Catena 237 (2024) 107802

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Climate change is threatening mountain grasslands and their cultural ecosystem services

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ARTICLE INFO

Keywords:
Mountain grassland
Soil erosion
Drought
Nature-based solutions
Climate change

ABSTRACT

Mountain grasslands are widespread ecosystems worldwide that provide economic and cultural ecosystem services. They serve as a source of food, carbon sequestration, clean water, and habitat, also hosting traditional practices such as transhumance. However, they are facing growing threats due to climate change, including extreme weather events like intensified rainfall causing soil erosion and prolonged droughts alongside high temperatures, impacting vegetation health and water resource management. Despite their strategic importance, there remains a gap in the comprehensive global mapping of these ecosystems and an exhaustive exploration of the critical challenges posed by climate change. In this context, we present an unprecedented satellite-based global mapping of mountain grasslands and conduct an analysis focusing on key climate change-related concerns. This includes an assessment of (1) soil erosion by water under diverse climate scenarios (RUSLE; 2015 vs. 2070-RCP8.5) and (2) the dynamics of extreme drought and high-temperature events (utilizing the Vegetation Health Index; VHI), with a specific focus on European mountain grasslands during the summer of 2022. Our findings indicate a potential future global aggravation of soil erosion in mountain grasslands (+2.3%), particularly in South America (+19.4%) and Africa (+10.0%), as well as localized hotspots. Furthermore, our analysis of the 2022 situation in Europe demonstrates the extensive impact of similar extreme events across a significant portion of grassland areas at a continental scale, with notable hotspots observed in southern Europe. Finally, we explore strategies to enhance mountain grassland management, specifically focusing on nature-based solutions (NbS) aimed at preserving their invaluable cultural ecosystem services in the face of climate change.

1. Introduction

Mountain grasslands are grassy expanses dominated by herbaceous species and non-woody plants at high elevations (Schirpke et al., 2017). They are important areas for mowing and livestock grazing, playing a crucial role in supporting local livelihoods (Montenegro-Díaz et al., 2022). In previous times, the primary focus of managing mountain grasslands revolved around providing forage. In contemporary understanding, there is a growing recognition of their significance in terms of regulating ecosystems and providing ecosystem services (Grigulis et al., 2013; Lamarque et al., 2011). They serve as habitats for a diverse array of plant and animal species, supporting biodiversity and preserving ecological balance (Wilson et al., 2012). They also act as carbon sinks, helping to mitigate climate change by sequestering carbon dioxide from the atmosphere (Ru et al., 2022; Smith, 2014). They contribute to water regulation, ensuring a stable water supply for downstream communities and reducing the risk of floods (Egoh et al., 2008; Zhao et al., 2017). Additionally, they play a crucial role in maintaining the biogeochemical cycles of biomass (Rumpel et al., 2015). In recent decades, there has been a growing recognition of the cultural ecosystem services they provide, including aesthetic appeal and recreational value (Bürgi et al., 2015). For this reason, UNESCO listed mountain grasslands sites for their distinctive landscapes and historical people-nature connections, such as “Pyrénées - Mont Perdu” site (France and Spain) or the “Qinghai Hoh Xil” site (Qinghai-Tibetan Plateau; China). An emblematic cultural practice of mountain grassland is transhumance, where herds are

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https://doi.org/10.1016/j.catena.2023.107802
Received 19 September 2023; Received in revised form 16 December 2023; Accepted 31 December 2023
Available online 11 January 2024
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relocated to different grazing areas at varying altitudes, taking advantage of seasonal cycles (Liechti and Bieber, 2016). In addition to providing food and related products, it offers a range of social benefits such as cultural diversity and a strong sense of regional identity among people (Nori and Gemini, 2011).

Mountain grasslands are increasingly facing degradation due to a range of factors. Climate change, especially weather extremes (Dong et al., 2022; Easterling et al., 2000), and unsustainable practices such as overgrazing (Torresani et al., 2019), are primary drivers of land degradation (Montenegro-Díaz et al., 2022). The abandonment of farmland can lead to an increase in negative environmental effects, such as a higher risk of wildfires, landscape homogenization, and a reduction in biodiversity over the medium and long term, also deeply affecting soil physico-chemical properties (Lasanta et al., 2015; Nadal-Romero et al., 2023). Altered climatic conditions can result in shifts in vegetation distribution, modifying the composition and structure of grassland communities (Dong et al., 2022; Easterling et al., 2000; Jentsch and Beierkuhnlein, 2008; Liu et al., 2014). Additionally, these changes can lead to alterations in water availability, plant growth, nutrient cycling, and overall productivity, including impairments in the rate of nitrogen mineralization in the soil (Bell et al., 2005; Piao et al., 2009; Wilcox et al., 2017).

