



Impacts of climate change on semi-natural alpine pastures productivity and floristic composition

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Abstract

Climate change impact on pasture floristic composition needs to be carefully assessed, given its key role for the resilience of pastoral systems and related ecosystem services. Nevertheless, variations in floristic composition are rarely taken into account in climate change impact studies. Here, we used the plant community model CoSMo to simulate future dynamics of biomass accumulation and floristic composition for high-altitude semi-natural alpine pastures. Dedicated multi-site field activities were conducted to collect data for model calibration. Simulations were run for four 20-year climate scenarios centered on 2040, resulting from the combination of two general circulation models (GISS-ES and HadGEM2) and two representative concentration pathways (RCP4.5 and RCP8.5). Results highlighted the capability of CoSMo to successfully reproduce the productivity and floristic composition of semi-natural pastures, modeling efficiency and R^2 being higher than 0.90 for above-ground biomass accumulation and relative abundance of species. CoSMo simulated an overall positive effect of increasing temperatures on pasture productivity (+ 10.7% on average), due to higher biomass accumulation rates and longer growing seasons. However, these benefits were highly heterogeneous among the monitored pastures (ranging from - 2.5 to + 16.2%), because of differences in floristic composition and in species-specific thermal requirements that led to complex, non-linear reactions to climate variations. A negative impact of climate change was simulated for grazing value (- 11.1% on average), due to the higher suitability to future conditions of *Nardus stricta*, which has low grazing value compared to other species. Our results highlight that floristic composition should be explicitly considered while assessing climate change impacts on semi-natural pasture productivity and connected ecosystem services.

Keywords Biodiversity · CoSMo · Ecosystem services · Grassland · Grazing value · Plant community

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Introduction

Grasslands are among the major ecosystems worldwide, covering more than 40% of the terrestrial area (Suttie et al. 2005). Along with their relevance for wildlife habitat and biodiversity reservoir (Marriott et al. 2004), one of the primary roles played by grasslands is forage production for livestock feeding (Suttie et al. 2005). Given that pastures often cover areas unsuitable for conventional agriculture, the resulting livestock grazing system represents a key source of income in many areas worldwide (Godfray et al. 2010). Other benefits that grasslands provide deal with their role for carbon sequestration (Cong et al. 2014; da Silva et al. 2022), reduction of pollution and soil erosion, increase of pollination, and improvement of landscape value for tourism activities (Bellocchi et al. 2018). Grasslands thus play a pivotal role in the context of ecosystem services, which can be defined as all the material and

not material benefits provided by an ecosystem that affect human activities in terms of economy, health, and quality of life (Tribot et al. 2018).

Grasslands are environments characterized by the coexistence of many different herbaceous plant species and, as such, by an elevated biodiversity (Habel et al. 2013). The floristic composition of grasslands is a key factor for the quality of the ecosystem services they provide (Oliver et al. 2015), because it can markedly affect forage quality (Daget and Poissonet 1971; Werner and Paulissen 1987; Dragomir et al. 2011; Argenti et al. 2021), as well as the resilience of the plant community to environmental constraints (Simpson 1949; Mackie et al. 2018). However, pasture floristic composition is highly variable in relation to multiple environmental factors like latitude, elevation, light intensity and quality, soil properties, availability of nutrients and water, and climate conditions (Buxton and Fales 1994; Jeangros et al. 1999). In the case of pastures, management also plays a key role, by defining water and nutrient availability (through irrigation and/or fertilization), the mowing frequency, the kind of grazing livestock, and the grazing intensity (Matches 1992; Ren et al. 2012). The different species of grazing animals are indeed known to have clear preferences for some plant species and this—together with the types of breeds—affects pasture floristic composition (Daget and Poissonet 1971; Cutter et al. 2022).

Alpine pastures are usually characterized by complex plant communities (Pornaro et al. 2019), and they can be defined as semi-natural, being just grazed, thus neither sown and mowed nor irrigated and fertilized. They are particularly exposed to changes in climatic conditions and in land use, with the abandonment of pastures especially in areas considered as unfavorable for reasons dealing with climate or accessibility (Schirpke et al. 2012).

Ongoing and forecasted changes in climate are expected to influence the productivity and floristic composition of grasslands (Mooney and Hobbs 2000) and, in turn, the related ecosystem services (Oliver et al. 2015). However, whether this influence will be positive or negative is something still debated and likely heterogeneous across different contexts. A meta-analysis on different European grasslands carried out by Dellar et al. (2018) indicated a reduction of grassland productivity as response to climate change in center and southern Europe and an opposite trend for northern Europe. Dibari et al. (2020) estimated a general reduction of grassland suitability and a loss of biodiversity in the Alps in the coming decades, whereas Riedo et al. (2000) highlighted a positive trend in net biomass accumulation of differently managed Swiss grasslands at different altitudes in response to climate change. Nevertheless, most of these studies did not explicitly reproduce the climate-induced variations in grassland floristic composition, thus overlooking the effect of species-specific adaptation to climate change on the dynamics of plant competition and related pasture

productivity and quality. A seminal work in this sense was conducted by Liu et al. (2018), who analyzed variations in plant community composition of alpine grasslands as response to climate variability, although the analysis was limited at the level of plant functional groups (grasses, forbs, and sedges).

Eco-physiological models are powerful tools for estimating climate change impact on cropping systems (Tubiello et al. 2007; Soussana et al. 2010) and for investigating the complex dynamics characterizing multi-species plant communities (e.g., Soussana et al. 2012; Sándor et al. 2018). Among the models suitable for large-area applications, the CoSMo plant community model (Confalonieri 2014) is one of the few approaches able to explicitly and dynamically simulate changes in the floristic composition of grasslands as a function of environmental and management drivers, thus allowing a comprehensive quantification of climate change impacts on pasture productivity and related ecosystem services.

The objective of this study was to assess climate change impacts on high-altitude semi-natural alpine pastures productivity and floristic composition. This will allow to extend the analysis of climate change effects on pasture by accounting for aspects dealing with pasture quality and biodiversity.

