Climate change impacts on the Alpine, Continental and Mediterranean grassland systems of Italy: A review

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Highlights

- *This review highlights grassland systems responses to climate change in the Alpine, Apennine and Mediterranean areas of Italy.*
- *Future climate will determine deep changes in grassland composition, extension and productivity.*
- *Droughts is considered the main factor affecting forage quality and palatability.*
- *Further research is needed to understand climate change impacts on grassland vegetation in the Mediterranean.*

Abstract

The ongoing climate change, which is threatening grassland agroecosystems throughout Europe, is also evident in the Italian grasslands. These systems, often located in marginal areas, are species-rich ecosystems characterized by variable, and often unreliable, grass and forage production and strongly dependent on interactions between climate, soil and agricultural management practices (*e.g.* land abandonment, lack of investments on innovation, stocking rates reduction, *etc.*), making them very sensitive and vulnerable to climate change. This review draws from the scientific literature the impacts of current and expected climatic changes on grassland and forage crop systems framed in three different bio-climatic zones of Italy, namely the Alpine, Continental and Mediterranean, and focussing on: i) grassland biodiversity and vegetation; and ii) forage production and quality. The main aims of this review are to: i) revise the existing literature in the domain, highlighting different or common trends among different Italian biogeographical regions; ii) provide information on the main climatic impacts analysed and drivers involved in the studied evolutions; and iii) point out the knowledge gaps currently pending in order to hypothesize the future scenarios of research in this sector.

Even if this review has pointed out differences in approaches, adopted methodologies and purposes of conducted researches, some common trends can be highlighted, though located in three different environments. Expected warming and modification on rainfall pattern will produce deep changes in vegetation of grassland types, with reduction or the disappearance of cold tolerant species and a spread of xeric/thermophilus ones and shrubby vegetation and with a general upward shift of vegetation types in mountain areas. Moreover, a general reduction of aboveground biomass is expected, as summer droughts is considered a main driver able to force grassland productivity. Finally, warming and rainfall reduction are considered the main factors able to reduce forage quality and palatability of grasslands, as a consequence of reduction of nitrogen content in the available biomass and of the higher spread of less unpalatable species and shrubs. The hypothesis is that the information gained from this review can provide insights on the current level of knowledge on the expected impacts of climate change on Italian grassland systems, and support the development of policy strategies for adaptation at national level.

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Introduction

Italian grasslands are predominantly large-scale grazing systems based on rainfed rangelands, permanent grasslands or forage crops located in the Mediterranean areas or on mountain rangelands and permanent grasslands in the Alps and Apennines. These systems, characterized by high floristic richness, have been affected by land abandonment and the lack of investments on innovation (Targetti *et al.*, 2013; Probo *et al.*, 2016), as proved by the dramatic decrease in the number of grazing animals in mountain areas occurred in the last decades (Lasanta *et al.*, 2017).

Moreover, they are mostly located in areas with oligotrophic soils and/or extreme climatic conditions and are largely dependent on seasonal dynamics in pasture productivity (Orlandi *et al.*, 2016), requiring the accumulation of sufficient stock of hay or silage to feed the animals during unfavourable seasons. However, Italian grasslands are highly diverse, depending on the livestock production systems and on the local environmental conditions. In general, they are characterized by variable, and often unreliable grass and forage production, that is concentrated in a short time-span in spring and/or early summer (Cavallero *et al.*, 2007; Argenti *et al.*, 2011), however some specificities can be observed among the three Italian biogeographical regions. For instance, grasslands of the Italian Alps are the main source of livestock feeding in this area, bearing important economic, social and ecological values, such as forage production and related ecosystem services provided to support the dense population in Alpine valleys (Deléglise *et al.*, 2015). Instead, the Italian continental mountain grasslands, referable to the Apennine chain, provide forage resources for livestock (Sundseth, 2010) but with a lower quality than that of Alpine pasturelands (Targetti *et al.*, 2013), as result of higher pedological and climatic variability along the latitudinal transect of the Italian peninsula (Metzger *et al.*, 2005). Finally, Mediterranean grasslands provide a wide range of supporting, regulating and cultural ecosystem services, among which feed provision and biodiversity conservation are the most important (Seddaiu *et al.*, 2018; Aguilera *et al.*, 2020), as characterized by abundance of annual self-reseeding species (Porqueddu *et al.*, 2016; Pulina *et al.*, 2018) that are adapted to both climatic conditions and anthropic management, which have shaped the landscape since centuries (Bagella *et al.*, 2013).

The performances of extensively managed grasslands and forage crops are largely dependent on interactions between climate, soil and agricultural management practices. Among them, climate plays one of the most relevant role especially in marginal areas (Subedi *et al.*, 2016), influencing crop production or shaping plant species distribution and/or dynamics across spatial and elevation gradients (Petitpierre *et al.*, 2016). To this, global warming and variations in precipitation are deeply altering forage production and quality as well as the botanical composition of rainfed pastures and meadows (Soussana *et al.*, 2010; Targetti *et al.*, 2010), making these systems very sensitive and vulnerable to climate change (Jarzyna *et al.*, 2016). Hence, understanding the main drivers, processes and environmental conditions likely threatening the functioning of these ecosystems and the associated services, can be valuable in predicting how forage production and quality will be affected by climate changes and in identifying sustainable management options for decision making (Malek and Verburg, 2018).

The climate change impacts on European grassland ecosystem services, bearing implications from an agronomic point of view, are different in different continents and sub-regions, in relation to both local farming and environmental conditions (Gauly *et al.,* 2013). Furthermore, these impacts are framed in a context of dramatic changes related to socio-economic drivers (Veysset *et al*., 2005; Mottet *et al.,* 2006), because of which diverging trends occur almost everywhere in European countries: crop intensification in fertile areas or grassland abandonment in marginal lands (Lasanta *et al.*, 2017). According to the Fifth Assessment Report of the IPCC (2014) the Alpine and Southern sub-regions of Europe are going to face a loss of feed provisioning for livestock with a good level of agreement emerging from the literature, while contrasting evidence, even if tending towards a general loss, arise about the climate change impacts on biodiversity. While impacts of climate change on grassland productivity and forage quality can be contrasting across Northern and Mediterranean Europe (Graux *et al.*, 2013; Ergon *et al.*, 2018), these are expected to arise with greater severity and bringing negative effects on grassland traits in Southern areas including the Alps (Kipling *et al.*, 2016; Chang *et al.*, 2017; Balzan *et al*., 2020).

According to these premises, a better understanding of the consequences of the observed and predicted climatic changes on forage production and vegetation characteristics of the main forage resources for Italian livestock systems is urgent, to design the necessary strategies and adaptation pathways.

The hypothesis is that the information gained from the literature review can provide insights on the current level of knowledge on the impacts of climate change on Italian grassland systems, and support the development of policy strategies for adaptation. This paper draws from the literature the impacts of climate change in different Italian grassland and forage crop systems (Alpine, Continental-Apennine, and Mediterranean). The main aims of the review are to: i) revise the existing literature in the domain, highlighting different or common trends among Italian biogeographical regions; ii) provide information on the main climatic impacts analysed and drivers involved in the studied evolutions; and iii) point out the knowledge gaps currently pending in order to hypothesize the future scenarios of research in this sector.

The focus of the climate change impact assessment in this paper is framed on two distinct aspects: i) grassland vegetation and biodiversity; and ii) forage production and quality in the three identified biogeographic regions of Italy.

Current and expected trends of the main grasslands climatic drivers on the three biogeographical regions

The three biogeographic regions of Italy (Alps, Apennine and Mediterranean) are peculiar areas where climate and land use change are strongly influencing ecosystem processes by challenging grassland composition and productivity. In the last century, the Alps experienced a surface air warming of about 2°C (+1.8°C in the 1979-2018), nearly two times higher than the global average (Auer *et al.*, 2005, 2007; Brugnara, 2020), and the climatic model projections indicate increases up to +3.3°C by the end of the century (Gobiet *et al.*, 2014). Additionally, the altitude gradients of warming were found to significantly change, with a higher increase of temperature at higher elevations in all seasons (Gobiet *et al.*, 2014). Over the last decades, warming has been associated with variations in precipitation which in turn depends on the area (*e.g.* increases in the north-west and decreases in the south-east) and the seasonal pattern, with overall decreases in summer (Schmidli and Frei, 2005; Auer *et al.*, 2007; Brunetti *et al.*, 2009; Chelli *et al.*, 2017). Future projections, even if affected by uncertainties depending on the global and regional circulation models considered, indicate the same trend: *i.e.* decreases in summer precipitation (especially in the southern Alps) and slight increases in winter by the end of the century (Gobiet *et al.*, 2014). Furthermore, more intense and frequent extreme events (*e.g.* heavy rainfall, drought periods, heatwaves and possibly also storms) are foreseen in the near future along the whole Alpine region. Consequently, the snow mass of the Italian Alps is expected to reduce in the future, with uneven heavy snowfall events in winters, though likely awaited to decrease in occurrence in the next future (Soncini and Bocchiola, 2011), and leading to water scarcity in summer periods. In particular, the synchronous effect of drought and heatwaves in the Alpine areas, during summer, increases the forest evapotranspiration, which is essentially sustained by water availability in the soil. Thus, such increased evapotranspiration reduces the water runoff fraction that feeds streams and rivers from valleys to plains.

The resulting water deficit is consequently transferred to remote plains even far away from the Alpine region (Zampieri *et al.*, 2016; Mastrotheodoros *et al.*, 2020).

Among the climatic drivers relevant in altering grasslands located in the Italian continental environments, the most analysed in the scientific literature is undoubtedly the effect of warming. The increases in surface air temperature are expected in a range of 3-5°C in the next decades, depending on the climatic scenarios analysed (Dibari *et al.*, 2015; Petriccione and Bricca, 2019). An air temperature distribution shift to warmer values is projected to occur in all seasons, especially for the minimum temperature, while the maximum temperature shows a more intense warming and a pronounced peak during summer (Tomozeiu *et al*., 2018). This behaviour, started back in the 1980s with an acceleration in the 2000s (Toreti and Desiato, 2008), is expected to further increase in the near future (Tomozeiu *et al*., 2018). Along with seasonal mean values, the extremes changed significantly with an extension of the summer period characterized by an increasing occurrence of intense heat waves (Zampieri *et al*., 2016). Besides temperature, precipitation is also a climatic driver addressing growth and development of grasslands along the Apennines, showing high variability and projected to decrease during the vegetative period determining increases of summer droughts and decreases in the duration of snow cover (Scocco *et al.*, 2016a, 2016b; Tardella *et al.*, 2016). This significant reduction of precipitation expected in the future decades, is estimated more intense during spring and summer, regardless of the emission scenarios adopted (Tomozeiu *et al*., 2018). Such precipitation decline, embedded in a structural warming trend, will alter significantly the hydrological cycle with an increasing trend of drought length and intensity and further accumulation of water deficits under all different levels of future warming (Naumann *et al*., 2018). Such combined drivers will lead to an increased risk of exposing natural ecosystems and pastoral resources to abiotic stresses.

The Mediterranean bioclimatic zone of Italy, which includes the coastal areas, the southern Italian peninsula and the islands, shows a warm or hot summer where in general July is the warmest month, with maximum temperatures often close to 35°C in many locations. A strong seasonal trend is also evident for rainfall, with summer generally drier than the rest of the year over most of the region. This typical feature of Mediterranean climate was affected by climate change, which has led in the last 30 years to an increase in temperatures and to a change in the annual pattern of rainfall distribution. Temperatures showed an increasing trend while in summer the rainfall rate is decreasing (Toreti and Desiato, 2008; Lionello *et al.*, 2014; Longobardi *et al.*, 2016; Cramer *et al.*, 2018; Caloiero *et al.*, 2018; Cherif *et al*., 2020), and this was associated to an increased dry spell (Moberg and Jones, 2005). Chelli *et al.* (2017) highlighted that, although in the whole Italy changes in temperatures and precipitation occurred, the pattern of these changes was different in the northern and mountain zones with respect to the Mediterranean bioclimatic zone. According to Corti *et al.* (2009), in this region the decrease of precipitation in summer was higher than the other Italian areas, with a lower number of rainy days associated to a higher intensity of precipitation events and more severe drought periods.

