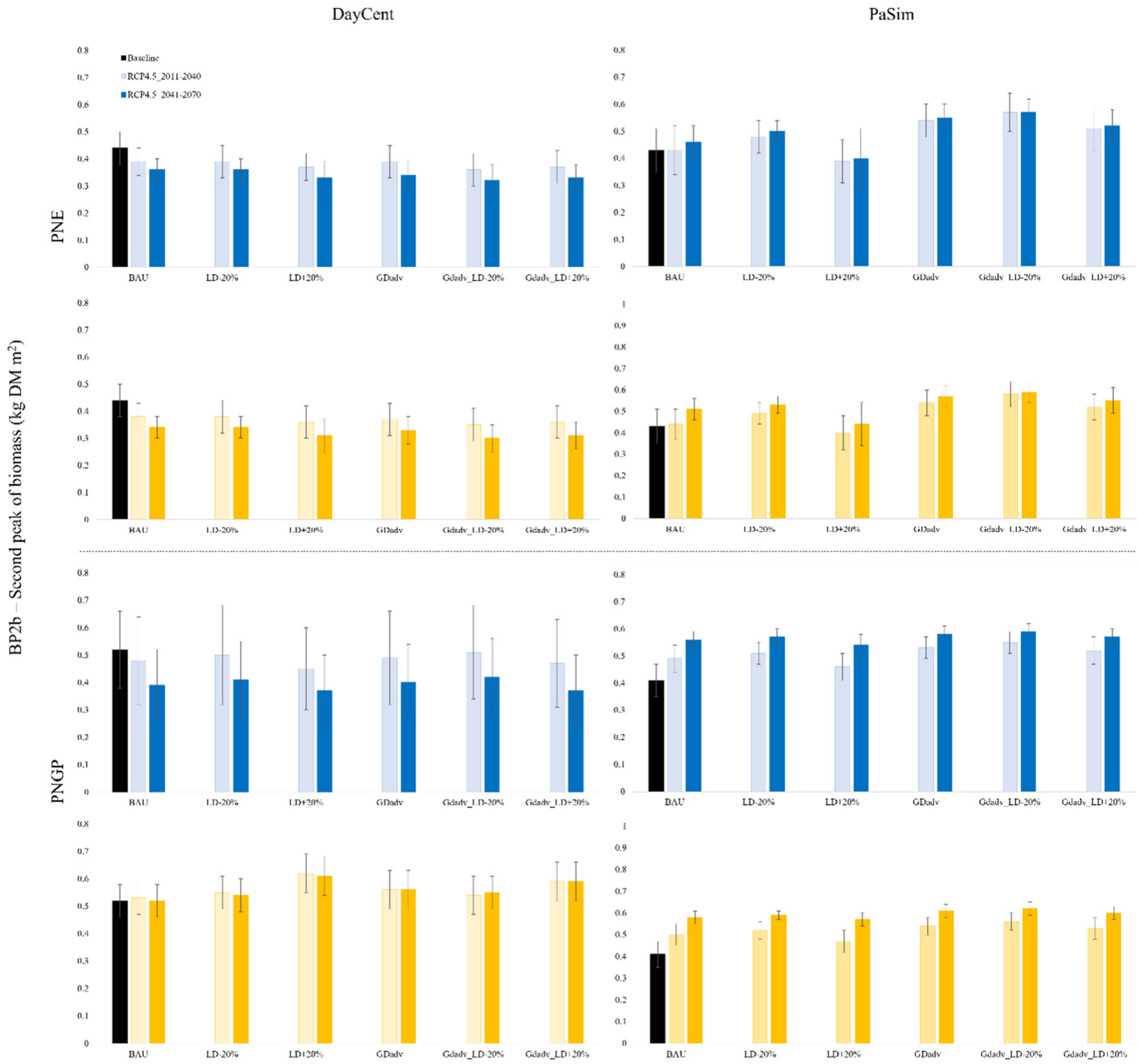

Figure S9. Changes in the second (BP2b) aboveground biomass peak (kg DM m⁻²) between business-as-usual management under baseline climate (black histogram) and all alternatives management options under RCP4.5 (cyan and blue histograms) and RCP8.5 (clear and dark orange histograms) for the high productivity pasture (HP) in both parks as provided by DayCent and PaSim. Vertical bars are standard deviations.