Materials and methods

Experimental data

Field observations were collected in 2019 at three sites in a semi-natural alpine pasture (sites 1, 2, and 3, hereafter) at 2200 m above sea level on the Rhaetian Alps in the Sondrio province (site 1: 46.419° N, 10.200° E; site 2: 46.421° N, 10.198° E; site 3: 46.422° N, 10.198° E). The area is a wide moraine hollow of Val Dosedè characterized by important and typical forms left by morphogenetic agents of glacial, periglacial, fluvial, and fluvio-glacial origin (Scotti et al. 2017). The three experimental sites were in a wide flat valley at about 500m distance from each other, the size of each site being about 1000 m². The soil in the area is loam, with high (20%) skeleton content, subacid, with medium organic carbon content and bulk density equal to 1.5 g cm⁻³. Mean annual rainfall and temperature are 1323 mm and 4 °C, respectively, with a snow period from around November 15 to the end of April. Mean annual snow depth is about 40 cm (Casale and Bocchiola 2022). Within each site, plant communities were homogeneous. The pasture that hosted the three experimental sites was representative of moraine hollow conditions and it was neither irrigated and fertilized nor mown, with spontaneous vegetation. The grazing in the pasture (dairy cows, Italian Pezzata Rossa) is open, with a grazing period from end of June to mid-September and

a grazing pressure ranging from 0.8 (site 2) to 2.8 (site 3) livestock units per ha. The differences in grazing pressure (derived from direct observations and in line with dynamics described by Parolo et al. 2011) among the three sites were due to the distance from the barn (site 3 and 1 were the closest and farthest, respectively), the frequent presence of ponding water in site 2 (to be passed through to reach site 1), and to the presence of obstacles in the experimental area, like a stream and a scree.

From a vegetational point of view, there are acidophilous *Nardus stricta*-dominated grasslands (*Nardion strictae* Br.-Bl. in Br.-Bl. & Jenny 1926), which are being studied, silicolous, alpine heaths dominated by nano-phanerophytes and lichens (*Loiseleurio procumbentis-Vaccinion microphylli* Br.-Bl. in Br.-Bl. & Jenny 1926), communities composed of oligotrophic to mesotrophic small sedges and bryophytes that grow in acid fens (*Caricion nigrae* Koch 1926 em. Klika 1934) and acidophilous, mesophilous and xerophilous shrub communities dominated by *Rhododendron ferrugineum* L. (*Rhododendro ferruginei-vaccinion myrtilli* A. Schnyd. 1930). These phytocoenoses form a complex mosaic reflecting the morphological and pedological micro-variations of the hollow. The phytosociological nomenclature follows the rules of the International Code of Phytosociological Nomenclature (Weber et al. 2000). For the definition of the syntaxa, the Prodrome of Italian Vegetation was followed (Biondi et al. 2014; see the specific interactive site of the Italian Botanical Society: <http://www.prodromo-vegetazione-italia.org/>), with reference to the Prodrome of European Vegetation (Mucina et al. 2016).

The nomenclature of the species follows Bartolucci et al. (2018).

For each site, dry aboveground biomass (AGB, t ha⁻¹) for the different species, canopy leaf area index (LAI, -) and height (H, cm), and floristic composition were estimated twice during the season (July 25 and August 29). Floristic composition was derived separating the different species from fresh aboveground biomass, and after oven dried. The sample size for AGB and floristic composition was 0.5 m² casually taken in the pasture. Ten casual sampling in the pasture were averaged for determining LAI and canopy height; the used tools were the AccuPAR ceptometer (Decagon, Pullman, WA, USA) and a ruler, respectively. All the measurements were replicated at three points randomly identified at the beginning of the season in each site. For each site, soil texture was derived from the WISE database (Batjes 2016). Daily minimum and maximum temperature, net solar radiation, and rainfall were retrieved from the weather service of the University of Milan Cassandra Lab, which provides historical, near real time and forecasted daily weather data at 0.016° × 0.016° spatial resolution for the whole Europe. The service is based on the integration of data from regional networks of agrometeorological stations and dedicated

geo-statistical and modeling techniques (accounting for the effect of elevation; USGS Gtopo30) to spatially downscale data from international networks (NOAA-GSOD, METAR, and SYNOP) (Mariani et al. 2012, 2016; Cola et al. 2020). Reference evapotranspiration was estimated at runtime based on the Penman–Monteith method (Allen et al. 1998).

The modeling approach

The generic grassland model CoSMo (Community Simulation Model; Confalonieri 2014) was used to simulate the dynamics of the different species in the phytocoenosis, and it was coupled with the generic crop model CropSyst (Stöckle et al. 2003) for the simulation of the physiological processes involved with plant growth and development (Movedi et al. 2019).

CoSMo is a daily time step model that dynamically simulates changes in the composition of a phytocoenosis and—coupled with a generic crop model—its productivity. While CoSMo estimates the variations in the relative abundance of different species as a function of the species suitability to environmental and management drivers, the crop model daily reproduces soil and plant biophysical processes as a function of weather and soil properties and of the phytocoenosis composition. CoSMo represents an intermediate solution between complex individual-based models and simplified approaches relying on the calibration of a single set of parameters of a crop model to mimic the behavior of a plant community, and it has proved to successfully reproduce the dynamics of mowed grasslands composition and productivity (Movedi et al. 2019) and of crop-weed interaction (Movedi et al. 2022).

Basically, at each time step, CoSMo estimates the suitability of each species in the community to the explored environmental and management conditions, and the overall suitability of each species is used to dynamically reproduce the changes in their relative abundance. The overall suitability is derived from factors defining the response of each species to drivers (Table 1) that may affect inter-specific competition. Drivers account for both continuous variables (e.g., global solar radiation, soil water content) and events (e.g., cut, grazing). The overall suitability of each species is then calculated by aggregating the suitability factors—estimated for each driver—while accounting for a hierarchical weighting procedure (Confalonieri 2014), which allows to reduce the impact of low-ranked drivers by considering the effect of each driver in influencing the following one in the hierarchy (Table 1).