An increase in the frequency of extreme rainfall events is one of the most concerning consequences of climate change for mountain grasslands. This can lead to higher rainfall erosivity (Gayen et al., 2020), posing these landscapes at risk of soil erosion (Turnbull et al., 2009). This is documented in several studies, for instance in Central Asia (Wiesmair et al., 2016), China (Liu et al., 2008) and Europe (Durán et al., 2020). Intense precipitation events could also trigger surface landslides (Zweifel et al., 2021). A primary reason is the low tensile strength of the root system (Löbmann et al., 2020). Nevertheless, plant diversity, vegetation composition, and the frequency of key species play a significant role in influencing such forces, either exacerbating or mitigating the issue (Krautzer et al., 2011). Drought is another significant issue linked to climate change, and 2022 stands out as a notable example, marked by numerous hotspots worldwide. Europe faced one of the most severe events in 500 years, exacerbated by heatwaves (Toreti et al., 2022). This led to devastating wildfires, reduced river levels with saltwater intrusion in some deltas, and significant challenges for the environment and human sectors due to water shortages, especially agriculture (ECMWF, 2022; Hall et al., 2022). Mountain grasslands were also exposed to such extreme event. This is a worrying fact, especially since similar occurrences are only at beginning due to climate change (Bonaldo et al., 2023; Corona Lozada et al., 2019). Prolonged water scarcity can lead to significant alterations in soil moisture, thereby affecting the microbial community structure, reducing extracellular enzyme activity, and decreasing litter decomposition rates, resulting in changes in soil nutrient cycling (Wang et al., 2014). Moreover, drought can severely affect plant productivity, altering biomass and impacting livestock, as observed for example in China (Zhou et al., 2018) and the USA (Carroll et al., 2021). The climate change-related risk to mountain grasslands extends beyond ecosystem damages, impacting the cultural ecosystem services they provide. It is therefore strategic to assess the extent of these ecosystems globally and investigate critical degradation factors driven by opposing climate change-related processes. Therefore, the primary objective of this study was to generate an unprecedented global map of mountain grasslands using high-resolution remote sensing satellite data. Moreover, the research aimed to explore two critical phenomena impacting these ecosystems: soil erosion and extreme drought events. The first analysis was based on data provided by Borrelli et al. (2020) covering the current conditions (baseline; 2015) and future projections (2070; RCP8.5 scenario) at a global scale using the Revised Universal Soil Loss Equation (RUSLE). Then, the study focused on evaluating drought severity in European mountain grasslands during the extreme drought and high-temperature event of summer 2022, utilizing the Vegetation Health Index (VHI). Understanding these risks holds significant value in developing measures such as nature-based solutions (NbS) to safeguard the cultural ecosystem services provided by mountain landscapes.

2. Material and methods

2.1. Mapping global mountain grasslands

The first goal of the paper was to provide a map of mountain grasslands worldwide. Mapping grasslands has been a topic of debate for decades due to their wide distribution, diverse types, and dynamic nature influenced by natural factors and human activities (Hobbs et al., 2007; Latham et al., 2014). However, remote sensing technology for Earth Observation (EO) has made significant advancements in understanding the land covers, successfully tackling challenges related to dynamic biomes and large-scale analyses, even if with some inherent limitations (Ali et al., 2016). In this research, we employed the Google Earth Engine platform to address the issue of handling extensive datasets. Land cover data were collected from the Copernicus Global Land Service (CGLS) product called “Dynamic Land Cover map (CGLS-LC100)”. It stands as one of the most accurate global land cover datasets, presenting 100-meter resolution geospatial information that includes discrete land cover classes and continuous layers for vegetation/ground cover (Tsendbazar et al., 2021). Data were collected from 2015 to 2019 and are derived from the PROBA-V 100 m time-series, a high-quality repository of land cover training sites and ancillary datasets. This iteration demonstrates an accuracy level of 80% at Level 1 throughout all included years (Buchhorn et al., 2020). From this dataset, we firstly selected the class “Herbaceous vegetation”, which contains areas dominated by herbaceous species, with less than 10% of tree and shrub cover, and without a defined forest structure, aligning with the grassland definition proposed by Dixon et al. (2014). Next, this data was filtered for only those areas located at an elevation above 600 m, a threshold commonly used to define mountainous landscapes (such as Körner et al. (2017)). The topographic data used for this operation was obtained from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), a U.S. Geological Survey dataset with a resolution of 7.5 arc-seconds. The distribution of mountain grasslands was investigated across various continents (data based on ESRI ArcGIS HUB; World Continents; https://hub.arcgis.com/datasets/esri::world-continents/exploreis). We finally evaluated the accuracy of the mountain grasslands map using Copernicus’ classification quality index, a validation measure utilized for assessing the accuracy of the CGLS dataset. This process entailed comparing more than 20,000 classified points against an independent reference dataset (Buchhorn et al., 2020). Higher index values indicate greater confidence in the accuracy of pixel classification.