The future climatic projection overall highlights that the trends of changes observed in the past century will continue with a higher magnitude. Giorgi and Lionello (2008), using an ensemble of 17 general circulation models (GCMs) projections, indicated that increase in temperature will be characterized by a strong seasonal trend where the highest increase will be centred on the summer season (Lionello and Scarascia, 2018), and this will be associated to a significant decrease in precipitation in summer from about 10-15% to 30% (Cramer *et al.*, 2018), which however is not so relevant given the very low rainfall probability in summer months in this area. An increase of extreme weather events as storms, floods and heatwaves is also expected in the coastal areas of the Mediterranean climatic zone (Medri *et al.*, 2013; Dono *et al.*, 2016; Chelli *et al.*, 2017; Zhang *et al.*, 2019).

Impacts of climatic drivers on Italian grasslands

Alpine region

Impacts on vegetation and biodiversity

Most studies, analysing the climate change impacts on the Alpine grassland biodiversity and forage production, consider increasing temperature and the variability in the precipitation pattern as the main climatic drivers affecting these ecosystems, especially at high mountain environments (Table 1). In the Alpine grasslands, the increases in temperature observed in the last decades caused expansion of communities dominated by shrubs (Cannone *et al.*, 2007) as well as greening dynamics of some temperate alpine areas were observed (Carlson *et al.*, 2017). However, there is substantial agreement in the literature about the observed upward shifts of grass vegetation communities as a consequence of temperature rise, more notable at high elevations than at low altitudes (Cannone *et al.*, 2008). Such shifts are threatening the persistence of endemic species at the highest peaks of the Alps (Schwager and Berg, 2019), where high altitude species have less opportunities for the upward migration with respect to those positioned at lower elevations (Engler *et al.*, 2011). Shifts across altitude gradients due to global warming has favoured the invasion of more competitive subalpine grasses (Descombes *et al*., 2017) or the encroachment of shrub and forested areas (Tasser *et al.*, 2017). The increasing temperature, coupled with reduction in the precipitation pattern and shortening of the snow cover, are causing notable increments in the vegetation cover (Rogora *et al.*, 2018) and plant growth (Pellissier *et al.*, 2018) in the Alpine belt. However, both authors indicated that sites located at the nival belt did not show any significant change in terms of greening, but rather on plant species turnover rates.

These processes are expected to worsen in the next future climate when, according to RCP4.5 and 8.5 scenarios, an overall (about 5-7%) decline of the extension of permanent grasslands is predicted, especially for high altitude grassland communities due to increasing temperatures and changes in the precipitation pattern (Dibari *et al.*, 2020). This will likely cause an alarming decline of endemic/rare high mountain species up to 44-50% (Dullinger *et al.*, 2012), more evident in communities dominated by *Carex curvula* (Cannone *et al.*, 2007; Dibari *et al*., 2020) and *Carex firma* (Dibari *et al.,* 2013; 2020) or in communities located above the treeline, as already observed by Carlson *et al.* (2017). These evolutions, depending also on the plant traits and the elevation gradient analysed (Matteodo *et al.*, 2013), are particularly evident for cold-adapted species/communities (Schwager and Berg, 2019) and projected to widely impact the eastern Alps by the end of the twenty-first century (Engler *et al.*, 2011; Scherrer and Körner, 2011; Dibari *et al.*, 2020).

Changes in Alpine grassland species dynamics, resulting into short-term decline in biodiversity, structure and ecological patterns, are also predicted by Cotto *et al.* (2017) in the future and observed by Stanisci *et al.* (2014) in response to climate warming. Conversely, only a negligible loss of biodiversity was predicted by Gottfried *et al.* (1999), who observed contrasting community changes, depending on aspect and altitude, and by Unterluggauer *et al.* (2016), who measured a decrease in the number of lost species along an altitude gradient. Both authors indicated that, as result of a warmer climate, high-summit grassland communities tend to respond quickly to upward shifts due to an enhanced strategy to colonize niches and to find microsites where they are absent today. In contrast, at the lowest summits, dominant graminoid species will outcompete the weaker alpine grasses. It is evident that these processes have led to a general homogenization of plant diversity (Liberati *et al.*, 2019), with different dynamics among plant communities, mainly due to micro-climate conditions and exposure to temperature extremes but also due to local dynamics among the species (Gritsch *et al.*, 2016).

Impacts on grassland productivity and forage quality

As summarized in Table 2, rising temperatures and summer droughts, together with the changes in rainfall patterns, are the main factors affecting grasslands productivity and forage quality. These impacts, evident both in the short and long term (Deléglise *et al.*, 2015), may be due to changes in the reproduction rate, as observed up to –28% by Dainese (2011) for *Dactylis glomerata* in the southeastern Alps areas when shifting from warmer to colder sites. Conversely, Berauer *et al.* (2019) found an overall increase in above ground biomass production, depending from the precipitation regimes; similarly, Filippa *et al.* (2019) observed an increase in grassland plant productivity with variations along an altitudinal range. This was confirmed by Schirpke *et al.* (2017), who found similar altitudinal patterns (*e.g.* increases in forage production by 9%-18% until 2050) in response to increasing temperatures in combination to land use changes. However, as general results, the authors recognized land abandonment as the main driver affecting ecosystem services at low altitudes by the middle of the century, while, at higher elevations and in the second half of the century, the climate becomes the dominant driver.

Summer drought is recognized as one of the main constraints to aboveground biomass productivity in pastoral ecosystems in relation to drought intensity (Schmid, 2017) and to the adopted management (Deléglise *et al.*, 2015). This is confirmed by Trnka *et al.* (2011), who indicated relevant losses in forage productivity of grasslands as a consequence of long lasting and intensive land use coupled with water scarcity during summer periods. A consistent body of literature (Trnka *et al.,* 2011; Dainese, 2011; Gavazov *et al.*, 2013; Dumont *et al.*, 2014; Deléglise *et al.*, 2015; De Boeck *et al.*, 2016; Schirpke *et al.,* 2017; Filippa *et al.*, 2019) indicates the intensity and duration of heat and drought stress as severe drivers affecting forage quality because of an alteration of the physical and chemical characteristics of plants related to forage digestibility.

While the rise of atmospheric CO_2 concentration, coupled with higher temperature, contributed to increase grassland productivity in the Alpine and EU northern regions (Dellar *et al.*, 2018), high concentrations of atmospheric CO_2 have significant negative effects on the nitrogen content of grassland forage (–9% on average), mainly due to changes in the forage protein-energy balance, which can affect, in turn, the microbial synthesis in the rumen (Dumont *et al.*, 2014; Dellar *et al.*, 2018). As regards forage quality, changes in forage palatability of high mountain permanent grasslands were foreseen by Dibari *et al.* (2020), who predicted a general expansion of hardy and less palatable communities (*e.g.* dominated by *Nardus stricta* and xeric species) in the near and far future of RCP 4.5 and 8.5 IPCC emission scenarios.

Changes in forage N concentration of the Alpine grasslands are also indicated under warming temperature and water-limited conditions (Deléglise *et al.*, 2015; Dellar *et al.*, 2018), at different rates

Table 1. Impacts of main climatic drivers on vegetation and biodiversity on Alpine grassland systems.

Climatic driver	Impacts on vegetation and biodiversity	References
Increasing temperatures	- Upward shifts of grasslands	Berauer *et al.*, 2019
	- Expansion of shrubs at altitudes 2400-2500 m, reductions at higher altitudes	Cannone *et al.*, 2007
	- More flexible dynamics of alpine (2400–2800 m) and nival (above 2800 m) vegetation	Cannone *et al.*, 2008
	- Contrasting dynamics of pioneer vegetation depending on altitudes	Cotto *et al.* 2017
	- Increases in speed of colonization of grasslands on lands left by retired glaciers	Descombes *et al.*, 2017
	- Expansions of thermophilic, perennial plant species, and graminoids	Dibari *et al.*, 2013
	- Increase of species number, especially at high summits	Dibari *et al.*, 2020
	- Decrease of the frequency of endemic species	Dullinger *et al.* 2012
	- Increases in competitiveness and turn-over among species at high summits	Engler *et al.* 2011
	- Loss of high mountain grassland types and/or habitats (*e.g.*, pastures dominated by *Carex firma*)	Gottfired *et al.* 1999
	- Reductions in grassland extent	Gritsch *et al.* 2016
	- Expansion of areas suited to hardier but less palatable pastures (*i.e.*, dominated by *Nardus stricta* and xeric species)	Liberati *et al.*, 2019
		Matteodo *et al.*, 2013
		Pellissier *et al.*, 2018
		Rogora *et al.*, 2018
		Scherrer and Körner, 2011
		Schwager and Berg, 2019
		Stanisci *et al.*, 2014
		Tasser *et al.*, 2017
		Unterluggauer *et al.*, 2016
Reduced precipitation	- Increases in speed of colonization of grasslands on lands left by retired glaciers	Cannone *et al.*, 2008
	- Ability to colonize not developed soils	Cotto *et al.* 2017
	- Persistence in unsuitable habitats of perennial plant species in the Austrian Alps	Unterluggauer *et al.*, 2016
	- high habitat loss at higher elevations	Dibari *et al.*, 2013
	- decline in species richness	Dibari *et al.*, 2020
	- decline in number of endemic species	Berauer *et al.*, 2019
Decreasing of snow	- Increasing water stress	Rogora *et al.*, 2018
	- Expansion of xeric tolerant and thermophilus species	Liberati *et al.*, 2019
	- Local extinction of cold adapted species	Carlson *et al.* 2017

according to moderate or high-water stress conditions. Contrasting and/or uncertain trends are expected in terms of soil N availability (Dumont *et al.*, 2014) and C/N ratios (Leingärtner *et al.*, 2014) and consequently in plant N uptake. However, these authors did not evidence any direct/reliable effects of extreme climatic events on forage quality, plant community composition and plant-herbivore interactions.

Continental region (Apennines)

Impacts on vegetation and biodiversity

Considering the expected increases in temperature, coupled with decreases in rainfall in summer periods, many studies highlighted the evolution of species distribution inside herbaceous communities and changes in the botanical composition of natural grasslands (Table 3). Higher temperatures and summer droughts will determine the dominance of thermophiles communities or species more adapted to xeric environments, which currently grow in environments located at lower altitudes, as observed by Frate *et al.* (2018) for massifs in Central Italy. According to these authors, climatic evolutions coupled with land use changes have strongly altered vegetation in the last 60 years and they will likely be the main drivers altering botanical composition, species distribution and length of the grasses vegetative period of the Apennine grasslands in the near future.

Ferrarini *et al.* (2017), using simulation models, predicted an increase of xeric species (such as *Brachypodium genuense*) in the near future, highlighting the importance of inter-species interactions and timing to response as drivers of plant communities'

Table 2. Impacts of main climatic drivers on grasslands productivity and forage quality on Alpine grassland systems.

Climatic driver	Impacts on grasslands productivity and forage quality	References
Increasing temperatures	- Increases in reproductive performances (*e.g., Dactylis glomerata*)	De Boeck, 2016
	- Increases in greening	Dainese, 2011
	- Reductions in productivity of open pastures	Filippa *et al.*, 2019
	- Contrasting effects (increases/decreases) in above ground dry biomass depending	
	- from altitude and management	Dellar *et al.*, 2018
	- Increases in plant growth	Dumont *et al.*, 2014
	- Reduced forage digestibility	Gavazov *et al.*, 2013
	- Expansion of areas suited to hardier but less palatable pastures	Dibari *et al.*, 2020
Reduced precipitation	- Reduction in grassland productivity	De Boeck, 2016
	- Reduction in forage quality	Deléglise *et al.*, 2015
	- Decreases in above ground biomass	Dellar *et al.*, 2018
	- Increases in below-ground biomass	Trnka *et al.*, 2011
	- Increases in forage N content	Dumont *et al.*, 2014
	- Increases in forage digestibility	Leingärtner *et al.*, 2014
	- Slight changes in forage C/N ratio	Schmid, 2017
	Schirpke, 2017	
Increases in atmospheric CO_2 concentration	- Reductions in forage N content, especially for shrubs and forbs	Dellar *et al.*, 2018
	- Increases in above ground dry biomass	Dumont *et al.*, 2014
	- Increases in plant growth	
	- Increases in total non-structural carbohydrates of forage tissues	
	Increased legume abundance in multispecies swards	

Table 3. Impacts of main climatic drivers on vegetation and biodiversity on Apennines grassland systems.