The effect of grazing or cut events is top-ranked because their impact on the overall species suitability is so marked that the role of other drivers becomes negligible. Phenology is ranked second because of its overall influence on plant dynamics and given that, for annual self-seeding species, once

Table 1 Drivers affecting the competition capability of different species in the CoSMo model, with their category, hierarchical position, and associated suitability factor (from Confalonieri 2014; Movedi et al. 2019)

Driver	Category	Hierarchical position	Suitability factors
Grazing/cut	Event	1	$f_{[liking]}$ (liking of the grazing animals), SL (length of the shock period after the event)
Phenology (maturity reached)		2	M (is maturity reached?)
Air temperature	Continuous	3	$f_{[temp]}$
Global solar radiation		4	$f_{[rad]}$ (competition for light)
Soil water availability/excess		5	$f_{[water]}$ (competition in case of insufficient water availability or in case of water excess)
Nitrogen availability		6	$f_{[N]}$ (competition for soil N)

maturity is reached the species is considered not competing anymore until germination and emergence of the next generation of individuals. The hierarchy of the remaining drivers is consistent with other modeling approaches dealing with interspecific competition (e.g., Kropff and van Laar 1993). The overall suitability value for the different species is then used to derive the relative abundance of the different species at the following time step, which is in turn used to weight the species-specific parameter values of the crop model (derived for the species in monoculture) while deriving the parameter values of the crop model for the community as a whole. The resulting community parameter values—which dynamically change at each time step as the phytocoenosis evolves—allow the crop model to simulate key biophysical processes of the community at each time step. As a result, rate and state variables from the crop model (AGB, LAI, plant height, root depth, and green LAI) are available at the level of the whole plant community, whereas the relative abundance of species—needed to update the crop model parameter values for the phytocoenosis at each time step—is provided by CoSMo.

The effect of grazing livestock is accounted for by CoSMo both directly—by estimating the amount of AGB daily grazed (Eq. (1)) (Minson and McDonald 1987)—and indirectly, because grazing affects the community LAI and thus light interception and photosynthesis. Grazing, also, affects the relative abundance of the different species, thanks to functions representing (i) the degree of the liking of different categories of animals for the different species ($f_{[liking]}$; Table 1), (ii) the species-specific capability to resprout after a grazing event (SL ; Table 1), and (iii) the effect of LAI and height on the species competitiveness for light ($f_{[rad]}$; Table 1).

$$AGB_g = \begin{cases} 0.108 \cdot AW^{0.719} & AGB \geq 0.108 \cdot AW^{0.719} + AGB_{min} \\ AGB - AGB_{min} & AGB_{min} < AGB < 0.108 \cdot AW^{0.719} + AGB_{min} \\ 0 & AGB \leq AGB_{min} \end{cases} \quad (1)$$

where AGB_g ($\text{kg ha}^{-1} \text{ day}^{-1}$) is the daily grazed AGB, AW is the livestock live weight per unit surface (kg ha^{-1}), and AGB_{min} is the minimum AGB to allow grazing (set to 50 kg ha^{-1}). In this study, the value of AW was derived by assuming an average weight of an adult cattle of 800 kg and the site-specific animal pressure (LU ha^{-1}) collected during the field activities. The same percentage reduction of community AGB due to grazing is applied to the community LAI and height.

For the description of the remaining CoSMo equations, readers may refer to Confalonieri (2014) and Movedi et al. (2019).

Concerning the crop model to be coupled with CoSMo, CropSyst (e.g., Stockle et al. 2003) was chosen because of its favorable relationship between parsimony (in terms of number of parameters) and reliability, as shown in previous studies dealing with mown grasslands (Movedi et al. 2019). CropSyst is a generic, daily time step model that reproduces crop growth and development as a function of weather variables, physical and chemical soil properties (soil texture, soil moisture, organic matter content, and pH), and crop management practices. Phenological development is simulated as a function of mean air daily temperature and of parameters defining minimum and optimum thermal requirements, with an option to account for photoperiod. Light interception is estimated from LAI and extinction coefficient for solar radiation according to Beer's law analogy, and daily biomass accumulation (net photosynthesis) is derived as the minimum between the two values estimated using a temperature-limited radiation use efficiency approach and a vapor pressure deficit-corrected transpiration use efficiency one. Green leaf area expansion is calculated from AGB daily rate and state, the early stages specific leaf area and the empiric stem/leaf partition coefficient. Leaf senescence is simulated when daily-emitted LAI units reach a specific thermal time threshold. Concerning the simulation of soil water dynamics, a cascading model with

travel time (Neitsch et al. 2002) was used, whereas hydrological soil properties were estimated by using the van Genuchten and Nielsen (1985) pedotransfer functions.

Model initialization and parameterization

Simulations were carried out by considering plant growth as limited by water—given pastures in the area are not irrigated—but not by nitrogen availability because of the continuous livestock presence. Concerning model initialization, the first observed values of floristic composition, AGB, LAI, and plant height were used. The initial soil moisture was assumed to be at field capacity, considering the autumn and spring rainfalls characterizing the area and the contribution of melting snow to soil moisture.

Data from the second sampling event were used for the definition of the values of the parameters for which literature data or values from previous modeling activities were not available (Tables S1, S2 and S3, Online Resource 1). A daily simulation was run for each site and model outputs of floristic composition, AGB, LAI, and plant height were compared to the data measured during the second sampling event. Parameters whose values were calibrated are indicated in Tables S2 and S3 (Online Resource 1), together with sources of information for non-calibrated parameters.

The parameterization was performed only for the species representing more than 0.75% of the sampled AGB in at least one of the two sampling events.

The agreement between observed and simulated floristic composition, AGB, LAI, and plant height was quantified by using the relative root mean square error (RRMSE, from 0 to $+\infty$, optimum: 0; Jørgensen et al. 1986), the mean absolute error (MAE, from 0 to $+\infty$, optimum: 0), the modeling efficiency (EF, from $-\infty$ to 1, optimum: 1; Nash and Sutcliffe 1970), the R^2 , and the slope of the linear regression equation between observed and simulated values.