Table S7. Simulated C-flux components (20-year mean) from the two study-areas (baseline climate), estimated using two grassland models (GPP: gross primary production; NPP: net primary production; RECO: ecosystem respiration).

Site	Model	GPP	NPP	RECO
			kg C m^{-2} yr^{-1}	
PNE	DayCent	1.57±0.2	0.63±0.07	1.2±0.1
	PaSim	1.25±0.2	0.63±0.1	1.2±0.13
PNGP	DayCent	2.1±0.5	0.83±0.19	1.8±0.3
	PaSim	0.98±0.15	0.54±0.09	1.1±0.14

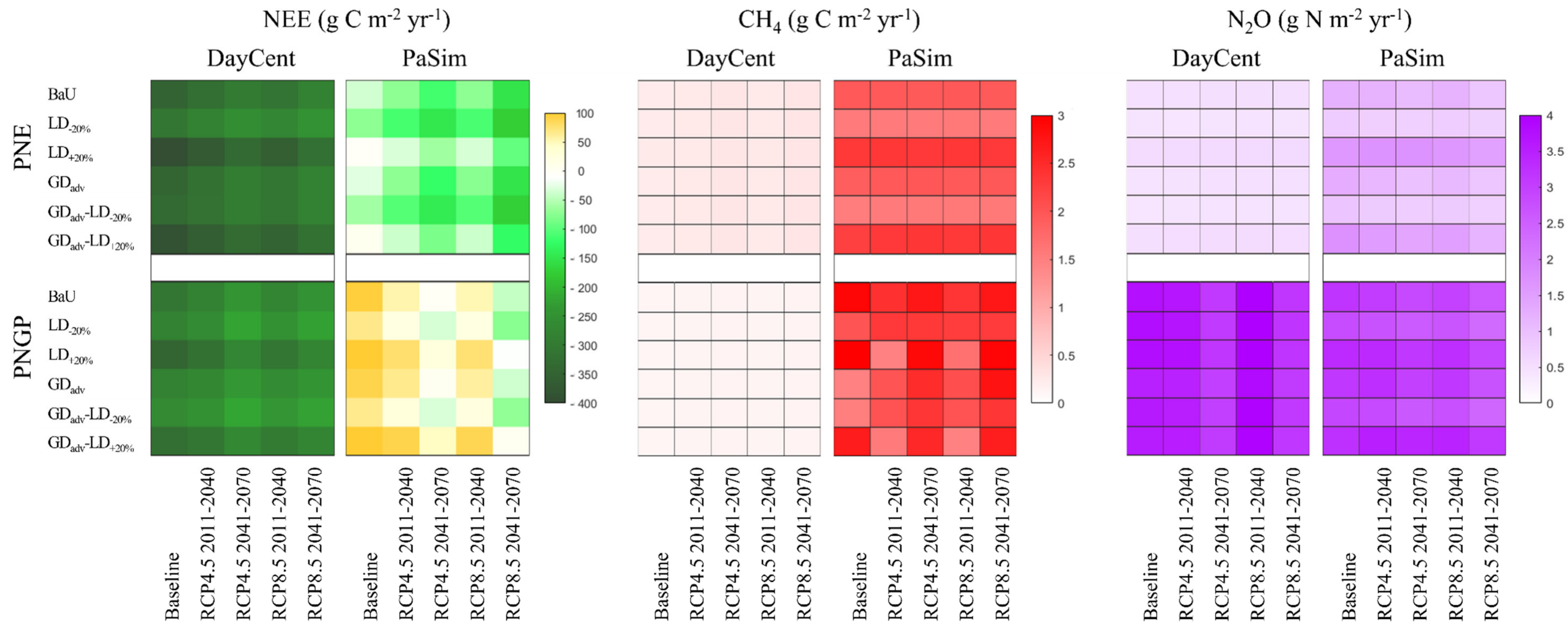

Figure S10. Heatmap visualisation of the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated in the high productivity pasture (HP) using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to current climate and management in the Parc National des Écrins (PNE) and Parco Nazionale Gran Paradiso (PNGP).