Climatic driver	Impacts on vegetation and biodiversity	References
Increasing temperatures	- Positive reaction of xeric species or of thermophiles species of lower habitats	Dibari *et al.*, 2015
	- Clear decline in several cryophilic species	Evangelista *et al.*, 2016
	- Increment of dwarf shrubs	Tardella *et al.*, 2016
	- Reduced overall pasturelands suitability	Ferrarini *et al.*, 2017
	- Increment in the frequencies of hemicryptophytes	Frate *et al.*, 2018
	- Probable spread of species from south to north-facing slopes	Petriccione and Bricca, 2019
	- Loss of habitat biodiversity	Porro *et al.*, 2019
	- Increasing of species richness	
	- Importance of species interaction and timing to response as drivers of plant communities	
	- Simple simulation model can explore potential changes in plant communities induced by climate warming	
Reduced precipitation	- Reduction of surface suitable for pastures in north and central Apennines	Dibari *et al.*, 2015
	- Expansion of surface suitable for pastures in south Apennines	Tardella *et al.*, 2016
	- Increasing xeric tolerant and thermophilus species	Petriccione and Bricca, 2019
	- Increasing of total number of species	
	- Probable spread of species from south to north-facing slopes	
Decreasing of snow	- Increasing water stress	Petriccione and Bricca, 2019
	- Increasing xeric tolerant and thermophilus species	
	- Local extinction of most of the cold adapted species	

dynamics. Under these complex conditions, as reported by these authors, simple simulation models, with reduced input data, can be extremely useful to explore potential changes in grassland associations induced by climate change. Similar results were reported by Evangelista *et al.* (2016a) who analysed the evolution of the botanical composition in a long-term assessment (42 years) at high mountain locations (Majella, central Apennines). These authors depicted the clear decline of cryophilic species and changes in floristic composition, with a general increase in the extent of hemicryptophytes. The clear floristic, ecological and structural variations reported by this study confirm a thermophilisation process endured by grassland ecosystems and also observed in other mountain environments of Italy. Moreover, these authors described an evolutionary trend towards a more nutrient-demanding vegetation, mainly driven by warming and by a general enrichment of soil fertility induced by climate change, determining an intensification in the decomposition rates and, in turn, a rise in nitrogen deposition from the atmosphere.Tardella *et al.* (2016) analysed the botanical composition of different pasture types of the Central Apennines by means of scattered samples and some Ellenberg's ecological indicators (soil moisture, air temperature, soil nitrogen content) as proxies of impacts due to temperature and soil moisture changes. Results showed variations in the vegetation composition as a response to higher competition for environmental factors: at higher altitudes, a reduced shift of species from the lower to the higher slopes was observed, coupled with a spread of species from south to north-facing slopes. Other structural changes induced by climate changes are expected in the extent of areas dominated by shrubs. Porro *et al.* (2019), adopting periodical re-survey on the same sample areas, reported a higher occurrence of communities dominated by graminoids and shrubs replacing cold tolerant and rare species. The same trend was observed by Frate *et al.* (2018) for dwarf shrubs in calcareous grassland types, as a result of the thermophilisation processes. An increase in floristic richness is expected by climate warming. Specifically, Petriccione and Bricca (2019) measured, in permanent areas continuously monitored, an increase of total number of species in all studied plots located along Gran Sasso high mountain grasslands, though the observed floristic enrichment was counterbalanced by the loss of specific taxa, more sensitive to the changed climatic conditions. Also variations in snow cover persistence have a strong impact on Apennine grassland species, as the prolonged absence of snow cover makes these biocoenosis more exposed and vulnerable to frost stresses. Similarly, Porro *et al.* (2019) depicted increases in botanical richness in four summit unmanaged rangelands of the Northern Apennines. In these sites, the increases in plant richness was ascribed to a global warming which in turn induced a general upward migration of species from the lower altitudes. Nevertheless, the observed increment in floristic richness was offset by any relevant trend in other diversity metrics (*e.g.* Simpson index, evenness), inducing to a general biotic homogenization and a consequent lower habitat diversity. Future climate variations will also alter pastoral land suitability, as foreseen by Dibari *et al.* (2015). Specifically, the authors used a machine learning modelling approach to assess the impacts of future SRES IPCC scenarios (namely A2 and B2) on pastoral resources across the entire Apennine chain. According to their simulations, an alarming reduction in the extent of lands currently suited to pastures is expected in the next future, notably in the northern and central areas of the Apennine, while noteworthy expansions are predicted in the south.

Impacts on grassland productivity and forage quality

The impacts of climate change on agronomic characteristics of grasslands, such as production or quality of forage biomass, are less studied in the Italian literature with respect to biodiversity (Table 4). Nevertheless, there is an overall agreement among studies in depicting a general reduction in aboveground biomass production as induced by increasing temperatures and reduced rainfall along the growing season. Specifically, the lower forage production induced by climate change can be less severe under particular conditions, such as in more fertile environments (Gargano *et al.*, 2017) or in north facing slopes (Chelli *et al.*, 2013). Scocco *et al.* (2016a) reported rainfall as one of the main drivers able to reduce forage biomass availability. Moreover, they observed a reduced regrowth ability of grasses after grazing, especially for the most fertile pastures, due to a reduction in soil water availability This means that climate change can affect not only the general extent of overall production but also the productivity pattern of herbaceous communities. Outstanding harmful effects of climate change are expected also on forage quality. Specifically, Tardella *et al.* (2016) foresee a reduction of forage quality in pastures where more palatable species will be replaced by the less palatable ones due to a higher tolerance to drought periods. This is confirmed also by Scocco *et al.* (2016b), who measured the chemical composition of herbaceous production, indicating a reduction of crude protein in grasses counterbalanced by an increase of fiber content under warmer and drier conditions. The authors also stated that decreases in forage quality and production, mainly due to summer droughts, can be indirectly assessed through the Body Conditions Score, as a proxy of forage nutritive value and digestibility in sheep grazing systems of the Apennine.

Mediterranean region

Impacts on vegetation and biodiversity

The scientific literature on the climate change impact on Italian Mediterranean grasslands productivity and biodiversity already acknowledged that decreasing rainfall, increasing dry spell and

Table 4. Impacts of main climatic drivers on grasslands productivity and forage quality on Apennines grassland systems.

Climatic driver	Impacts on grasslands productivity and forage quality	References
Increasing temperatures	- Plant palatability reduction and forage quality - Height plant reduction - Reduction of productivity	Tardella *et al.*, 2016 Gargano *et al.*, 2017
Summer drought	- Decrease of above ground biomass production, especially in north facing slope - Reduction of pasture quality - Higher presence of fibres, reduction of crude protein and lipid - Reduction of animal productive performances - Reduction of summer regrowth ability, especially in productive pastures	Chelli *et al.*, 2013 Scocco *et al.*, 2016a Scocco *et al.*, 2016b

higher temperatures are the main drivers of changes in these agroecosystems. The impacts of temperature rise and decreasing rainfall on the vegetation and biodiversity of Italian Mediterranean grasslands are mainly documented by studies from a forestry science perspective (Table 5). In their meta-analysis, Li *et al.* (2018) pointed out that under increasing temperature and decreasing rainfall, grasslands are expected to decrease their species richness to a greater extent under high-intensity grazing systems. Mairota *et al.* (2014) observed a loss of one-third of the grassland area, due to shrubs and trees encroachment and to a general increase of forested areas, according to the SRES A1B future climatic scenario (increasing temperature, decreasing rainfall). Moreover, shrub encroachment in grasslands can be favoured by the decreasing rainfall when the starting vegetation is characterized by high shrub species richness, as reported by Rodriguez-Ramirez *et al.* (2017) in an experiment conducted in southern France. Furthermore, in Spanish silvopastoral systems, Rolo and Moreno (2019) found that the shrub encroachment induced by climate change increased the competition between grassland and shrub vegetation for water resources, thus amplifying the effect of decreasing rainfall. It is well noted that the encroachment of woody species in Mediterranean grasslands represents an important global threat for these habitats, altering the capacity of grassland ecosystems to provide essential ecological, hydrological, and socioeconomic functions. Moreover, the expected changes could have a cascade effect across the food webs impacting several animal species at the landscape scale. Under IPCC A1B emissions scenario, Lozano *et al.* (2017) described expected changes in forest vegetation composition in the time span 2041-2070 and an increase of the probability of wildfire occurrence from 2% to 10%, as a result of reduced fuel moisture content. The increase of wildfire probability could lead to a substantial change in the plant assemblage composition and distribution or even to the desertification of slopes due to increased soil erosion (*e.g.* Karamesouti *et al.*, 2016). However, the effect of climate change on shrub encroachment of Mediterranean grasslands is also associated with the agronomic management of grasslands, particularly in oligotrophic soils, where NP fertilization can effectively contribute to maintain the grassland vegetation and prevent the encroachment of pyrophytic shrubs, as observed by Bagella *et al.* (2017).

Impact on grassland productivity and forage quality

The impacts of climate change on agronomic traits of the Italian Mediterranean grasslands emerge to be more studied with respect to vegetation and biodiversity (Table 6). Climate change is

Table 5. Impacts of main climatic drivers on vegetation and biodiversity on Mediterranean grassland systems.

Climatic driver	Impacts on vegetation and biodiversity	References
Increasing temperatures	- Increase in forest covered area - Decrease of species richness with a larger extent under high grazing intensity grassland systems in semi-arid environments	Li *et al.*, 2018 Mairota *et al.*, 2014 Karamesouti *et al.*, 2016 Bagella *et al.*, 2017
Reduced precipitation	- Loss of one-third of grassland area due to shrubs and trees encroachment and subsequent enhancing of drought exposure - Increase of fuel moisture content and of burn probability in far future (2041-2070) from about 2% to about 10% - Decrease of species richness with a larger extent under high grazing intensity grassland systems in semi-arid environments	Li *et al.*, 2018 Lozano *et al.*, 2017 Mairota *et al.*, 2014 Rodriguez-Ramirez *et al.*, 2017 Rolo and Moreno, 2019

Table 6. Impacts of main climatic drivers on grasslands productivity and forage quality on Mediterranean grassland systems.

Climatic driver	Impacts on grasslands productivity and forage quality	References
Reduced precipitation	- Overall decrease of grassland production - Increase of inter-annual variability of grassland production in spring under silvopastoral systems - Drought can override the positive effects of higher temperature - Severe reduction in autumn pasture biomass production under 50% of reduction of rainfall patterns - Grasses increase SLA by 7% and forbs by 10% on average under extreme drought - Changing in aboveground NPP with a different extent depending on season - Forages N content increase, NDF decrease, high variability of forage N and C/N	Dumont *et al.*, 2015 Chelli *et al.*, 2016 Dono *et al.*, 2016 Chelli *et al.*, 2017 Iglesias *et al.*, 2016 Pulina *et al.*, 2017 Wellstein *et al.*, 2017
Changing in rainfall distribution	- Increase of grassland autumn production in most productive years as result of interaction between higher water availability in autumn and higher temperature	Dono *et al.*, 2016 Dumont *et al.*, 2015
Increasing temperatures	- Enhanced plant growth - Decreasing forage digestibility and shifts in botanical composition	Dumont *et al.*, 2015 Chelli *et al.*, 2017
Increasing CO_2 concentration and interation between enhanced CO_2 and reduced rainfall	- Modification in heading date - Forage N content increasing by an average of 3% - Water soluble carbohydrates and total non-structural carbohydrates increase, while lack of effect on structural carbohydrates - Negative effect of less precipitation on productivity will override the positive effect of elevated CO_2 during summer and in dry regions - Under less dry conditions, the positive effects of increased temperature and elevated CO_2 on productivity will override the negative effect of less precipitation	Ergon *et al.*, 2018

expected to have an impact on forage production and its seasonal distribution, as a result of compensatory effects of higher winter temperature and CO_2 rise (Dono *et al.*, 2016; Chelli *et al.*, 2017). In their review, Ergon *et al.* (2018) highlighted that in summer the positive effect of enhancing CO_2 can be thwarted by severe drought-induced by lower precipitation. Combining decreasing rainfall with changes in the distribution and variability of autumn rainfall can result in a severe reduction in expected autumn pasture production (Pulina *et al.*, 2017). However, an increase in simulated average grassland autumn production in the most productive years is expected as a result of the interaction between higher water availability and higher temperature in the winter (Dono *et al.*, 2016). Under a two-year manipulative experiment inducing a gradient of water availability with respect to actual rainfall, Chelli *et al.* (2016) observed an overall increase of 52% aboveground net primary production with increasing water availability. The same authors showed that spring pasture production was higher in wet springs than in dryer springs, during which, however, the grassland productivity was not significantly affected by the rainfall gradient (current, additional, reduced). The higher inter-annual variability of spring forage production induced by changes in rainfall variability has been observed also in grasses of Spanish *Quercus*-based agroforestry systems (Iglesias *et al.*, 2016). An induced decreasing rainfall also led to changes in plant physiology depending on the plant functional groups. In their meta-analysis, Wellstein *et al.* (2017) showed that grasses increase the specific leaf area under induced drought by 7% on average, while other forbs reduced this parameter by 10% on average under the extreme drought treatment.