2.2. Global pattern of soil erosion in mountain grasslands under climate change

We applied the RUSLE to assess the potential soil loss by water of mountain grasslands worldwide. We integrated the localization of global grasslands (see section 2.1) with erosion data published by Borrelli et al., (2020). While accompanied by a degree of uncertainty, these data offer quantification of annual water erosion (expressed ad Mg/ha/yr) for approximately 96% of the Earth’s surface in an open-access format. Additionally, they provide insights into the current erosion status (baseline: 2015) and projected erosion rates for the future (2070) under various climate scenarios (RCP2.6, RCP2.4, and RCP8.5) and socio-economic scenarios (SSP1, SSP2, SSP5), adhering to the Intergovernmental Panel on Climate Change (IPCC) guidelines. We investigated the influence of climate change on soil erosion in global mountain grasslands with a specific focus on the most critical climate scenario (RCP8.5). To specifically emphasize the role of climate in the analysis, land use conditions were maintained unchanged. The quantification process involved two stages. First, we intersected the mountain grasslands mosaic with the potential erosion of 2015 to describe the current erosion rates; second, the same positions were cross-referenced with projected soil erosion for 2070. The comparison in percentage terms was made by taking advantage of the computational capability of Google Earth Engine, comparing the total erosion estimations for mountain grasslands in 2015 and 2070 globally, and for each continent.

2.3. The extreme drought of 2022 on European mountain grasslands

Mapping drought severity on mountain grasslands during extreme events and identify hotspots are vital for understanding potential ecological impacts, aiding in crop health assessment, yield loss anticipation, and promote water management strategies. This research concentrates on the extreme drought that affected European mountain grasslands during the extreme event of summer 2022, particularly during July, marked by low precipitation and high temperatures. We employed the VHI exploiting MODIS satellite data in Google Earth Engine, following Straffelini and Tarolli (2023). It is a well-established index for investigating agricultural drought recommended by the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER). It measures the severity of drought and high temperature on vegetation by combining two factors. The first is the Normalized Different Vegetation Index (NDVI) anomaly of the month of observation compared to a long-term average; the second is the land surface temperature anomaly (LST), again compared to the long-term average (in both cases about 20 years, according to MODIS availability). The index has already been successfully tested in extensive grassland regions in Mongolia (Chang et al., 2017), where authors have identified it as the most effective one among a set of nine indices for evaluating drought impacts in grassland environments.

3. Results and discussion

3.1. Global distribution of mountain grasslands

Fig. 1a presents the global map of mountain grasslands developed by implementing satellite-based data on land cover and elevation, while Fig. 1b their spatial distribution across the different continents. Results show that over half of the entire mountain grasslands are concentrated in Asia (53.9%), spanning from Central Asia to China, Mongolia, and northward into Russia. Following, North America ranks second in terms of mountain grasslands coverage (20.8%), primarily concentrated in the western regions. In Africa (12.9%), mountain grasslands are predominantly found in the central and southern regions, with a significant presence in South Africa. In South America (7.4%), they are mainly located along the Andes Mountain range, but also in the eastern countries, particularly in Brazil. In Europe (3.6%), the highest concentration