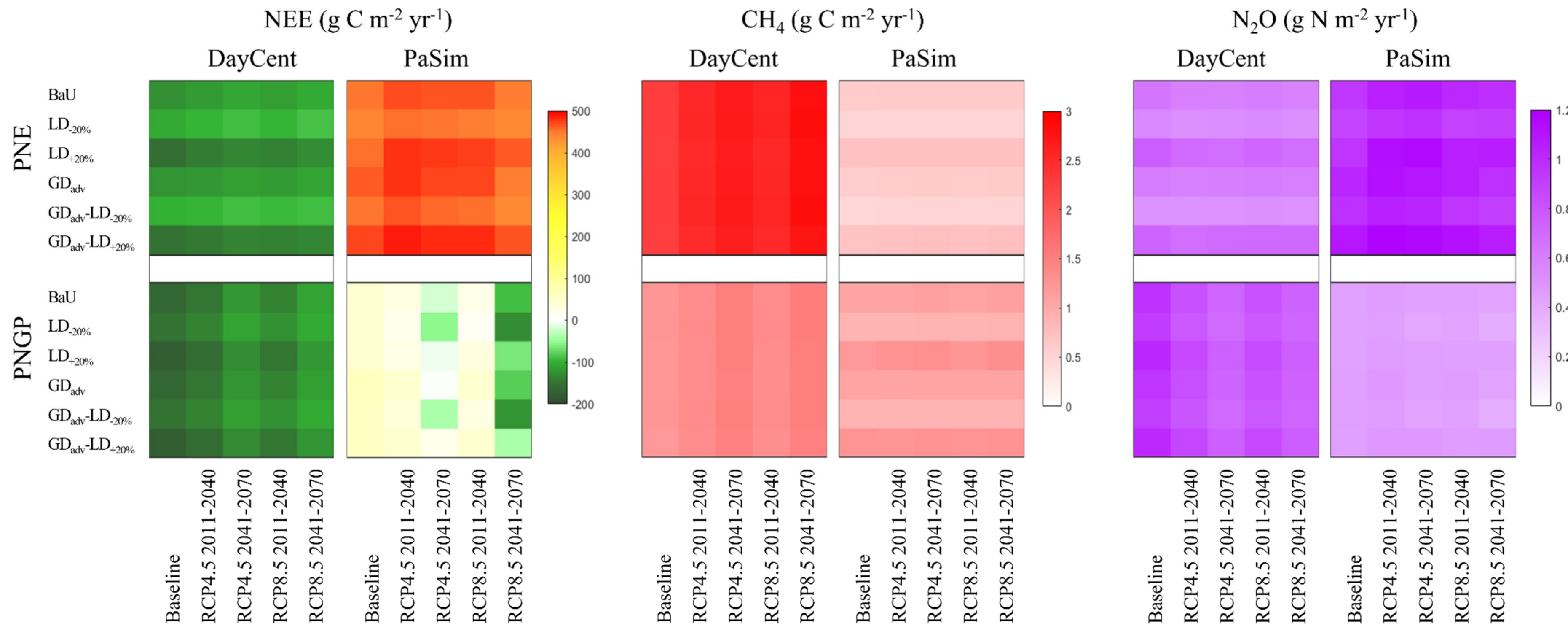

Figure S11. Heatmap visualisation of the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated in the medium productivity pasture (MP) using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to current climate and management in the Parc National des Écrins (PNE) and Parco Nazionale Gran Paradiso (PNGP).