Beyond the productivity aspects, the increase of CO_2 has been observed to be a determining factor that alters the quality of the forage by decreasing the C/N ratio (Dumont *et al.*, 2015; Ergon *et al.*, 2018). Dumont *et al.* (2015), in their meta-analysis conducted on manipulative experiments on climate change (increasing CO_2 concentration, decreasing rainfall, increasing temperature) under Mediterranean conditions, indicated a general reduction of forage quality and digestibility, mostly ascribed to limiting conditions in grasslands for legumes growth. Overall, the CO_2 concentration rise seems to have a weak direct effect on forage quality, except in terms of forage N content (+3%), non-structural and water-soluble carbohydrates, and total non-structural carbohydrates, which on average increased. However, increasing temperature caused decreased forage digestibility and shifts in the plant assemblage composition, while drought caused neutral detergent fiber (NDF) decrease, higher variability of forage N content and C/N ratio due to the lack of water availability (Dumont *et al.*, 2015).

Analysis of evidence and agreements of the literature across the regions

There is robust evidence, with a high level of agreement in the literature, that an increase of xeric tolerant and thermophilous grassland species, coupled with a reduction of cold-tolerant species, is expected in the future climate across the Alps and the Apennines. This will likely increase the extinction risks for the less tolerant and more specialized high-altitude grassland communities of these bioclimatic zones, especially where upwards or northwards migration is limited or even not possible. Furthermore, while studies analysing the impacts of climate change on the altitudinal shifts of pastoral communities are well represented in the Alps (robust evidence), they are less issued in the Apennines (medium evidence) and completely lacking in the Mediterranean area (Figure 1). Although the literature focussed on grasslands of the Alps (medium evidence; medium agreement) and the Apennines (medium evidence; high agreement) indicates decreases in biodiversity, contrasting results emerged on floristic richness: reductions for the Alps and the Mediterranean, increases in the Apennines with a medium frequency of the literature (medium evidence), but under a medium/high level of agreement for all areas. However, for the Alpine and Continental biogeographical regions, the expected climatic changes will alter species dynamics within the pastoral ecosystems, with alarming consequences on the preservation of some endemic species located at the higher altitudes, due to the expansion of more competitive species favoured by the occurrence of the new climatic conditions. There is agreement that climate change, if associated with land abandonment and reduction of grazing activities, will likely lead to a relevant homogenization of grassland landscapes, with loss of open areas and specific habitats in both the Alps and the Apennines. Conversely, limited knowledge emerged on the impacts of climate change on the grassland vegetation composition and biodiversity in the Mediterranean area, which becomes a priority for further investigations by means of modelling, long term experiments (LTEs) and/or finalized experiments to assess and monitor changes in endemic species located in this biogeographical area.

As regards grassland productivity, there is high agreement on a decreasing trend of grasses production across the three biogeographical regions, although some contrasting impacts are expected in terms of forage quality in the Alps under future climatic conditions, mainly depending on the climatic variables analysed (*e.g.* summer droughts, increasing temperature, variation in precipitation pattern, increasing atmospheric CO_2 concentration), the explored altitudinal range and the applied agronomic management, which can trigger new physiological processes and competitive dynamics within the grassland ecosystems.

Furthermore, the methods used in the literature reviewed in this study are different according to the areas investigated and to the scope of the research (Table 7). The most frequent methodological approach found in the literature is based on observations from LTEs or similar methodologies. This is more evident in the Alpine area, even if some examples can be found for the Apennines and Mediterranean biogeographical regions. Another widely used methodology concerns the implementation of model projections, often based upon Global and/or Regional Circulation Models coherent with the IPCC reports and often coupled with remote sensing techniques. This kind of studies is well represented in all the three analysed geographical regions. In contrast, researches based on the implementation of experimental trials are less represented in general, with differences in the three regions: more represented in the Alps than in the Apennines or Mediterranean areas. Finally, only a few papers were found based on the comparison of diachronic vegetation maps and meta-analysis approaches, all of them located on the Alpine chain.

Main trajectories of climate change, impacts on grasslands and management implications

Most studies reported in this review provide site-specific and sometimes diverging results. This because the climate change impacts analysed refer to grasslands located in three different biogeographical regions and environmental contexts, they are carried out by applying various approaches, methodologies and tools, they use contrasting spatial scale of analysis, and they were performed for different purposes. However, some clear common trends can be highlighted for the Italian peninsula (Figure 1) highlighting knowledge gaps, open research questions and providing suggestions of future perspective for research. From the climate change framework shown in the previous paragraphs, a high degree of coherence emerges among the three geographical regions. Air surface temperature has been growing in all seasons since the 1980s and faster than ever in the 2000s (Toreti and Desiato, 2008). Extreme high-temperature values occurrence and intensities, such as heatwaves, are increasing as well, contributing, in this way, to the Mediterranean basin warming (MedECC, 2020). The alpine region seems to be more exposed to such warming, especially at higher altitudes (Auer *et al*., 2005, 2007; Brugnara, 2021). During the next decades, this warming intensification is expected to further intensify (Gobiet *et al*., 2014). The precipitation distribution showed a more heterogeneous spatio-temporal pattern. If a generalized reduction is already observed in Italy, dry conditions are expected to intensify in the future. In particular drought occurrence, frequency and severity are projected to increase under all different levels of future warming (Naumann *et al*., 2018). Thus, the combined climatic change stress of warming and drying along the growing season will produce a relevant pressure on terrestrial biodiversity and ecosystems, especially in the Apennines and Mediterranean regions (Chelli *et al*., 2013; Scocco *et al*., 2016a; Gargano *et al*., 2017). Grassland ecosystem response to future climate is critically depending on the interaction between climate drivers and expected CO_2 concentration. Atmospheric CO_2 concentration, that has risen from 280 ppm before the industrial revolution to 410 ppm nowadays and expected to further increase by the end of this century (IPCC 2007), may have an impact on plant and soil responses in some cases exceeding that of projected climate change (Morgan *et al*., 2004).

The effect of CO_2 concentration on plant performances as a single driver has been long investigated focussing primarily on photosynthetic efficiency and water use. Rising CO_2 concentration enhances the photosynthetic efficiency especially of C3-pathway plant whose performances at the present are CO_2-limited. Conversely, C4 plants, whose photosynthetic efficiency is nearly saturated at the present, were predicted to be less responsive to further increase in CO_2. At the same time, increased CO_2 concentration reduces transpiration per unit leaf area in most herbaceous species, irrespective of their pathway, as effect of CO_2-induced stomatal closure. At canopy level, this may lead to a reduced evapotranspiration and higher soil moisture when compared to ambient carbon dioxide (Field *et al*., 1995).

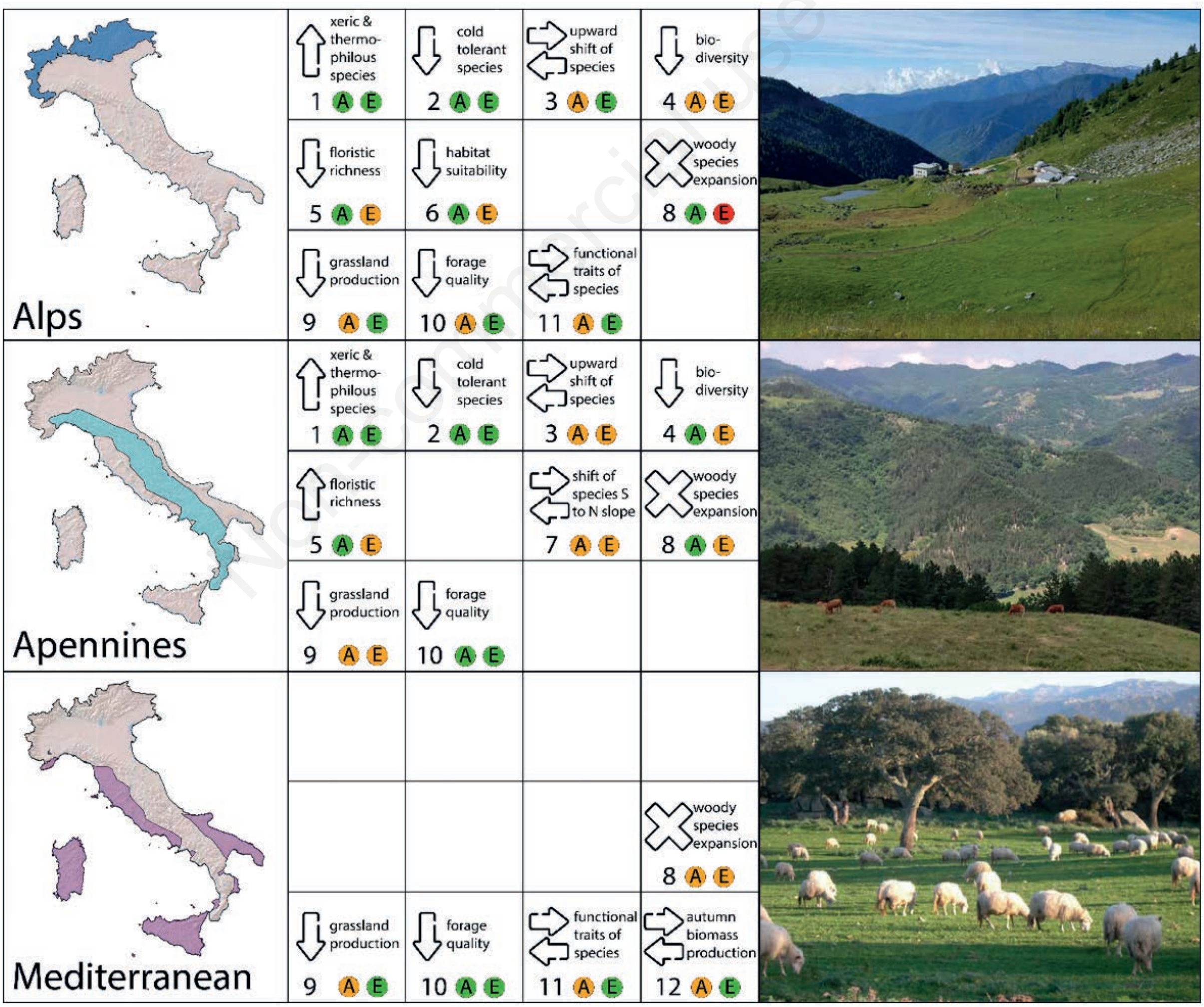

Figure 1. Agreement (level of agreement in the literature) and Evidence (frequency of a given impact) of the main climate change impacts as resulting from the literature review. Upward arrow: increases, downward arrow: decreases, two arrows: changes, cross: loss. (A): agreement, green colour: high, orange colour: medium. (E): evidence, green colour: high, orange colour: medium, red colour: low.