Evaluation of climate change impacts

The impact of projected changes in climate on each of the three sites was evaluated by running the model for two 20-year time frames, representing the baseline (1986–2005) and near future (centered on 2040) climate conditions. This allowed considering the effect of seasonality on yearly trends of weather variables. For each weather series, five additional years were considered to initialize the model (spin-up period) (Movedi et al. 2019). The uncertainty in future climate projections was handled by using the realizations of two representative concentration pathways (RCPs)—RCP 4.5 and RCP 8.5 (IPCC 2013)—as provided by two general circulation models (GCMs)—HadGEM2 (Collins et al. 2011) and GISS-ES (Schmidt et al. 2006). The two RCPs were selected to explicitly consider a wide range of potential future climate evolution, given they represent an optimistic (RCP 4.5; moderate

increase in CO₂ emissions in response to the adoption of mitigation strategies) and a pessimistic (RCP 8.5; no reduction in CO₂ emissions) scenarios. Spatial and temporal downscaling of GCM outputs was carried out using the stochastic weather generator LARS-WG (Semenov and Barrow 1997) and the historical weather series (1986–2005) retrieved from the European Center for Medium Range Weather Forecasts database (ECMWF). LARS-WG was used given its proved reliability for climate change studies (e.g., Höglind et al. 2013; Vesely et al. 2019). Beside variations in temperature and rainfall, the projected increase in atmospheric CO₂ concentration for each climate scenario was provided to the model to account for the CO₂-fertilization effect on AGB accumulation.

The model outputs obtained for the four climate change scenarios (RCP4.5-HadGEM2, RCP4.5-GISS-ES, RCP8.5-HadGEM2, and RCP8.5-GISS-ES) were compared with those simulated for the baseline using the following synthetic variables: the 20-year mean cumulated AGB, including grazed AGB (AGB_{avg} , t ha⁻¹), the 20-year mean daily rate of AGB during the period of active growth (AGB_r , t ha⁻¹ day⁻¹), the 20-year mean relative active growth duration (TAG , from 0 to 1; fraction of days in a year when the community AGB rate is not null), the 20-year mean relative abundance of plant species (p_i , from 0 to 1, i representing the i th species in the community), the Simpson-based diversity index ($D = 1/\lambda$, the larger the value of D , the highest the diversity, with λ calculated according to Eq. (2); Simpson 1949; Jost 2006), and the grazing value (GV, the larger, the better, indicating forage value and palatability; Eq. (3); Daget and Poissonet 1971):

$$\lambda = \sum_{i=1}^n (p_i)^2 \quad (2)$$

$$GV = \sum_{i=0}^n (p_i \cdot 100 \cdot GV_i) / 5 \quad (3)$$

where λ is the Simpson concentration index; n is the total number of plant species that coexist in the pasture; i is the i th species; and GV_i is an empiric parameter to evaluate the single plant species. In this study, the relative abundance daily estimated by CoSMo was used for each time frame (average of the 20-year simulation), and the values of GV_i reported by Werner and Paulissen (1987) scaled on the Daget and Poissonet, (1971) scale were used (Tables S4, Online Resource 1).

Results

Floristic composition, growth dynamics, and grazing value

The floristic composition and the relative abundance of species detected during the two sampling events are

reported in Table 2, whereas Table 3 shows pasture productivity and quality by reporting AGB, LAI, plant height, grazing value, and Simpson diversity index. Overall, 88 plant species were detected in the three sites, but only ten of them presented a relative abundance (expressed as percentage on the total dry mass) higher than 0.75% in at least one of the two sampling events (Table 2). Field observations highlighted a marked variability among the three monitored sites in terms of relative abundance of species (Table 2). The pasture in site 2 was a peat bog with prevalence of *Trichophorum cespitosum* (first part of the season) and *Eriophorum* sp.pl., whereas sites 1 and 3 were largely characterized by *Deschampsia cespitosa* and *Nardus stricta*, respectively. In site 3, the prevalence of *N. stricta* is explained by its low palatability and by the high grazing pressure that characterized the site. In site 1, the presence of *N. stricta* was relevant but the dominant species was *D. cespitosa* likely because the lower grazing pressure generated conditions less penalizing for this species as compared to site 3.

The floristic composition changed to large extent over time, with an increased diversity in the second sampling event (Table 3) because of the presence of species not previously detected or whose relative abundance was negligible (e.g., *Carex nigra* and *Poa alpina* in site 3, *Eriophorum angustifolium* in site 2). These temporal dynamics in the community composition reflected in the Simpson diversity index, which increased from 1.33 to 2.03 (average of the three sites) while moving from the first to the second sampling event (Table 3).

The mean AGB observed in the three sites ranged from 1.07 t ha⁻¹ in site 2 to 6.84 t ha⁻¹ in site 1, with small variability between the two sampling events. The lower grazing pressure in site 1 as compared to site 3 clearly reflected in the sampled AGB, which was 83% higher in the first site (mean of the two sampling events). The difference between AGB values in these two sites increased over time, with the largest difference observed during the second event (114% higher in site 1). This is likely due to the continuous presence of the grazing livestock in site 3 starting from the end

Table 2 Floristic composition and relative abundance (%) of the species detected in the three sites during the two sampling events. Only the species with more than 0.75% of the sampled AGB are reported and were used to calculate the relative abundance