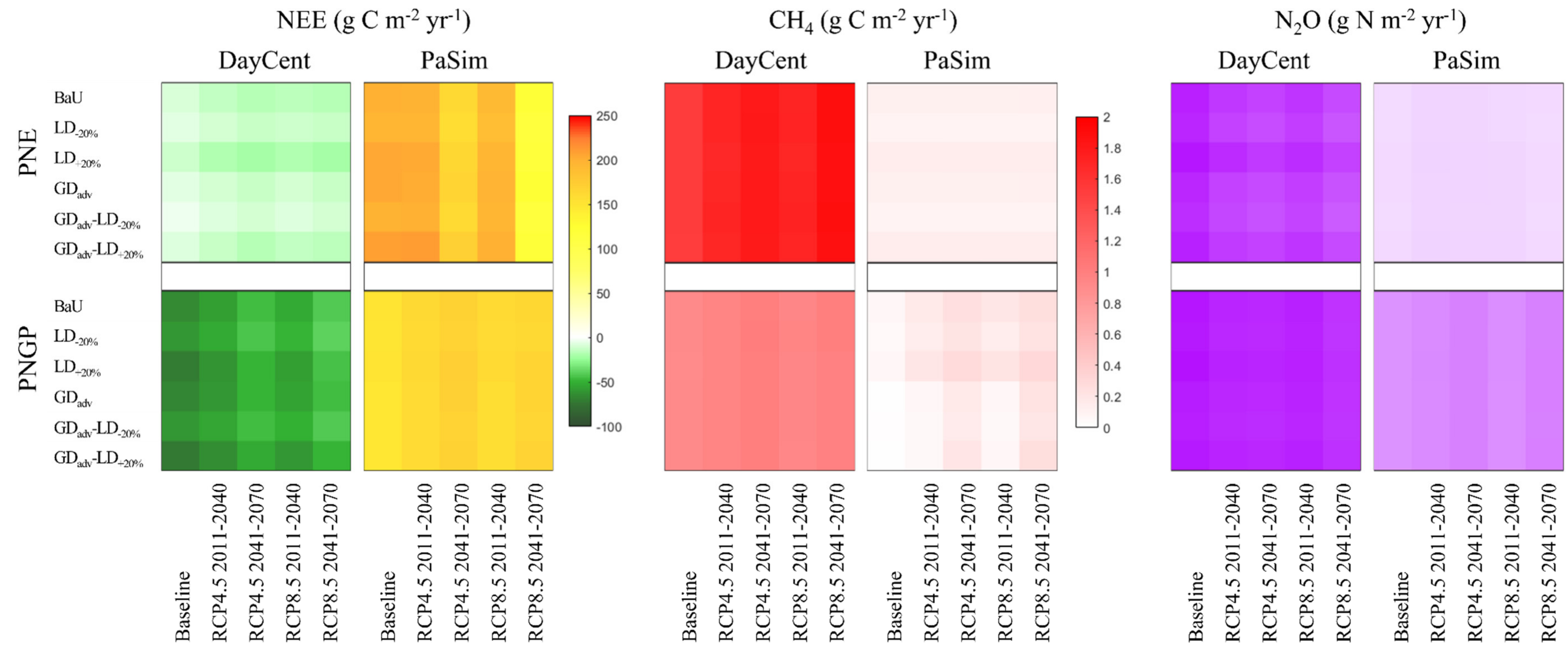

Figure S12. Heatmap visualisation of the three main greenhouse gas emissions (NEE: net ecosystem exchange; CH_4: methane; N_2O: nitrous oxide), estimated in the low productivity pasture (LP) using two grassland models (DayCent, PaSim), for alternative management and climate-change scenarios compared to current climate and management in the Parc National des Écrins (PNE) and Parco Nazionale Gran Paradiso (PNGP).