However, the response to CO_2 of grassland ecosystems in terms of biomass accumulation and partitioning, richness and competition between species is largely dependent on other drivers such as climate (Lee *et al*., 2010) and nitrogen, whose natural deposition is expected to further increase in the next future (Galloway *et al*., 2004). As such, the interaction between these single drivers plays a key role in shaping the grassland ecosystem function in the next future and experimental designs are going along these needs by combining the expected changed in climate (temperature and rainfall) with those expected in carbon dioxide concentration and nitrogen deposition (Zalaveta *et al*., 2003; Dukes *et al*., 2005). The global survey reported in Lee *et al*. (2010) evidences that CO_2 enrichment has a positive effect on above and below ground biomass of both C3 and C4-dominated grassland (~+11%) even though in the range of explored CO_2 concentration (439 to 720 ppm) there is no linear response of biomass to increasing carbon dioxide concentration. Neither mean annual temperature or cumulated rainfall altered the strength of biomass response to CO_2 enrichment, not supporting the hypothesis that increasing CO_2 concentration have a greater effect on plants grown in limited water conditions despite this interaction has been occasionally observed (Niklaus and Korner, 2004). Conversely, the absence of the interaction between climate and CO_2 concentration on grassland biomass is likely related to the fact that other drivers may control grassland response to higher CO_2, such as N or P availability (Dukes *et al*., 2005) or the length of the growing season (Lee *et al*., 2010). Aboveground biomass is more responsive to increasing nitrogen with respect to CO_2 but only in sites with high precipitation, reflecting the fact that in these areas grassland are more nitrogen that water limited in contrast to dry regions, where a lower water availability prevents the nitrogen to be in solution (Lee *et al*., 2010).

The experiments using a multivariate approach to consider the effects of CO_2, changes in temperature and rainfall and increased nitrogen availability on different grassland ecosystems indicate that the interaction between these drivers and species richness are consistent. These ranges from no interaction in a California annual grassland, where the negative effects of N and CO_2 on species richness were additive (Zalaveta *et al*., 2003) to antagonistic interaction (Reich, 2009), where CO_2 enrichment reduced the negative effect of increasing N on species richness, in a temperate perennial grassland in Minnesota. Recently, Zhu *et al*. (2020) pointed out that while neither increasing N nor CO_2 enrichment alone altered species diversity in an Alpine grassland, their combination did. Despite these experiments Encompass different climatic zone and ecosystems, the decrease in species richness generally observed by increasing N and CO_2 is likely mediated by increasing biomass in response to these changes and increasing competition for water resources.

The response of plant species to observed and projected climate change (*i.e.* increasing temperatures, modification of rainfall pattern and reduction of snow cover duration) can result into a floristic simplification particularly in mountain areas of the Alps and the Apennines, due to upward shifts, in some cases hampered by natural barriers (*e.g.* rocks; Elsen and Tingley, 2015), or to a reduced dispersal ability of grassland species (Engler *et al.*, 2009; Gottfried *et al.*, 2012), posing new threatening challenges to biodiversity conservation. This can lead to the decrease of occurrence for specific cold tolerant vegetation types, that cannot colonize upward areas characterized by not evolved soils or by rocky surfaces (with loss of some species occurring in this types), with a general reduction of suitable areas for pastures in the higher mountain belts (Engler *et al*., 2011). Regarding modifications related to vegetation, changes will concern botanical composition of natural grasslands, inside which a turnover among different plant types is expected (Tardella *et al*., 2016), with the reduction or the complete loss of species suitable to colder environments and a spread of xeric/thermophilus ones and/or shrubby vegetation (Dibari *et al*., 2020).

As concerns grassland productivity, a general reduction of

Table 7. Methods used in the retrieved studies at the three biogeographical zone considered for the review.

	Long term experiments	Modelling/remote sensing	Experimental trials	Diachronic vegetation maps comparison and meta-analysis approaches
Alps	Cannone *et al.*, 2008 Rogora *et al.*, 2018 Matteodo *et al.*, 2013 Stanisci *et al.*, 2014 Unterluggauer *et al.*, 2016 Gritsch *et al.*, 2016 Carlson *et al.*, 2017 Descombes *et al.*, 2017 Liberati *et al.*, 2019	Gottfried *et al.*, 1999 Engler *et al.,* 2011 Dullinger *et al.*, 2012 Dibari *et al.*, 2013 Gavazov *et al.*, 2013 Cotto *et al.*, 2017 Schirpke *et al.*, 2017 Pellissier *et al.*, 2018 Schwager and Berg, 2019 Filippa *et al.*, 2019 Dibari *et al.*, 2020	Dainese, 2011 Leingärtner *et al.*, 2014 Deléglise *et al.*, 2015 Schmid, 2017 Scherrer and Körner, 2011 De Boeck *et al.*, 2016 Berauer *et al.*, 2019	Cannone *et al.*, 2007 Tasser *et al.*, 2017 Trnka *et al.*, 2011 Dumont *et al.*, 2014 Dellar *et al.*, 2018
Apennines	Stanisci *et al.*, 2014 Evangelista *et al.*, 2016a, 2016b; Frate *et al.*, 2018 Petriccione and Bricca, 2019 Porro *et al.*, 2019 Gargano *et al.*, 2017	Dibari *et al.*, 2015 Ferrarini *et al.*, 2017 Frate *et al.*, 2018	Scocco *et al.*, 2016a, 2016b Tardella *et al.*, 2016	-
Mediterranean	Chelli *et al.*, 2013	Mairota *et al.*, 2014 Dono *et al.*, 2016 Iglesias *et al.*, 2016 Lozano *et al.*, 2017 Pulina *et al.*, 2017 Rolo and Moreno, 2019	Chelli *et al.*, 2016 Rodriguez-Ramirez *et al.*, 2017	Dumont *et al.*, 2015 Wellstein *et al.*, 2017 Ergon *et al.*, 2018 Li *et al.*, 2018

aboveground biomass is observed and projected under climate change in the three regions, as summer droughts are considered the main driver altering grassland productivity (Schmid, 2017). This climatic factor is predicted also to affect possible plants regrowth after animal utilization and, consequently, the overall biomass production pattern (Scocco *et al*., 2016a). Finally, an overall decrease of forage quality and palatability of grasslands is observed and predicted, mainly related to increase warming and rainfall reduction that are considered the main factors able to lessen nitrogen percentage in the available biomass and consequently crude protein content (Dumont *et al*., 2015) and to stimulate a spread of less unpalatable species and shrubs (Tardella *et al*., 2016).

However, grassland management seems to have a role of mitigating drought impacts on grassland productivity in the Alps, as pointed out by Deléglise *et al.* (2015), who showed that the canopy-cover gradient is a notable driver affecting changes in biomass productivity under warmer/drier conditions. Similarly, climate change is expected to reduce the grassland forage production in open pastures, while it is expected to stimulate grass productivity in densely wooded pastures (Gavazov *et al.,* 2013).

The impacts of climate change on vegetation and forage quality and productivity could lead to dramatic changes in grassland management, with a different extent related to the area, farming and grazing systems. The upward shift of species expected in both Alps and Apennines, as well as the expected shift of grassland species from northern to southern slopes, could likely cause limitations for business as usual management of mountain grasslands such as the vertical transhumance during summer (Liechti and Biber, 2016). The need to move grazing animals at higher altitudes may exacerbate the already existing challenges that are facing transhumant householders such as the declining of infrastructures (*e.g.* processing facilities) and services (*e.g.* veterinary and agricultural extension) in these areas and increasing distances to markets (Liechti and Biber, 2016). Furthermore, the general reduction of the suitability of mountain grazing areas and the decrease of forage productivity and quality could lead to increasing conflicts for resources among diverse actors with claims on pastoral commons (Brown, 2003). Conflicts between pastoralists and other land users under lower resources conditions can amplify tensions and conflicting views on, for instance, the need to protect or eliminate predatory animals (Dressel *et al.*, 2015) and the rising demand for extra-agricultural and livestock activities such as the touristic valorisation (Montrasio *et al.*, 2020). These situations may ultimately lead to enhancing the risk of more marginal highlands abandonment which is associated with shrubs invasions, loss of biodiversity and increasing wildfires (Komac *et al.*, 2013; Mantero *et al.*, 2020). Trends of mountain land abandonment, which started in Europe in the second half of the 20th century as a consequence of people displacement from rural areas to cities mainly for socio-economic reasons (Garcìa-Ruiz and Lana-Renault, 2011), will play a combined role with climate change forcing grasslands evolution and leading to a biodiversity decline. The strong interconnectivity between climate change and land abandonment impacts limits the possibility of estimating their mutual role as stressors. At the same time, it calls for further study for a salient and effective planning of regional policies on future land use trends in marginal and rural areas of the Mediterranean mountain regions (MedECC, 2020).

Patterns of intensification may also occur in the less marginal mountain areas with increased stocking rates, and, thus, higher risks of overgrazing, as a consequence of lower availability of suitable grazing areas or pasture productivity reduction. These indirect negative implications could be particularly marked in the highlands that are frequently held and managed in common (Caballero *et al.*, 2007; Baur and Binder, 2013). Livestock activities in mountain areas are threatened not only for the reduction of highland grasslands but also for expected lowering of forage productivity in lowland areas, from where farmers usually produce hay to supply animals requirements during winter (Caballero *et al.*, 2007). In the Swiss alpine areas, pipelines are in fact being built to transport water to farm units that regularly suffer from lack of water in summer to allow forage production for periods when grazing is not possible (Herzog and Seidl, 2018).

In the Mediterranean basin, the loss of grassland areas and the expected decrease in forage availability will cause severe changes in livestock activities and farm management. The increase of shrub invasions, which is also worsened by land abandonment trends, could lead to an under-exploitation of forage resources leading to an increase of fuel biomass, thus intensifying the wildfire risk during summer (Lovreglio *et al.*, 2014; Mantero *et al.*, 2020). Moreover, the increasing uncertainty on forage availability and quality could strongly affect the maintenance of the business as usual practices of the Mediterranean grassland-based farming systems (Porqueddu *et al.*, 2016). The dairy sheep and beef cattle livestock systems, which are sized based on autumn and spring pasture herbage availability, as well as hay spring production which guarantees to meet the nutritional livestock requirements during the last weeks of gestation in the late autumn, may need to drastically change farming practices to be still economically viable. Dono *et al.* (2016) estimated a net income reduction under climate change scenarios in Mediterranean dairy sheep farms up to –13% mainly related to increased costs of purchasing fodder to counterbalance the reduced fodder production in spring.

Knowledge gaps, open research questions and future perspectives

The scientific agreement and robustness emerging from this analysis is sufficient to answering the research demand on having a comprehensive insight on climate change impacts on the Italian grasslands, as well as it clearly highlights knowledge gaps, for which further studies are needed.

In the Alpine environment, medium or little agreement between studies on the impact of climate change on biodiversity maintenance, upward shift of some species, changes of plant functional traits and decrease of grassland biomass production and quality was highlighted by the analysis of the literature. However, few scientific evidences are available on the loss of grassland areas in the Italian Alps, and still uncertainties, even if at a lesser extent, were highlighted for the habitat suitability, biodiversity and floristic richness trends.

In the Apennines grassland systems, several knowledge gaps emerged on the impacts of climate change on plant functional traits, future habitats suitability and grasslands loss. Nevertheless, it is recognized that these agroecosystems have suffered from decades of both abandonment and intensification trends, which lead to a loss of extensive grasslands, independently on the climate change driver. Similar to the Alpine areas, the low agreement between studies about the upward and S-N slope shift of species and the quantity of forage production, suggests the need for further research insights.

A severe knowledge gap about climate change impacts on grassland biodiversity and vegetation emerged from the literature review on the Mediterranean biogeographic areas of Italy. Although grassland biodiversity, vegetation, and floristic richness are well investigated, *e.g.* across different gradients of land uses and management (Bagella *et al.*, 2014; Bagella *et al.*, 2016), insufficient research evidence was found on the implications of climate change on the grassland-related ecosystem services provision. The low agreement and weak evidences on grassland loss emerged especially from studies on forest vegetation dynamics. The impacts of climate change on grassland production have been adequately investigated, particularly regarding the quality of forage. Nevertheless, there is low agreement on the overall impacts of climate change on grassland productivity, in particular on the autumn production, and on changes of functional traits of pasture species.

Overall, this review highlighted that a comprehensive understanding about the grassland species responses to changes in climate in the Alpine, Apennine and Mediterranean areas of Italy is still required to predict changes in the grassland species distribution. This is particularly important for Mediterranean grasslands composition, for which insufficient knowledge is available so far. The reasons for contrasting research findings, could be related to several aspects such as the different methodologies used for the impact assessment (*e.g*. observational or manipulative studies; field experiments or simulation models; plot, field, farm or landscape scale of investigation), the different duration of the studies, the high variable nature of the measured traits and the complexity of the ecological, management, environmental interrelationships of the multispecies grassland systems that are highly site-specific.