Site	Family	Species	Life form	25 July 2019	29 August 2019
1	Poaceae	<i>Deschampsia cespitosa</i> (L.) P. Beauv.	Hemicryptophytes	85.96	64.64
	Poaceae	<i>Nardus stricta</i> L.	Hemicryptophytes	10.25	34.47
	Poaceae	<i>Anthoxanthum nipponicum</i> Honda	Hemicryptophytes	3.06	0.00
	Apiaceae	<i>Mutellina adonidifolia</i> (J. Gay) Gutermann	Hemicryptophytes	0.73	0.89
2	Cyperaceae	<i>Trichophorum cespitosum</i> (L.) Hartm.	Hemicryptophytes	87.30	26.24
	Cyperaceae	<i>Eriophorum angustifolium</i> Honck.	Geophytes	0.00	50.89
	Cyperaceae	<i>Eriophorum vaginatum</i> L.	Hemicryptophytes	12.70	22.87
3	Poaceae	<i>Nardus stricta</i> L.	Hemicryptophytes	84.45	77.44
	Poaceae	<i>Anthoxanthum nipponicum</i> Honda	Hemicryptophytes	8.35	11.47
	Apiaceae	<i>Mutellina adonidifolia</i> (J. Gay) Gutermann	Hemicryptophytes	4.59	3.40
	Asteraceae	<i>Scorzoneroideis helvetica</i> (Mérat) Holub	Hemicryptophytes	2.61	2.23
	Poaceae	<i>Poa alpina</i> L.	Hemicryptophytes	0.00	3.30
	Cyperaceae	<i>Carex nigra</i> (L.) Reichard	Geophytes	0.00	2.16

Table 3 Observed dry aboveground biomass (AGB), leaf area index (LAI), height (H), grazing value, and Simpson diversity index of the pastures in the three sites at each sampling event. The grazing value and the Simpson diversity index were calculated considering only the species listed in Table 2

Sampling event	Site	AGB (t ha ⁻¹)	LAI (m ² m ⁻²)	H (m)	Simpson diversity index	Grazing value
25 July 2019	1	5.99	2.17	0.46	1.33	31.86
	2	1.17	0.80	0.30	1.28	14.29
	3	4.03	1.23	0.32	1.39	7.29
29 August 2019	1	7.68	1.37	0.37	1.85	24.00
	2	0.96	0.22	0.24	2.63	14.29
	3	3.44	1.20	0.26	1.61	9.86

of June. The pasture in site 2 showed instead an overall low productivity, due to the peculiar edaphic conditions (peat bog soil) that favored the presence of species with a low potential in terms of AGB accumulation (*T. cespitosum* and *Eriophorum* sp.pl.).

To a certain extent, a similar pattern was found for LAI and height, with the largest and lowest values observed in site 1 and 2, respectively, although AGB was poorly correlated with both LAI ($R^2=0.51$; $p=0.11$) and height ($R^2=0.57$; $p=0.08$). The differences in the species relative abundance observed in the two sampling events explain the different temporal dynamics observed for AGB and LAI. Indeed, despite LAI was always decidedly lower in the second sampling event, AGB was more stable in sites 2 and 3 and increased in site 1, likely because of a lower LAI to AGB ratio in *N. stricta* compared to *D. cespitosa* (Table 2).

The highest diversity was observed in site 2 at the second sampling event, because of the largest homogeneity in the relative presence of *T. cespitosum*, *E. angustifolium*, and *E. vaginatum*, whereas the pasture in site 1 had the highest grazing value, regardless of the sampling time (Table 3).

Model evaluation

The agreement between observed and simulated variables describing pasture growth, composition, and grazing value was overall satisfactory (Table 4), with the values of all metrics achieving values close to their optima for all the variables and sites. The only exception was the relative abundance in site 2, for which the values of the agreement metrics were less satisfactory. CoSMo successfully reproduced pasture productivity: the values of MAE and RRMSE for AGB were 0.42 t ha^{-1} and 15.55%, EF and R^2 were higher than 0.95, and systematic under- or over-estimations were not observed. Despite the capability of CoSMo to reproduce community LAI and height was never evaluated before against observations, the results obtained

are promising, especially for canopy height (MAE equal to 0.03 m and EF higher than 0.5). The simulation of community LAI was instead affected by higher uncertainty and—despite the overall trend in LAI values was successfully captured (positive EF, R^2 , and MAE equal to 0.73 and $0.4 \text{ m}^2 \text{ m}^{-2}$, respectively), the model presented a certain tendency to overestimate observations.

The model accurately reproduced the relative abundance of species in site 1 and site 3 (Table 4): MAE was lower than 3%, EF and R^2 were equal to 0.99 and RRMSE was always lower than 17%. The peculiarities of site 2 (peat bog and periods with few cm standing water) that clearly defined its floristic composition (prevalence of species not detected in the other sites) were instead not properly interpreted by the model, this leading to poorer results with respect to the other two sites.

The comparison between observed and simulated relative abundance for all the single species is reported in Fig. 1. Most of the points are close to the 1:1 line, emphasizing the capability of CoSMo to successfully reproduce the time dynamics of floristic composition in the three pastures. The model reliability while simulating the relative abundance of the single species in the phytocoenosis clearly reflected on the agreement obtained for the grazing value and the Simpson diversity index, which were both successfully simulated, with all the metrics close to their optima (Table 4).

Parameter values are presented in Tables S2 and S3, Online Resource 1.

Climate change impacts

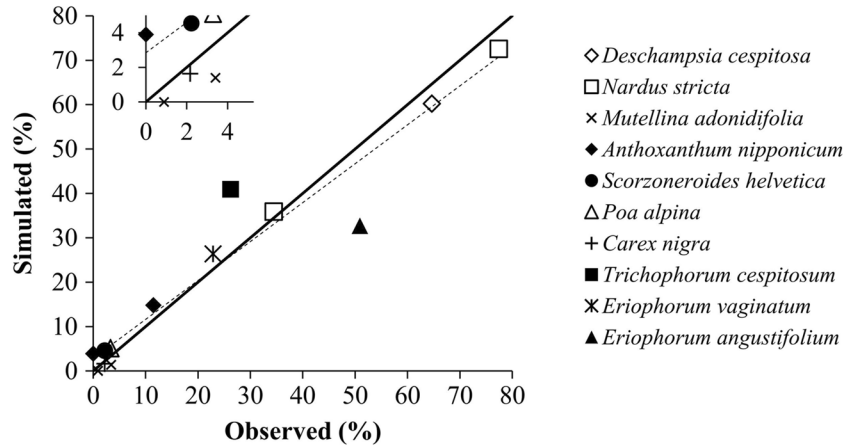
According to the climate change scenarios considered, the mean annual temperature in the study area is expected to increase from the $3.99 \text{ }^\circ\text{C}$ of the baseline to 4.76, 5.18, 5.76, and $5.93 \text{ }^\circ\text{C}$, respectively, for the scenarios RCP4.5-GISS-ES, RCP8.5-GISS-ES, RCP4.5-HadGEM2, and