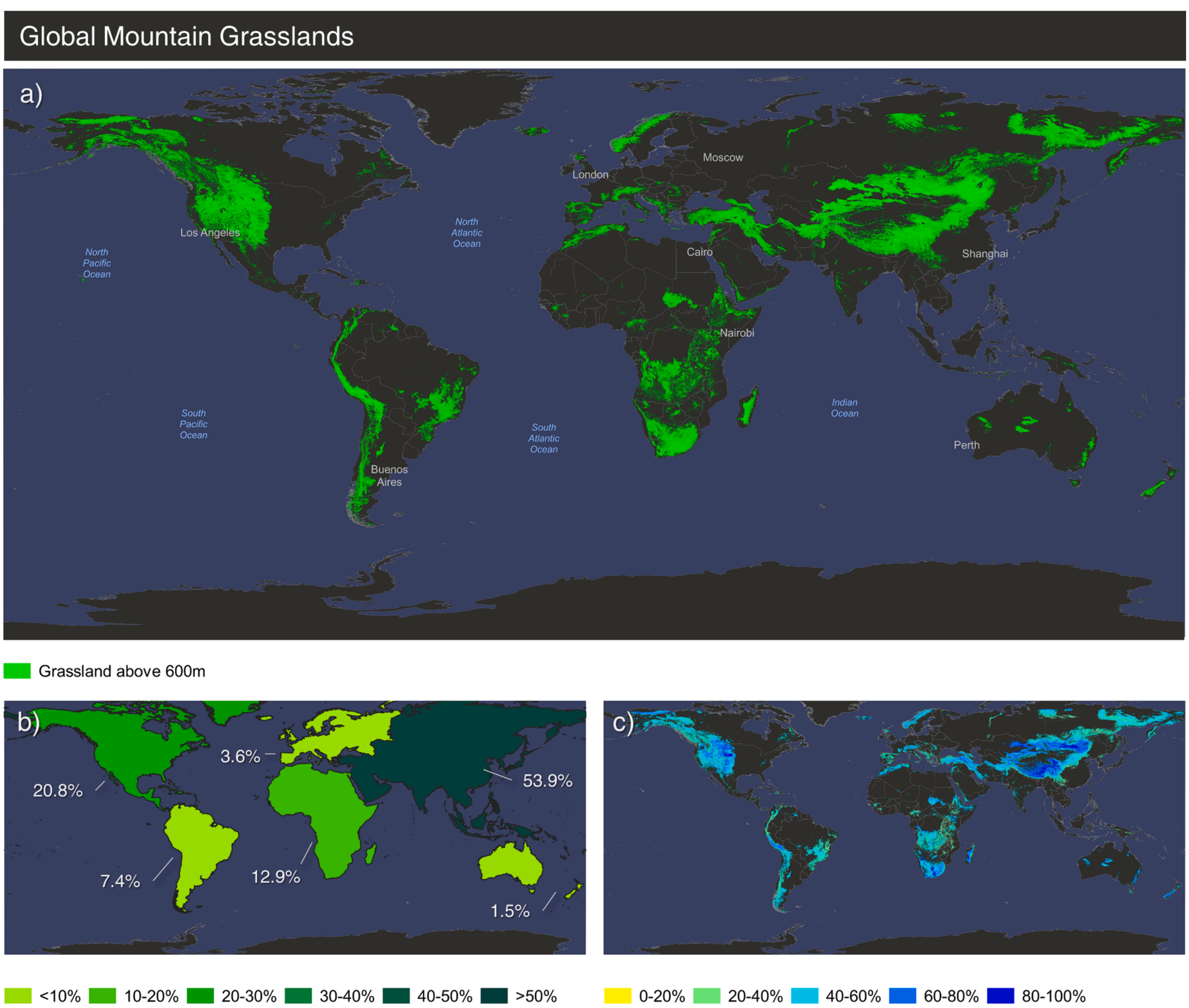

Fig. 1. a) Global distribution of mountain grasslands (elevation greater than 600 m) derived from Copernicus Global Land Service (CGLS) data for the year 2019; b) Mountain grasslands distribution in different continents; c) quality index which describes the pixel classification accuracy for the 'grassland' class (CGLS validation data).

was found in Spain (including the Pyrenees shared with France), the Alps, the Balkans, and Norway. Australia and Oceania host the smallest fraction of mountain grasslands (1.5%), mainly situated in the central and eastern parts of Australia and New Zealand. A summary of results is reported in Table 1. The pixel classification quality related to mountain grasslands is presented in the form of a quality index in Fig. 1c. Higher performance could be observed in the great plain of Northen America, South Africa, and China.

3.2. Soil erosion in global mountain grasslands: present scenario

Fig. 2a shows the map depicting water-induced soil erosion in mountain grasslands worldwide under the current scenario (2015). 14.5% of such landscapes globally experienced high erosion rates (greater than 10 Mg/ha/yr; from the orange-coloured class in Fig. 2). The main hotspots could be found in South America, particularly along the Andes Mountain range and in Brazil. The continent stands out for having the higher erosion values in mountain grasslands. 53.2% of them are characterized by rates exceeding 10 Mg/ha/yr. A reason can be attributed to a vigorous hydrogeological cycle. Most of the continent (approximately north of 33° degrees south) has high rainfall erosivity values (R-factor parameter of RUSLE equation), often exceeding 1800 (MJ mm)/(ha h yr) (Borrelli et al., 2020; Riquetti et al., 2020). This is a critical problem for example in Brazil, where several mountain grasslands are severely affected by the erosion process. Here, the R-factor can exceed 6000 (MJ mm)/(ha h yr), especially in the central-eastern regions (Oliveira et al., 2013). Grazing practices also contribute to soil erosion, as highlighted in more specific studies, not only in Brazil (Antoneli et al., 2018; Sobral et al., 2015), but also in Chile (Bonilla et al., 2010) and Venezuela (Sánchez et al., 2002). In Africa, 17.0% of the mountain grasslands are classified as severe potential soil erosion. Major hotspots are in the eastern regions, including Ethiopia, the borderland of Congo, Uganda, Rwanda, Burundi, and Tanzania, as well as in South Africa and Madagascar. Few studies have been conducted at a more local scale in Africa, for instance about the controlling factors of sheet erosion in steep slope degraded grasslands (Dlamini et al., 2011) or on the impact of land-use change in Ethiopian grassy landscapes (Negese, 2021). In Asia, 14.0% of the total mountain grasslands are at risk due to severe potential soil loss. A significant portion of Central Asia hosts some of the most severely affected mountain grasslands globally. The area extends from Kyrgyzstan, Tajikistan, Afghanistan, and Pakistan southwards to India and Nepal. A study on the hydrology and soil erosion of the Central Asian grasslands was proposed by Spaeth et al. (2020). In China, some of the largest mountain grasslands could be found in the Qinghai-Tibet Plateau, where water-induced soil erosion is a known and well-recognized problem. Zhou et al. (2023) recently published a review on the degradation status of these ecosystems, analyzing the factors contributing to degradation and the techniques adopted for their restoration. Another hotspot is the semi-arid grasslands of the Loess Plateau in central China. The region has some of the highest erosion rates on the planet and for this reason massive reforestation campaigns are underway, such as the "Grain-for-Green" project (Chen et al., 2015). Here grassland cover plays a crucial role, particularly in the initial soil conservation phase, where it could outperform forests (Wei et al., 2007). High erosion patterns are also in eastern Eurasia and in the southern regions of the Asian continent, such as in Indonesia. In Europe, 9.6% of the mountain grasslands exceeds 10 Mg/ha/yr of potential soil loss. Main hotspots could be found in the Alps, Apennines, Pyrenees, and Balkans. Multiple studies have been carried out on this continent, such as on grasslands' vulnerability to land degradation in the Alps (Geitner et al., 2021) or their contribution to mitigating erosion and flood dynamics (Milazzo et al., 2023). Finally, lower erosion magnitude could be observed for North America (2.6% classified as experiencing more than 10 Mg/ha/yr of potential soil loss), Australia, and Oceania (less than 1.0%, primarily on the east coast mainly concentrated in the East coast of Australia and New Zealand; (Kirschbaum et al., 2012)).