The role of LTEs emerged as a strategic approach in improving the understanding of the long-term effects of climate change on grassland vegetation dynamics and biodiversity. This approach was extensively used in the Apennines and Alps, although in the latter case only few LTEs studies were located on the Italian side of Alps. The LTE approach on grasslands is rare in the Mediterranean bioclimatic zone and should be further implemented to build robust scientific knowledge on climate change impacts on grassland biodiversity and vegetation. Long term datasets derived from LTEs are also very useful for model calibration and for the improvement of model performances in simulating vegetation dynamics under future climate scenarios. On the other hand, although under mountain environments LTEs have provided strong scientific evidences on climate change impacts on vegetation, few studies were carried out in these areas to evaluate the impacts of climate change on forage production and quality, as well as on morphological, phenological and physiological traits of plant communities. Thus, future research activities on this topic should be developed by combining field experiments with modelling and remote sensing approaches, to evaluate the interaction between climatic and management scenarios. Most biophysical/biogeochemical simulation models of grassland systems ignore the dynamics of plant species composition (Van Oijen *et al*., 2018), and this leads to considerable uncertainty about the models' reliability to assess vegetation responses against abiotic stresses such as drought, temperature raise, *etc*. A promising field of research is therefore to implement biogeochemical models with modules able to modelling the plant assemblage composition dynamics in relation to climatic and management pressures (Confalonieri, 2014; Movedi *et al*., 2019).

Another open field of research is about the assessment of the response of the biomass and plant assemblage composition to direct and indirect CO_2 effects. The free-air carbon dioxide enrichment (FACE) experiments approach, for instance, has never been applied on Italian grassland species, with the exception of the SWISS FACE experiment (Van Kessel *et al*., 2000). The rise of CO_2 concentration can have effects on the plant-animal interactions in the grassland under grazing and/or on physical and chemical characteristics of plants and plant communities (Dumont *et al.*, 2015).

The development of climate change policies for grassland-based systems would require a more interdisciplinary research approach (Gibson and Newman, 2019). In fact, poorly managed grasslands due to farming abandonment are under threat as a consequence of fragmentation, habitat loss, land-use change, introduction of invasive species and endemic species loss. These impacts are possibly exacerbated by the effects of climate change. The strong interdependence between social and economic causes for land abandonment and the environmental factors, including climate change, is a priority for supporting the long-term sustainability of Italian grassland-based habitats and farming systems, and related human communities. The effectiveness of such integrated approaches has implications on how research programme topics are prioritized and how they tackle the apparent conflict between the need for long term experiments to address environmental and societal challenges related to long term grassland dynamics, and the administrative constraints associated to short-term funding of the current research programmes.

References

Aguilera E, Díaz-Gaona C, García-Laureano R, Reyes-Palomo C, Guzmán GI, Ortolani L, Sánchez-Rodríguez M, Rodríguez-Estévez V, 2020. Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. Agr. Syst. 181:102809.

Argenti G, Bottai L, Chiesi M, Maselli F, Staglianò N, Targetti S, 2011. Analisi e valutazione di pascoli montani attraverso l'integrazione di dati multispettrali e ausiliari. Riv. Ital. Telerilevam. 43:45-57.

Auer I, Böhm R, Jurkovic A, Orlik A, Potzmann R, Schöner W, Ungersböck M, Brunetti M, Nanni T, Maugeri M, Briffa K, Jones P, Efthymiadis D, Mestre O, Moisselin JM, Begert M, Brazdil R, Bochnicek O, Cegnar T, Gajic-Capka M, Zaninivic K, Majstorovic Z, Szalai S, Szentimrey T, 2005, A new instrumental precipitation dataset for the greater alpine region for the period 1800-2002. Int. J. Climatol. 25:139-66.

Auer I, Böhm R, Jurkovic A, Lipa W, Orlik A, Potzmann R, Schöner W, Ungersböck M, Matulla C, Briffa K, Jones PD, Efthymiadis D, Brunetti M, Nanni T, Maugeri M, Mercalli L, Mestre O, Moisselin J-M, Begert M, Müller-Westermeier G, Kveton V, Bochnicek O, Stastny P, Lapin M, Szalai S, Szentimrey T, Cegnar T, Dolinar M, Gajic-Capka M, Zaninovic K, Majstorovic Z, Nieplova E, 2007. HISTALP - Historical instrumental climatological surface time series of the Greater Alpine Region. Int. J. Climatol. 27:17-46.

Bagella S, Caria M, Farris E, Rossetti I, Filigheddu R, 2016. Traditional land uses enhanced plant biodiversity in a Mediterranean agro-silvo-pastoral system. Plant Biosyst. 150:201-07.

Bagella S, Filigheddu R, Caria MC, Girlanda M, Roggero PP, 2014. Contrasting land uses in Mediterranean agro-silvo-pastoral systems generated patchy diversity patterns of vascular plants and below-ground microorganisms. C. R. Biol. 337:717-24.

Bagella S, Salis L, Marrosu GM, Rossetti I, Fanni S, Caria MC, Roggero PP, 2013. Effects of long-term management practices on grassland plant assemblages in Mediterranean cork oak silvo-pastoral systems. Plant Ecol. 214:621-31.

Bagella S, Sitzia M, Roggero PP, 2017. Soil fertilization contributes to mitigating fire hazards associated to Cistus monspeliensis L. (rockrose) shrublands. Int. J. Wildland Fire 26:156-66.

Balzan MV, Hassoun AER, Aroua N, Baldy V, Bou Dagher M, Branquinho C, Dutay J-C, El Bour M, Médail F, Mojtahid M, Morán-Ordóñez A, Roggero PP, Rossi Heras S, Schatz B, Vogiatzakis IN, Zaimes GN, Ziveri P, 2020 Ecosystems. In: Cramer W, Guiot J, Marini K (Eds.), Climate and environmen-

tal change in the Mediterranean Basin - Current situation and risks for the future. First Mediterranean assessment report. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, p. 151. [In press].
Baur I, Binder CR, 2013. Adapting to socioeconomic developments by changing rules in the governance of common property pastures in the Swiss Alps. Ecol. Soc. 18.
Berauer BJ, Wilfahrt PA, Arfin-Khan MA, Eibes P, Von Heßberg A, Ingrisch J, Schloter M, Schuchardt MA, Jentsch A, 2019. Low resistance of montane and alpine grasslands to abrupt changes in temperature and precipitation regimes. Arct. Antarct. Alp. Res. 51:215-31.
Brogli R, Sørland SL, Kröner N, Schär C, 2019. Causes of future Mediterranean precipitation decline depend on the season. Environ. Res. Lett. 14:114017.
Brown KM, 2003. New challenges for old commons: the implications of rural change for crofting common grazings. in Proc. Proceedings from a workshop on "Commons: Old and New.", Centre for Avenced Study, Oslo, Norway.
Brugnara Y, 2020. Alpine climate change derived from instrumental measurements. Oxford Research Encyclopedia of Climate Science, Oxford, UK.
Brunetti M, Lentini G, Maugeri M, Nanni T, Auer I, Boehm R, Schoener W, 2009. Climate variability and change in the Greater Alpine Region over the last two centuries based on multi□variable analysis. Int. J. Climatol. 29: 2197-225.
Caballero R, Riseth JÅ, Labba N, Tyran E, Musial W, Molik E, Boltshauser A, Hofstetter P, Gueydon A, Roeder N, Hoffmann H, Moreira MB, Coelho IS, Brito O, Gil Á, 2007. Comparative typology in six European low□intensity systems of grassland management. Adv. Agron. 351-420.
Caloiero T, Coscarelli R, Ferrari E, 2018. Analysis of monthly rainfall trend in Calabria (Southern Italy) through the application of statistical and graphical techniques. Proceedings 2:629.
Cannone N, Diolaiuti G, Guglielmin M, Smiraglia C, 2008. Accelerating climate change impacts on alpine glacier forefield ecosystems in the European Alps. Ecol. Appl. 18:637-48.
Cannone N, Sgorbati S, Guglielmin M, 2007. Unexpected impacts of climate change on alpine vegetation. Front. Ecol. Environ. 5:360-64.
Carlson BZ, Corona MC, Dentant C, Bonet R, Thuiller W, Choler P, 2017. Observed long-term greening of alpine vegetation - a case study in the French Alps. Environ. Res. Lett. 12:114006.
Cavallero A, Aceto P, Gorlier A, Lombardi G, Lonati M, Martinasso B, Tagliatori C, 2007. I tipi pastorali delle Alpi piemontesi. Alberto Perdisa Editore, Bologna, Italy.
Chang J, Ciais P, Viovy N, Soussana JF, Klumpp K, Sultan B, 2017. Future productivity and phenology changes in European grasslands for different warming levels: implications for grassland management and carbon balance. Carbon Balance Manag. 12:11.
Chelli S, Canullo R, Campetella G, Schmitt AO, Bartha S, Cervellini M, Wellstein C, 2016. The response of sub-Mediterranean grasslands to rainfall variation is influenced by early season precipitation. Appl. Veg. Sci. 19:611-9.
Chelli S, Wellstein C, Campetella G, Canullo R, Tonin R, Zerbe S, Gerdol R, 2017. Climate change response of vegetation across climatic zones in Italy. Clim. Res. 71:249-62.
Chelli S, Wellstein C, Campetella G, Bartha S, Cervellini M, Canullo R, 2013. Effects of extreme weather events on Apennines grasslands productivity. pp 97-102 in Proc. of 5th Symposium for Research in Protected Areas, 10-12 June 2013, Mittersill, Austria.
Cherif S, Doblas-Miranda E, Lionello P, Borrego C, Giorgi F, Iglesias A, Jebari S, Mahmoudi E, Moriondo M, Pringault O, Rilov G, Somot S, Tsikliras A, Vila M, Zittis G, 2020 Drivers of change. In: Cramer W, Guiot J, Marini K (Eds.), Climate and environmental change in the Mediterranean Basin - Current situation and risks for the future. First Mediterranean assessment report. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, p. 128 pp. [In press].
Confalonieri R, 2014. CoSMo: A simple approach for reproducing plant community dynamics using a single instance of generic crop simulators. Ecol. Model. 286:1-10.
Corti S, Decesari S, Fierli F, Fuzzi S, Provenzale A, Sabbioni C, Santoleri R, Vitale V, 2009. Clima, cambiamenti climatici globali e loro impatto sul territorio nazionale. Quaderni dell'ISAC 1:978-88.
Cotto O, Wessely J, Georges, D, Klonner G, Schmid M, Dullinger S, Thuiller W, Guillaume F, 2017. A dynamic eco-evolutionary model predicts slow response of alpine plants to climate warming. Nat. Commun. 8:1-9.
Cramer W, Guiot J, Fader M, Garrabou J, Gattuso J-P, Iglesias A, Lange MA, Lionello P, Llasat MC, Paz S, Peñuelas J, Snoussi M, Toreti A, Tsimplis MN, Xoplaki E, 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. Nat. Clim. Change 8:972-80.
Dainese M, 2011. Impact of land use intensity and temperature on the reproductive performance of Dactylis glomerata populations in the southeastern Alps. Plant Ecol. 212:651-61.
De Boeck HJ, Bassin S, Verlinden M, Zeiter M, Hiltbrunner E, 2016. Simulated heat waves affected alpine grassland only in combination with drought. New Phytolo. 209:531-41.
Deléglise C, Meisser M, Mosimann E, Spiegelberger T, Signarbieux C, Jeangros B, Buttler A, 2015. Drought-induced shifts in plants traits, yields and nutritive value under realistic grazing and mowing managements in a mountain grassland. Agr. Ecosyst. Environ. 213:94-104.
Dellar M, Topp CFE, Banos G, Wall E, 2018. A meta-analysis on the effects of climate change on the yield and quality of European pastures. Agr. Ecosyst. Environ 265:413-20.
Descombes P, Vittoz P, Guisan A, Pellissier L, 2017. Uneven rate of plant turnover along elevation in grasslands. Alp. Bot. 127:53-63
Dibari C, Costafreda-Aumedes S, Argenti G, Bindi M, Carotenuto F, Moriondo M, Padovan G, Pardini A, Staglianò N, Vagnoli C., Brilli L, 2020. Expected changes to alpine pastures in extent and composition under future climate conditions. Agronomy 10:926.
Dibari C, Argenti G, Catolfi F, Moriondo M, Staglianò N, Bindi M, 2015. Pastoral suitability driven by future climate change along the Apennines. Ital. J. Agron. 10:109-16.
Dibari C, Argenti G, Moriondo M, Staglianò N, Targetti S, Bindi M, 2013. Climate change impacts on distribution and composition of the Alpine Natural Pasturelands. pp 578-86 in Implications on ecosystem services. Italian Society for Climate Sciences (SISC), Lecce, Italy.
Dono G, Cortignani R, Dell'Unto D, Deligios P, Doro L, Lacetera N, Mula L, Pasqui M, Quaresima S, Vitali A, Roggero PP, 2016. Winners and losers from climate change in agriculture: Insights from a case study in the Mediterranean basin. Agric. Syst. 147:65-75.
Dressel S, Sandström C, Ericsson G, 2015. A meta-analysis of studies on attitudes toward bears and wolves across Europe 1976-2012. Conserv. Biol. 29:565-574.
Dullinger S, Gattringer A, Thuiller W, Moser D, Zimmermann NE, Guisan A, Willner W, Plutzar C, Leitner M, Mang T, Caccianiga M, Dirnböck T, Ertl S, Fischer A, Lenoir J, Svenning JC, Psomas A, Schmatz DR, SilC U, Vittoz P, Hülber K, 2012. Extinction debt of high-mountain plants under twen-