Table 4 Agreement between observed and simulated variables describing pasture growth, floristic composition and grazing values in the three sites. AGB, LAI, and H are the community aboveground biomass, leaf area index, and height, respectively. The relative abundance represents the percentage contribution of each species to the community AGB

Variable	MAE ^a	RRMSE (%)	EF	R^2	Slope
AGB (t ha^{-1})	0.42	15.55	0.95	0.97	1.02
LAI ($\text{m}^2 \text{ m}^{-2}$)	0.40	53.80	0.03	0.73	0.71
H (m)	0.03	13.91	0.53	1.00	0.61
Grazing value (-)	1.14	8.73	0.94	1.00	1.30
Simpson diversity index (-)	0.21	10.52	0.75	1.00	0.90
Relative abundance (%), site 1	2.65	12.23	0.99	0.99	1.08
Relative abundance (%), site 2	12.11	40.89	-0.19	0.00	0.08
Relative abundance (%), site 3	2.48	16.97	0.99	0.99	1.08
Relative abundance (%), all sites	4.76	30.47	0.92	0.93	1.06

^aUnits for MAE are the same as reported in the first column

Fig. 1 Observed and simulated relative abundance of single species (percentage contribution of each species to the community AGB). The small chart zooms in the range 0 to 5% to increase readability for values close to zero. Solid line: 1:1 line, representing the perfect agreement between observed and simulated values. Dotted line: linear regression equation between simulated and observed data



RCP8.5-HadGEM2. In general, the increase in temperature was more marked during the summer months, with the maximum monthly increase in temperature (+3.09 °C) achieved in September for the scenario RCP8.5-HadGEM2. Concerning precipitations, the total annual rainfall was equal to 1270 mm in the baseline and to 1304 mm, 1300 mm, 1155 mm, and 1217 mm for, respectively, the scenarios RCP4.5-GISS-ES, RCP8.5-GISS-ES, RCP4.5-HadGEM2, and RCP8.5-HadGEM2. A small increase in annual

rainfall was thus projected by the GCM GISS-ES, whereas HadGEM2 indicated a decrease—especially for RCP 4.5—with the largest reduction during summer months.

Simulations highlighted how these climate variations would have an overall positive impact on pasture productivity (Fig. 2a), with an expected increase in cumulated AGB regardless of the climate scenario considered (+10.7% on average). This positive effect on biomass accumulation is explained by the average increase in the number of days

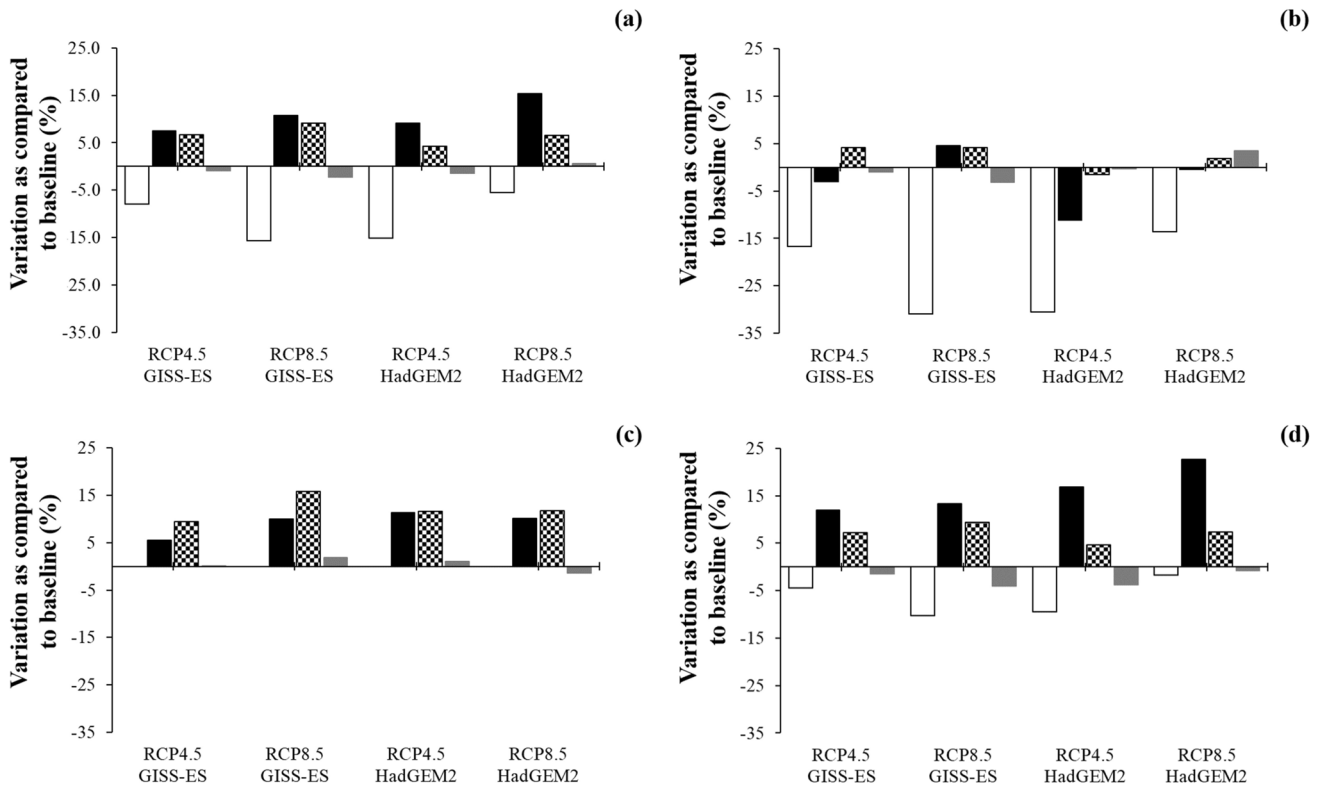


Fig. 2 Climate change impacts quantified in terms of percentage variation of aboveground biomass accumulation (black bars), length of the active growth period (checkered bars), grazing value (white bars),