Table 1
Summary results of mountain grasslands spatial distribution (%; in different regions) and total/severe projected change in soil erosion by water (%; baseline: 2015; future scenario: 2070 - RCP8.5).

Region	Mountain grasslands distribution	Change in mountain grasslands soil erosion (2015 > 2070; RCP8.5)	Change in severe mountain grasslands soil erosion (>10 Mg/ha/yr) (2015 > 2070; RCP8.5)
Globe	100.0%	+2.3%	+0.2%
Africa	12.9%	+10.0%	+0.7%
Asia	53.9%	−2.6%	−0.8%
Australia/ Oceania	1.5%	−1.2%	0.0%
Europe	3.6%	−0.6%	−0.1%
North America	20.8%	−0.1%	0.0%
South America	7.4%	+19.4%	+6.6%

3.3. Soil erosion in global mountain grasslands: future scenario

Fig. 2b presents the map of water-induced soil erosion in global mountain grasslands under a future climate scenario (2070; RCP8.5). Our analysis indicates a projected global increase of +2.3% in potential annual water-induced soil erosion compared to the current scenario. Fig. 2c highlights the disparities between the baseline (2015) and the future scenario (2070). Fig. 2d illustrates the frequency distribution of soil erosion values (on a logarithmic scale) for both simulations. Up to approximately 30 Mg/ha/yr, the two distributions exhibit similar trends, but more pronounced distinctions become evident for higher values, with the future scenario projecting higher estimates of soil loss. South America could face an increase (+19.4%) in the future due to climate. The most critical area is located towards the east, mainly in Brazil. One of the main contributing factors could be the projected rise in rainfall erosivity for much of the areas occupied by mountain grasslands (R-factor potentially increasing up to 1500 (MJ mm)/(ha h yr), as observed in Borrelli et al. (2020)). Other studies have also reported an increase in the R-factor for South America; projections suggested an up to 109% rise in the period 2007–2040 for Brazil (Almagro et al., 2017) and for the eastern part of the continent along the Andes (Riquetti et al., 2020b). The second continent facing significant risk is Africa, with results indicating a 10.0% increase in potential erosion. The areas most impacted could primarily be the central-eastern states, South Africa, and Madagascar. The role of rainfall erosivity will be crucial in this context as well, particularly in Ethiopia (Nyssen et al., 2005), South Africa and Madagascar (Vrieling et al., 2010). For Asian mountain grasslands, the outcomes indicated a slight decrease in the potential soil loss (−2.6%). Worsening conditions may be observed along the Himalayas and the Loess Plateau; however, such variations could be compensated by expected lower values in the southern Qinghai-Tibet Plateau, where rainfall erosivity could decrease by over 20% in the future (2010–2050; Scenario 2.6; (Panagos et al., 2022)). More moderate variations (<2.0%) could be observed in other continents, although it is important to stress the presence of localized hotspots with potential increases in soil erosion. In North America, the mountain grasslands that could experience worsening erosion values are those in the central States, from Colorado to southwards. In Europe, the areas at greater risk could be the mountain grasslands of the western Alps, the Apennines, and the Pyrenees. For example, in Italy, there is an estimated increase of about +1.5% in severe erosion, especially in the hotspots of Pre Alps of Veneto and Lombardy (about +4.5%), values similar to the Apennines of central Italy and northeastern Sicily. The grassland of the Swiss Alps is another critical area of soil erosion, a fact already investigated by other authors (Schmidt et al., 2019; Zweifel et al., 2019). Here, we estimated an