ty-first-century climate change. Nat. Clim. Change 2:619-22.
Dukes JS, Chiariello NR, Cleland EE, Moore LA, Shaw MR, Thayer S, Tobeck T, Mooney HA, Field CB, 2005. Responses of grassland production to single and multiple global environmental changes (M. Loreau, Ed.). PLoS Biol. 3:e319.
Dumont B, Andueza D, Niderkorn V, Lüscher A, Porqueddu C, Picon-Cochard C, 2015. A meta-analysis of climate change effects on forage quality in grasslands: specificities of mountain and Mediterranean areas. Grass Forage Sci. 70:239-54.
Dumont B, Andueza D, Niderkorn V, Lüscher A, Porqueddu C, Picon-Cochard C, 2014. A meta-analysis of climate change effects on forage quality in grasslands: perspectives for mountain and Mediterranean areas. pp 49-65 in Joint meeting of the Mountain Pastures, Mediterranean Forage Resources (FAO-CIHEAM) and Mountain Cheese networks, 24-26 June, Clermont-Ferrand, France.
Elsen PR, Tingley MW, 2015. Global mountain topography and the fate of montane species under climate change. Nat. Clim. Change 5:772-76.
Engler R, Randin CF, Vittoz P, Czáka T, Beniston M, Zimmermann NE, Guisan A, 2009. Predicting future distributions of mountain plants under climate change: does dispersal capacity matter? Ecography 32:34-45.
Engler R, Randin CF, Thuiller W, Dullinger S, Zimmermann NE, Araújo MB, Pearman PB, Le Lay G, Piedallu C, Albert CH, Choler P, Coldea G, De Lamo X, Dirnböck T, Gégout JC, Gómez□García D, Grytnes JA, Heegaard E, Høistad F, Nogués□Bravo D, Normand S, Puşcaş M, Sebastià MT, Stanisci A, Theurillat JP, Trivedi MR, Vittoz P, Guisan A, 2011. 21st century climate change threatens mountain flora unequally across Europe. Glob. Chang. Biol. 17:2330-41.
Ergon Å, Seddaiu G, Korhonen P, Virkajärvi P, Bellocchi G, Jørgensen M, Østrem L, Reheul D, Volaire F, 2018. How can forage production in Nordic and Mediterranean Europe adapt to the challenges and opportunities arising from climate change? Eur. J. Agron. 92:97-106.
Evangelista A, Frate L, Carranza ML, Attorre F, Pelino G, Stanisci A, 2016a. Changes in composition, ecology and structure of high-mountain vegetation: a re-visitation study over 42 years. AoB Plants. 8.
Evangelista A, Frate L, Stinca A, Carranza ML, Stanisci A, 2016b. VIOLA-the vegetation database of the central Apennines: structure, current status and usefulness for monitoring Annex I EU habitats (92/43/EEC). Plant Sociol. 53:47-58.
Ferrarini A, Alatalo JM, Gervasoni D, Foggi B, 2017. Exploring the compass of potential changes induced by climate warming in plant communities. Ecol. Complex. 29:1-9.
Field CB, Jackson RB, Mooney HA (1995) Stomatal responses to increased CO2: implications from the plant to the global scale. Plant Cell Environ. 18:1214-25.
Filippa G, Cremonese E, Galvagno M, Isabellon M, Bayle A, Choler P, Carlson BZ, Gabellani S, Morra di Cella U, Migliavacca M, 2019. Climatic drivers of greening trends in the Alps. Remote Sens. 11:2527.
Frate L, Carranza ML, Evangelista A, Stinca A, Schaminée JH, Stanisci A, 2018. Climate and land use change impacts on Mediterranean high-mountain vegetation in the Apennines since the 1950s. Plant Ecol. Divers. 11:85-96.
García-Ruiz, J. M., & Lana-Renault, N. (2011). Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region-A review. Agric. Ecosyst. Environ. 140:317-38.
Gargano D, Aiello S, Abeli T, Schettino A, Bernardo L, 2017. Monitoring biodiversity patterns in three Mediterranean mountain pastures in the Pollino National Park (S-Italy). Plant Sociol. 54:51-9.
Gauly M, Bollwein H, Breves G, Brugemann K, Danicke S, Das G, Demeler J, Hansen H, Isselstein J, Konig S, Loholter M, Martinsohn M, Meyer U, Potthoff M, Sanker C, Schroder B, Wrage N, Meibaum B, von Samson-Himmelstjerna G, Stinshoff H, Wrenzycki C, 2013. Future consequences and challenges for dairy cow production systems arising from climate change in Central Europe - a review. Animal 7:843-59.
Gavazov K, Peringer A, Gillet F, Buttler A, Spiegelberger T, 2013. Dynamics of forage production in pasture-woodlands of the Swiss Jura Mountains under projected climate change scenarios. Ecol. Soc. 18:38.
Gibson DJ, Newman JA, 2019. Grasslands and climate change. Cambridge University Press, Cambridge, UK.
Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, Stoel M, 2014. 21st century climate change in the European Alps - A review. Sci. Total Environ. 493:1138-51.
Gottfried M, Pauli H, Futschik A, Akhalkatsi M, Barančok P, Benito Alonso JL, Coldea G, Dick J, Erschbamer B, Fernández Calzado MaR, Kazakis G, Krajči J, Larsson P, Mallaun M, Michelsen O, Moiseev D, Moiseev P, Molau U, Merzouki A, Nagy L, Nakhutsrishvili G, Pedersen B, Pelino G, Puscas M, Rossi G, Stanisci A, Theurillat J-P, Tomaselli M, Villar L, Vittoz P, Vogiatzakis I, Grabherr G, 2012. Continent-wide response of mountain vegetation to climate change. Nat. Clim. Change 2:111-15.
Gottfried M, Pauli H, Reiter K, Grabherr G, 1999. A fine scaled predictive model for changes in species distribution patterns of high mountain plants induced by climate warming. Divers. Distrib. 5:241-51.
Graux AI, Bellocchi G, Lardy R, Soussana J-F, 2013. Ensemble modelling of climate change risks and opportunities for managed grasslands in France. Agr. Forest Meteorol. 170:114-31.
Gritsch A, Dirnböck T, Dullinger S, 2016. Recent changes in alpine vegetation differ among plant communities. J. Veg. Sci. 27:1177-86.
Herzog F, Seidl I, 2018. Swiss alpine summer farming: current status and future development under climate change. Rangeland J. 40.
Iglesias E, Báez K, Diaz-Ambrona CH, 2016. Assessing drought risk in Mediterranean Dehesa grazing lands. Agr. Syst. 149:65-74.
IPCC, 2014. Climate Change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. In: V.R. Barros, Field C.B., Dokken D.J., Mastrandrea M.D., Mach K.J., Bilir T.E., Chatterjee M., K.L. Ebi, Estrada Y.O., Genova R.C., Girma B., Kissel E.S., Levy A.N., MacCracken S., Mastrandrea P.R., White L.L. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.
Jarzyna MA, Zuckerberg B, Finley AO, Porter WF, 2016. Synergistic effects of climate and land cover: grassland birds are more vulnerable to climate change. Landscape Ecol. 31:2275-90.
Karamesouti M, Petropoulos GP, Papanikolaou ID, Kairis O, Kosmas K, 2016. Erosion rate predictions from PESERA and RUSLE at a Mediterranean site before and after a wildfire: comparison & implications. Geoderma 261:44-58.
Kipling RP, Bannink A, Bellocchi G, Dalgaard T, Fox NJ, Hutchings NJ, Kjeldsen C, Lacetera N, Sinabell F, Topp CFE, van Oijen M, Virkajärvi P, Scollan ND, 2016. Modeling European ruminant production systems: Facing the challenges of climate change. Agr. Syst. 147:24-37.
Komac B, Kefi S, Nuche P, Escos J, Alados CL, 2013. Modeling shrub encroachment in subalpine grasslands under different