and Simpson diversity index (gray bars) with respect to the baseline. Panels a, b, c, and d refer to the results obtained for, respectively, the three sites (averaged together), site 1, site 2, and site 3

in which pastures are actively growing (+6.7% on average, Fig. 2a) and by the higher daily rate of AGB accumulation during the growing season (+4.1% on average, Fig. 3) as compared to current climate conditions. The differences in the temperature increase projected by the four climate scenarios reflected in the extent of the changes simulated for both biomass accumulation and duration of the active growth period, with warmest scenarios (RCP4.5-HadGEM and RCP8.5-HadGEM) achieving the higher daily rate of AGB accumulation (Fig. 3) and the lowest extension of active growth period (Fig. 2a), the latter being explained by the faster accumulation of thermal time as compared to the scenarios characterized by milder temperature increase (GISS-ES realizations of RCP4.5 and RCP8.5).

The heterogeneity in the results obtained for the different sites (Figs. from 2b to 2d) highlighted how changes in climate would not affect the different pastures in the same way since their different floristic composition (Table 2) and the heterogeneity in the response to temperature of the species in the communities (Tables S2 and S3, Online Resource 1) would turn into complex, non-linear responses to changes in climate. The geographical position of the three pastures excludes indeed that the variability between sites is due to differences in future climate projections. Site 3 (Fig. 2d) showed the most positive variation of pasture productivity under climate change scenarios, with an average increase in biomass accumulation and length of active growth period equal to 16.2% and 7.2%, respectively (mean of the four climate scenarios). On average, no benefits due to climate change were instead simulated for site 1 in the mid-term, with daily rate of AGB accumulation ranging from −11.1 to +4.6% as compared to the baseline (−2.5% was the mean for the four climate scenarios). In this site, the climate scenario with the largest reduction of daily AGB accumulation (RCP4.5-HadGEM2) was also the only one for which a shortening—although negligible—in the active growth period was simulated (−1.5%). For all the

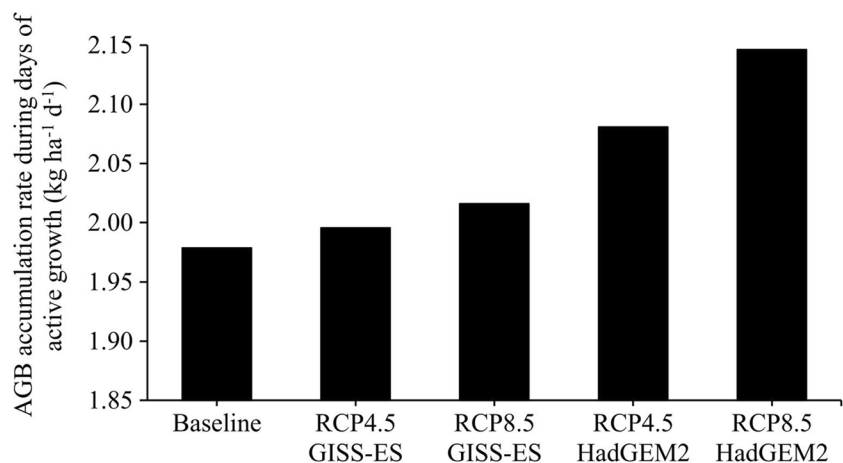
other combinations site × climate scenario, in fact, the active growth duration is expected to increase, to an extent that ranges from 1.8% (site 1, RCP8.5-HadGEM2) to 15.8% (site 2, RCP8.5-GISS-ES).

The simulation of climate change impact on floristic composition led to an average (all site × climate scenario combinations) variation of the Simpson diversity index equal to −1.0%, with values ranging between −4.1% (Fig. 2d) and +3.4% (Fig. 2b). This indicates a similar level of codominance between the different species under future climate projections. On the contrary, the grazing value showed a clear decrease under climate change scenarios (−11.1% on average; Fig. 2a), with values ranging from −5.5 to −15.7% (average of all sites). This negative trend was especially marked in site 1 (−22.9%; Fig. 2b), and, to a large extent, this can be explained by the fact that *N. stricta*—which has a poor value for livestock feeding (Table S4, Online Resource 1)—is expected to increase its relative abundance under future climate conditions (Fig. 4; changes in the relative abundance of the other species are shown in Fig. S1, Online Resource 1), thus leading to a worsening of the overall pasture grazing value. A similar trend was observed for site 3 (Fig. 2d), although to a lesser extent (−6.5% on average), given *N. stricta* is already dominant in this site under baseline conditions (Table 2), thus leading to lower relative worsening under future climate projections. Concerning site 2 (Fig. 2c), no changes in the grazing values under future climate conditions were simulated, given the three species that coexist in this site have the same specific grazing value (Table S4, Online Resource 1). This means that any changes in the floristic composition will not affect the grazing value of the pasture in site 2.

Discussion

The modeling solution developed by coupling the CoSMo plant community model and the crop model CropSyst demonstrated its suitability for reproducing key dynamics

Fig. 3 Daily rate of above-ground biomass accumulation during the active growth period simulated for the current conditions (baseline) and the four climate scenarios