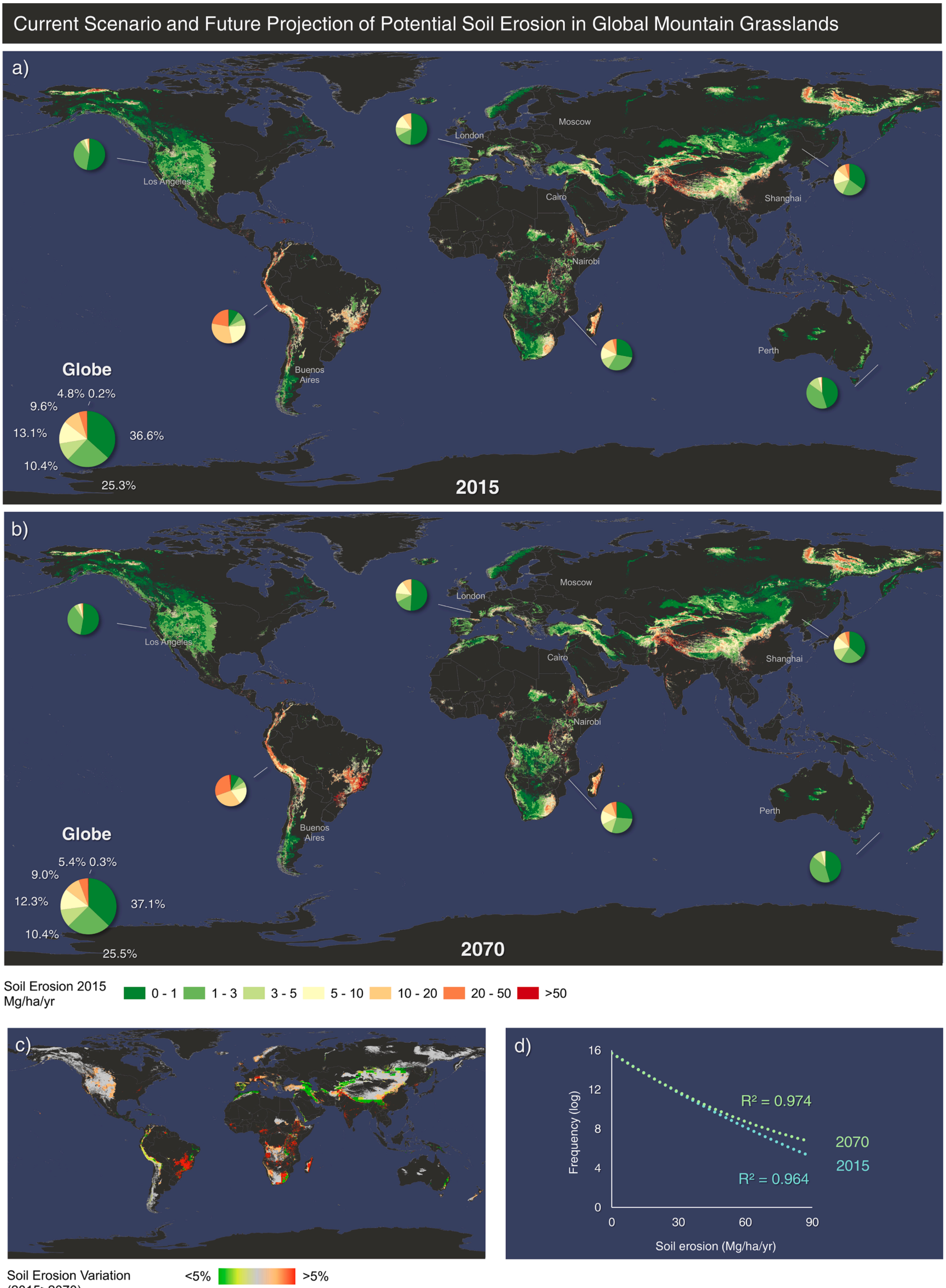

Fig. 2. a) and b) Potential annual soil loss for global mountain grasslands estimated using the RUSLE equation for 2015 (baseline) and 2070 (scenario RCP8.5), respectively. Pie charts investigate a single class of soil loss for each continent and globally; c) Map of the soil loss variation between present and future scenarios; d) graph comparing 2015 and 2070 soil loss data (log-scale). Note the higher frequency of higher soil loss values in the 2070 scenario. All soil loss data were based on Borrelli et al. (2020).

increase of about +3.8% in 2070, with peaks above +5.0%. Instead, a major change is not expected for much of the grasslands in Spain and the southern Balkans (a pattern consistent with the observation of Borrelli et al., (2020)). For Australia and Oceania, major variations are not predicted as in other parts of the World, but there is still a hotspot in the mountain grasslands of New Zealand. A summary of results is reported in Table 1. By gaining insights into erosion dynamics and identifying high-risk areas worldwide, our research contributes to promoting land management and conservation strategies, safeguarding mountain grasslands amid the challenges posed by climate change.