environmental and management scenarios. J. Environ. Manage. 121:160-9.
Lasanta T, Arnáez J, Pascual N, Ruiz-Flaño P, Errea MP, Lana-Renault N, 2017. Space-time process and drivers of land abandonment in Europe. Catena 149:810-23.
Lee M, Manning P, Rist J, Power SA, Marsh C, 2010. A global comparison of grassland biomass responses to CO 2 and nitrogen enrichment. Phil. Trans. R. Soc. B 365:2047-56.
Leingärtner A, Hoiss B, Krauss J, Steffan-Dewenter I, 2014. Combined effects of extreme climatic events and elevation on nutritional quality and herbivory of alpine plants. PLoS One. 9:e93881.
Li W, Li X, Zhao Y, Zheng S, Bai Y, 2018. Ecosystem structure, functioning and stability under climate change and grazing in grasslands: current status and future prospects. Curr. Opin. Env. Sust. 33:124-35.
Liberati L, Messerli S, Matteodo M, Vittoz P, 2019. Contrasting impacts of climate change on the vegetation of windy ridges and snowbeds in the Swiss Alps. Alp. Bot. 129:95-105.
Lionello P, Abrantes F, Gacic M, Planton S, Trigo R, Ulbrich U, 2014. The climate of the Mediterranean region: research progress and climate change impacts. Reg. Environ. Change 14:1679-84.
Liechti K, Biber JP, 2016. Pastoralism in Europe: characteristics and challenges of highland-lowland transhumance. Rev. Sci. Tech. 35:561-575.
Lionello P, Scarascia L, 2018. The relation between climate change in the Mediterranean region and global warming. Reg. Environ. Change 18:1481-93.
Longobardi A, Buttafuoco G, Caloiero T, Coscarelli R, 2016. Spatial and temporal distribution of precipitation in a Mediterranean area (southern Italy). Environ. Earth Sci. 75:189.
Lozano OM, Salis M, Ager AA, Arca B, Alcasena FJ, Monteiro AT, Finney MA, Del Giudice L, Scoccimarro E, Spano D, 2017. Assessing climate change impacts on wildfire exposure in Mediterranean areas. Risk Anal. 37:1898-916.
Mairota P, Leronni V, Xi W, Mladenoff DJ, Nagendra H, 2014. Using spatial simulations of habitat modification for adaptive management of protected areas: Mediterranean grassland modification by woody plant encroachment. Environ. Conserv. 41:144-56.
Malek Ž, Verburg P, 2017. Mediterranean land systems: representing diversity and intensity of complex land systems in a dynamic region. Landsc. Urban Plan. 165:102-16.
Mantero G, Morresi D, Marzano R, Motta R, Mladenoff DJ, Garbarino M, 2020. The influence of land abandonment on forest disturbance regimes: a global review. Landscape Ecol. 35:2723-2744.
Mastrotheodoros T, Pappas C, Molnar P, Burlando P, Manoli G, Parajka J, Rigon R, Szeles B, Bottazzi M, Hadjidoukas P, Fatichi S, 2020. More green and less blue water in the Alps during warmer summers. Nat. Clim. Chang. 10:155-61.
Matteodo M, Wipf S, Stöckli V, Rixen C, Vittoz P. 2013. Elevation gradient of successful plant traits for colonizing alpine summits under climate change. Environ. Res. Lett. 8:024043.
MedECC; Cramer W, Guiot J, Marini K (Eds.), 2020. Climate and environmental change in the Mediterranean Basin - Current situation and risks for the future. First Mediterranean assessment report. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632 pp. [In press].
Medri S, Venturini S, Castellari S, 2013. Overview of key climate change impacts, vulnerabilities and adaptation action in Italy. CMCC Research Paper No. 178.
Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW, 2005. A climatic stratification of the environment of Europe. Global Ecol. Biogeogr. 14:549-63.
Montrasio R, Mattiello S, Zucaro M, Genovese D, Battaglini L, 2020. The perception of ecosystem services of mountain farming and of a local cheese: an analysis for the touristic valorization of an Inner Alpine Area. Sustainability 12.
Morgan JA, Pataki DE, Körner C, Clark H, Del Grosso SJ, Grünzweig JM, Knapp AK, Mosier AR, Newton PCD, Niklaus PA, Nippert JB, Nowak RS, Parton WJ, Polley HW, Shaw MR, 2004. Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO_2. Oecologia 140:11-25.
Mottet A, Ladet S, Coqué N, Gibon A, 2006. Agricultural land-use change and its drivers in mountain landscapes: A case study in the Pyrenees. Agric. Ecosyst. Environ. 114:296-310.
Movedi E, Bellocchi G, Argenti G, Paleari L, Vesely F, Staglianò N, Dibari C, Confalonieri R, 2019. Development of generic crop models for simulation of multi-species plant communities in mown grasslands. Ecol. Model. 401:111-28.
Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts RA, Carrao H, Spinoni J, Vogt J, Feyen L, 2018. Global changes in drought conditions under different levels of warming. Geophys. Res. Lett. 45:3285-96.
Niklaus PA, Körner Ch, 2004. Synthesis of a six-year study of calcareous grassland responses to in situ CO_2 enrichment. Ecol. Monogr. 74:491-511.
Orlandi S, Probo M, Sitzia T, Trentanovi G, Garbarino M, Lombardi G, Lonati M, 2016. Environmental and land use determinants of grassland patch diversity in the western and eastern Alps under agro-pastoral abandonment. Biodivers. Conserv. 25:275-93.
Pellissier L, Descombes P, Hagen O, Chalmandrier L, Glauser G, Kergunteuil A, Defossez E, Rasmann S, 2018. Growth-competition-herbivore resistance trade-offs and the responses of alpine plant communities to climate change. Funct. Ecol. 32:1693-703.
Petitpierre B, McDougall K, Seipel T, Broennimann O, Guisan A, Kueffer C, 2016. Will climate change increase the risk of plant invasions into mountains? Ecol. Appl. 26:530-44.
Petriccione B, Bricca A, 2019. Thirty years of ecological research at the Gran Sasso d'Italia LTER site: climate change in action. Nature Conserv. 34:9-39.
Porqueddu C, Ates S, Louhaichi M, Kyriazopoulos AP, Moreno G, del Pozo A, Ovalle C, Ewing MA, Nichols PGH, 2016. Grasslands in 'Old World' and 'New World' Mediterranean-climate zones: past trends, current status and future research priorities. Grass Forage Sci. 71:1-35.
Porro F, Tomaselli M, Abeli T, Gandini M, Gualmini M, Orsenigo S, Petraglia A, Rossi G, Carbognani M, 2019. Could plant diversity metrics explain climate-driven vegetation changes on mountain summits of the GLORIA network? Biodivers. Conserv. 28:3575-96.
Probo M, Pittarello M, Lonati M, Lombardi G, 2016. Targeted grazing for the restoration of sub-alpine shrub-encroached grasslands. Ital. J. Agron. 11:268-72.
Pulina A, Lai R, Salis L, Seddaiu G, Roggero PP, Bellocchi G, 2018. Modelling pasture production and soil temperature, water and carbon fluxes in Mediterranean grassland systems with the Pasture Simulation model. Grass Forage Sci. 73:272-83.
Pulina A, Mula L, Seddaiu G, Roggero PP, 2017. Modelling autumn production of Mediterranean pastures under variable rainfall regimes. pp 211-13 in Atti del XX Convegno AIAM e XLVI Convegno SIA, Milano, Italy.
Rodriguez-Ramirez N, Santonja M, Baldy V, Ballini C, Montès N, Michalet R, 2017. Shrub species richness decreases negative impacts of drought in a Mediterranean ecosystem. J. Veg. Sci.

28:985-96.
Rogora M, Frate L, Carranza ML, Freppaz M, Stanisci A, Bertani I, Bottarin R, Brambilla A, Canullo R, Carbognani M, Cerrato C, Chelli S, Cremonese E, Cutini M, Di Musciano M, Erschbamer B, Godone D, Iocchi M, Isabellon M, Magnani A, Mazzola L, Morra di Cella U, Pauli H, Petey M, Petriccione B, Porro F, Psenner R, Rossetti G, Scotti A, Sommaruga R, Tappeiner U, Theurillat JP, Tomaselli M, Viglietti D, Viterbi R, Vittoz P, Winkler M, Matteucci G, 2018. Assessment of climate change effects on mountain ecosystems through a cross-site analysis in the Alps and Apennines. Sci. Total Environ. 624:1429-42.
Rolo V, Moreno G, 2019. Shrub encroachment and climate change increase the exposure to drought of Mediterranean wood-pastures. Sci. Total Environ. 660:550-58.
Scherrer D, Körner C, 2011. Topographically controlled thermal□habitat differentiation buffers alpine plant diversity against climate warming. J. Biogeogr. 38:406-16.
Schirpke U, Kohler M, Leitinger G, Fontana V, Tasser E, Tappeiner U, 2017. Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their resilience. Ecosyst. Serv. 26:79-94.
Schmid S, 2017. Impacts of climate change on alpine grassland ecosystems: responses in structure and function. PhD Thesis, ETH Zurich, Switzerland.
Schmidli J, Frei C, 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. Int. J. Climatol. 25:753-71.
Schwager P, Berg C, 2019. Global warming threatens conservation status of alpine EU habitat types in the European Eastern Alps. Reg. Environ. Change 19:2411-21.
Scocco, P, Piermarteri, K, Malfatti, A, Tardella, F M, Catorci, A, 2016a. Effects of summer rainfall variations on sheep body state and farming sustainability in sub-Mediterranean pastoral systems. Span. J. Agric. Res. 14:e03SC02.
Scocco P, Piermarteri K, Malfatti A, Tardella FM, Catorci A, 2016b. Increase of drought stress negatively affects the sustainability of extensive sheep farming in sub-Mediterranean climate. J. Arid. Environ. 128:50-8.
Seddaiu G, Bagella S, Pulina A, Cappai C, Salis L, Rossetti I, Lai R, Roggero PP, 2018. Mediterranean cork oak wooded grasslands: synergies and trade-offs between plant diversity, pasture production and soil carbon. Agroforest. Syst. 92:893-908.
Soncini A, Bocchiola D, 2011. Assessment of future snowfall regimes within the Italian Alps using general circulation models. Cold Reg. Sci. Technol. 68:113-23.
Soussana JF, Graux AI, Tubiello FN, 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. J. Exp. Bot. 61:2217-28.
Stanisci A, Frate L, Morra di Cella U, Pelino G, Petey M, Siniscalco C, Carranza ML, 2014. Short-term signals of climate change in Italian summit vegetation: observations at two GLORIA sites. Plant Biosyst. 150:227-35.
Subedi R, Taupe N, Pelissetti S, Petruzzelli L, Bertora C, Leahy JJ, Grignani C, 2016. Greenhouse gas emissions and soil properties following amendment with manure-derived biochars: Influence of pyrolysis temperature and feedstock type. J. Environ. Manage. 166:73-83.
Sundseth K, 2010. Natura 2000 - Nella regione Alpina. EC, Environment DG, Luxembourg.
Tardella FM, Piermarteri K, Malatesta L, Catorci A, 2016. Environmental gradients and grassland trait variation: insight into the effects of climate change. Acta Oecol. 76:47-60.
Targetti S, Messeri A, Staglianò N, Argenti G, 2013. Leaf functional traits for the assessment of succession following management in semi-natural grasslands: a case study in the North Apennines, Italy. Appl. Veg. Sci. 16:325-32.
Targetti S, Staglianò N, Messeri A, Argenti G, 2010. A state-and-transition approach to alpine grasslands under abandonment. iForest 3:44-51.
Tasser E, Leitinger G, Tappeiner U, 2017. Climate change *versus* land-use change - What affects the mountain landscapes more? Land Use Policy 60:60-72.
Tomozeiu R, Pasqui M, Quaresima S, 2018. Future changes of air temperature over Italian agricultural areas: a statistical downscaling technique applied to 2021-2050 and 2071-2100 periods. Meteorol. Atmos. Phys. 130:543-63.
Toreti A, Desiato F, 2008. Temperature trend over Italy from 1961 to 2004. Theor. Appl. Climatol. 91:51-8.
Trnka M, Bartošová L, Schaumberger A, Ruget F, Eitzinger J, Formayer H, Seguin B, Olesen JE, 2011. Climate change and impact on European grasslands. pp 39-51 in Proc. 16th Symposium of the European Grassland Federation, Gumpenstein, Austria.
Unterluggauer P, Mallaun M, Erschbamer B, 2016.The higher the summit, the higher the diversity changes-results of a long-term monitoring project in the Dolomites. Gredleriana 16:5-34.
Van Kessel C, Nitschelm J, Horwath W, Harris D, Walley F, Lüscher A, Hartwig U, 2000. Carbon-13 input and turnover in a pasture soil exposed to long term elevated atmospheric pCO2. Glob. Chang. Biol. 6:123-35.
Van Oijen M, Zoltán Barcza Z, Confalonieri R, Korhonen P, Kröel-Dulay G, Lellei-Kovács E, Louarn G, Louault F, Martin R, Moulin T, Movedi E, Picon-Cochard C, Rolinski S, Viovy N, Björn Wirth S, Bellocchi G, 2020. Incorporating biodiversity into biogeochemistry models to improve prediction of ecosystem services in temperate grasslands: review and roadmap. Agronomy 10:259.
Veysset P, Bebin D, Lherm M, 2005. Adaptation to Agenda 2000 (CAP reform) and optimisation of the farming system of French suckler cattle farms in the Charolais area: a model-based study. Agr. Syst. 83:179-202.
Wellstein C, Poschlod P, Gohlke A, Chelli S, Campetella G, Rosbakh S, Canullo R, Kreyling J, Jentsch A, Beierkuhnlein C, 2017. Effects of extreme drought on specific leaf area of grassland species: A meta-analysis of experimental studies in temperate and sub-Mediterranean systems. Glob. Chang. Biol. 23:2473-81.
Zampieri M, Russo S, Di Sabatino S, Michetti M, Scoccimarro E, Gualdi S, 2016. Global assessment of heat wave magnitudes from 1901 to 2010 and implications for the river discharge of the Alps. Sci. Total Environ. 571:1330-39.
Zavaleta ES, Shaw MR, Chiariello NR, Mooney HA, Field CB, 2003. Additive effects of simulated climate changes, elevated CO_2, and nitrogen deposition on grassland diversity. Proc. Natl Acad. Sci. 100:7650-4.
Zhang R, Corte-Real J, Moreira M, Kilsby C, Burton A, Fowler HJ, Blenkinsop S, Birkinshaw S, Forsythe N, Nunes JP, Sampaio E, 2019. Downscaling climate change of mean climatology and extremes of precipitation and temperature: Application to a Mediterranean climate basin. Int. J. Climatol. 39:4985-5005.
Zhu J, Zhang Y, Yang X, Chen N, Jiang L, 2020. Synergistic effects of nitrogen and CO 2 enrichment on alpine grassland biomass and community structure. New Phytol. 228:1283-94.