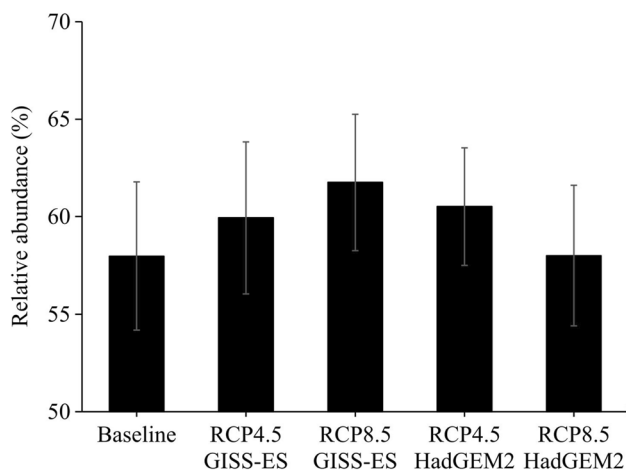


Fig. 4 Relative abundance (%) of *Nardus stricta* simulated for current conditions (baseline) and for future climate scenarios in the two sites where this species is currently present (sites 1 and 3). For each climate scenario, the mean (error bars indicate the standard deviation) of the values from the two sites is reported

involved with biomass accumulation and floristic composition in semi-natural alpine pastures. Concerning the simulation of pasture productivity, the model performance can be regarded as satisfactory, especially if compared to results from other grassland models (e.g., Soussana et al. 2012) and from previous works where the CoSMo model was used (Movedi et al. 2019). Despite the higher complexity compared to single-species system, the degree of accuracy in the simulation of pasture AGB was consistent with most studies where single crops were simulated (e.g., Belder et al. 2007; Coucheney et al. 2015). The only variable involved with pasture growth for which the agreement with observations was—to a certain extent—less satisfying was LAI. Besides the uncertainty intrinsic in whatever modeling approach, the lower accuracy in LAI simulation is often underlined in modeling studies (e.g., Yu et al. 2006; Tartarini et al. 2019) and it is partly due to the larger uncertainty in the methods for estimating this variable as compared to methods for estimating, e.g., AGB or plant height (e.g., Confalonieri et al. 2009). Moreover, the low number of LAI observations available in this study could have contributed to the uncertainty during model evaluation.

The changes in the relative abundance of the different species were successfully captured, thus allowing to extend the evaluation of climate change impacts at the level of changes in floristic composition and related ecosystem services provided by pastures (e.g., feeding grazing livestock). The results obtained in this study highlighted how the simulation of inter-specific dynamics is a key point for a comprehensive evaluation of climate change effects, given the complex interactions between the current floristic composition, the heterogeneity in the response

to environmental drivers of the different species in the community, and the variability in pasture management. All these factors can lead to divergent dynamics in the mid-term for pasture biomass accumulation and grazing value. A better understanding of the drivers on the basis of climate change impacts on pasture productivity is indeed a crucial prerequisite for developing effective adaptation strategies (Soussana et al. 2010).

Our estimates of a general increase in pasture biomass accumulation as response to expected climate variation are in partial agreement with other studies. They are in line with results reported by Riedo et al. (2000), who outlined a positive trend in net biomass accumulation for managed (mowed and grazed strategies were evaluated) grasslands at three Swiss sites differing for altitude and, thus, thermal and pluviometric regimes. Other authors, applying machine learning and GIS techniques to seven macro-types of Alpine pastures, highlighted a potential decrease in areas characterized by high-quality pastures in favor of the expansion of areas suited to *Nardus stricta* and xeric species (Dibari et al. 2020). This is consistent with the increased competitiveness of *Nardus stricta* projected in the mid-term by our analysis. An overall increase in productivity was projected for *Trisetum flavescens* and *Nardus stricta* by Casale and Bocchiola (2022) in Valtellina valley (Italian Alps), although their simulations highlighted an increased impact of heat stress at low altitudes. However, the heterogeneity in the results we obtained for the different sites suggests that the variability in floristic composition can markedly affect the dynamics of pasture growth under future climate projections, thus partly explaining the variability in results from different studies. The increase in the length of the active growth period also varied across the different sites, in line with the expected variability in the occurrence of vegetative restart in spring and the end of the growing season in autumn outlined by different authors (e.g., Schwartz et al. 2006; Ren et al. 2018; Casale and Bocchiola 2022). Concerning the floristic composition, the projected reduction of forage quality under future climate conditions due to the increase in the relative presence of *N. stricta* is in agreement with the findings from Dibari et al. (2020), who underlined how pastures macro-types dominated by this species will expand in the Alps in the coming decades.

Although the model demonstrated the potential for detailed and quantitative analyses of climate change impact on the productivity and floristic composition of semi-natural alpine pastures, further experimental activities targeting the reduction of the uncertainty in parameter estimation would increase the robustness of parameterization and, in turn, of simulated results. These activities should involve the collection of observations from other seasons and sites, which would allow refining the simulation of the time dynamics involved with both the inter-specific competition in the

phytocoenosis and animal-plant interaction. Moreover, simulations were performed targeting a small area, and this could limit the generalizability of the outcomes to other high-altitude alpine pastures.

Conclusions

Despite the limits of this study previously discussed, we showed the suitability of the plant community model CoSMo for reproducing the dynamics of grazed pastures in terms of biomass accumulation, growing season duration, floristic composition, biodiversity, and, in turn, forage quality. This— together with the low requirements in terms of data needed to parameterize the model and running simulations—makes CoSMo a valuable tool to support the estimate of forage production in semi-natural alpine pastures, which is one of the most important ecosystem services provided by grasslands.

Our results highlighted that the projected mid-term increase in temperatures will favor high-altitude semi-natural alpine pastures in two ways: by increasing the daily biomass accumulation rate and by extending the length of the active growth period. However, despite the biodiversity is expected to increase, the quality of the forage could be negatively affected because of the positive response to future climate conditions of species with a low grazing value. This underlines once more how the evaluation of climate change impacts on pastures cannot overlook the effects on the floristic composition of the community, this being a crucial issue to obtain a comprehensive evaluation of pasture responses to climate change and to target the definition of effective adaptation strategies.

Moreover, this study could open to new opportunities in the analysis of ecological scenarios involved with the mid-term assessment of the capability of plant species to persist in a given site or to successfully invade new areas.

Further improvements to the simulation system proposed in this study could involve the possibility of simulating the impact of climate change on shifts in the spatial distribution of different species, this affecting the characteristics of plant communities and related provision of ecosystem services. Further extensions of this study could involve the analysis of climate change impacts on other ecosystem services, given the current study only focused on forage production, floristic composition, and biodiversity within the plant communities.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10113-023-02158-4>.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interest The authors declare no competing interests.

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