3.4. The extreme drought of 2022 on European mountain grasslands

This section investigates the impact of extreme drought and high temperature in European mountain grasslands during the event of July 2022. Fig. 3 presents the results of the VHI index calculation as an indicator of agricultural drought severity. On average, nearly a quarter of the entire system was affected by drought, with 5.7% classified as severe or extreme. Southern Europe experienced the most difficult conditions, with France and Spain being among the hardest-hit countries, with almost 80.0% of their mountain grasslands affected by drought. Other hotspots were visible in the Balkan region, particularly in Bosnia and Herzegovina (72.9%) and Montenegro (66.2%), as well as in Italy (48.3%) and Romania (32.5%). Spain faced the most worrying conditions, with 14.3% experiencing extreme drought and 22.2% severe drought. Areas severely affected included the western and southern regions of Salamanca, the mountainous area north of León extending eastward to Bilbao, the Pyrenees Mountain range, and several central areas of Aragon. A critical zone was also identified in the south, although to a smaller extent, such as in the Sierra Nevada National Park. France ranked second in terms of drought severity in mountain grasslands during the summer of 2022, with 10.0% experiencing extreme drought and 17.6% severe drought. Many of those areas were situated along the Pyrenees and the Alps, with a smaller portion in the region of national parks between the cities of Clermont-Ferrand and Montpellier and on the island of Corsica. Italy, relatively less affected (2.7% extreme drought and 6.6% severe drought), saw the northern regions of the Alps and Pre-Alps affected, with a critical point being the Lessinia Regional Park. The severe drought of 2022 is already driving scientific research efforts to help protect alpine grasslands in Italy, also involving local consortia. An example is reported by Castelli et al. (2023), which proposed a satellite-based approach to estimate yield losses attributed to drought events in the mountain grasslands of northeastern Italy. In the central regions, the Apennines, particularly the Monti Sibillini National Park and the Sirente-Velino Regional Natural Park, also experienced severe drought. The severity was lower in the southern regions and on the islands, with the northern part of Sardinia being a hotspot. In eastern European areas, severe drought conditions were observed in Bosnia and Herzegovina (south of the city of Sarajevo) to Montenegro and in Romania (north of Brașov and west of Cluj-Napoca).

A growing body of evidence indicates that drought, often in combination with high temperatures, can cause a range of different effects on mountain grassland ecosystems, encompassing alterations in community composition, functioning, and the upward migration of species (Beniston et al., 2018; Sloat et al., 2015; Steinbauer et al., 2018). Drought can significantly reduce soil microbial carbon (C) while increasing nitrogen (N), compromising the carbon sink role attributed to global mountain grasslands (Fuchslueger et al., 2019; Hasibeder et al., 2015), a phenomenon also described by Zhang et al. (2023). Furthermore, it can have serious consequences on vegetation response in such

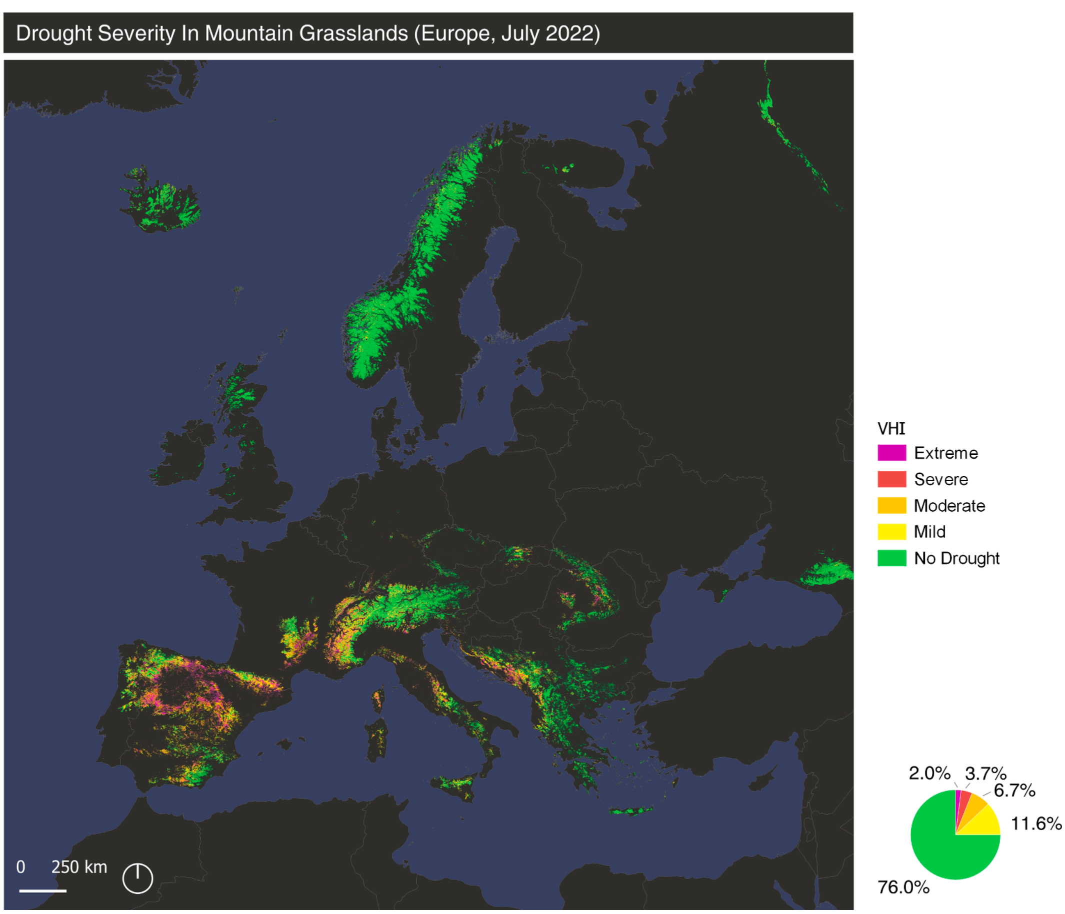

Fig. 3. Agricultural drought severity map and pie-chart for mountain grasslands in Europe during July 2022, calculated using the MODIS-based VHI.

landscapes. Hoover et al. (2014) found that extreme drought affected both aboveground and belowground net productivity of plants, with a more pronounced impact observed when the drought persisted for two consecutive years throughout the growing season. This observation was also confirmed by recent research conducted in northern Italy (Lessinia Regional Park, Veneto Region; (Chen et al., 2023). The authors investigated two successive dry periods in 2012 and 2013, which resulted in a decrease in soil water content, subsequently leading to a reduced capacity of vegetation to recover in the following year. Therefore, in light of the challenges posed to mountain grasslands by climate change impacts such as intense rainfall and extreme drought, it is important to promote sustainable solutions for the conservation of ecosystems and associated ecosystem services.

3.5. Preserving ecosystem services

Preserving the ecosystem services provided by mountain grasslands requires effective conservation strategies to address the challenges posed by climate change. Such interventions could be implemented where human activity persists and serve various purposes. On one hand, they aim to ensure the protection of biodiversity and ecological functionality; on the other hand, they contribute to maintaining traditional mountain activities such as pastoralism or transhumance. Firstly, it is important to promote protected areas, conservation corridors and wetlands to safeguard the integrity and connections of grassland ecosystems (Samways et al., 2010; Żmihorski et al., 2016). They can provide refuges for different species, enabling natural processes to continue, and allowing for the long-term monitoring and research necessary for conservation efforts (Zhou and Song, 2021). Secondly, it is vital to incorporate nature-based solutions (NbS), which are increasingly recognized techniques for preserving ecosystem services (Cohen-Shacham et al., 2019). They can be used for protecting ecological function and mitigating land degradation processes, becoming valuable tools against climate change impacts. An example is rotational grazing, which implies moving animals in different pastures following a regular schedule, avoiding overgrazing (Eagle and Olander, 2012). Li et al. (2023) reported a positive and progressive long-term ecological benefit for pasture managed with this solution. NbS could also be adopted to for the restoration of degraded and abandoned grasslands. For instance, they are crucial interventions for mitigating soil erosion and shallow landslides, as these problems tend to be more common in bare hillslopes compared to those with healthy grass (Apollonio et al., 2021). Török et al. (2011) provide a comprehensive technical overview of a number of NbS restoration techniques for this purpose. Sowing seed mixtures is the most common practice, where different target species are selected according to the aim of the restoration and the site characteristics. It is then recommended to promote the use of native/regional species (Prach et al., 2014). Indeed, species-rich grass is more resilient in facing various environmental changes or disturbances, including land degradation drivers (Lavorel et al., 2019; Muller et al., 1998; Zhu et al., 2015). Other solutions are proposed by Cervasio et al. (2016), which conducted a five-year observation in the grasslands of the northern Apennines under different managements (such as soil tillage, adjustments to forage mixtures, and bracken removal). Their conclusions emphasized the significance of bracken cutting to improve native species colonization and the sowing of forage mixtures to preserve pasture quality, strategies also confirmed by previous research (Prach et al., 2014; Stewart et al., 2007). Continuous maintenance is then a crucial activity to ensure the long-term sustainability and functionality of interventions (Carbutt and Kirkman, 2022; Schermer et al., 2016). Finally, in the case of steep slope grasslands, an excellent example of more structural solutions for mitigating surface processes and soil erosion is agricultural terracing. These are traditional soil and water conservation practices found in various parts of the world and are recognized for their cultural significance. For example, in the Swiss Alps, terraced grassland primarily served as meadows and pastures for goats, sheep, and donkeys for centuries (Rusterholz et al., 2020). Many articles investigated terrace performance in protecting soil; for instance, in a Brazilian case study, researchers observed that well-managed terraced pastures could achieve a remarkable reduction of over 700% in soil erosion rates caused by rainfall when compared to non-terraced landscapes (Galdino et al., 2016).

NbS are valuable interventions also in mitigating drought impacts. Multiple droughts tolerated grass species were found in previous studies, such as *D. glomerate*, *viciifolia* Scop. and *M. sativa* (Dumont et al., 2015; Kallida et al., 2016). The use of a grass-legume mix, which may include subclovers and medics, can also be employed; legumes, in particular, serve as a crucial protein source that helps mitigate the adverse effects of low soil moisture and rising temperatures on forage yield (Dumont et al., 2015). In addition, mountain grasslands resilience can be improved including water ponds, or topographic depressions that serve as water reservoirs (Jooste et al., 2020). Traditional mountain communities have historically relied on these systems to increase water availability for agricultural, livestock and sometimes fish farming purposes (Henderson et al., 2012; Verga et al., 2012). Firstly, they play a key role in preserving biodiversity within grasslands by providing habitat for numerous species (Knutson et al., 2004). Then, during times of drought, they can become valuable emergency water sources. However, they are close systems, primarily dependent on rainfall, and sensitive to evaporation; as a result, their number and distribution significantly affect the amount of water available and, consequently, their effectiveness in mitigating drought impacts. A recent study conducted by Chen et al. (2023) in northern Italy delves into these issues. They highlighted the pivotal role of ponds in supporting mountain grasslands' functionality and the importance of maintaining these traditional solutions in a changing climate. Finally, it is important to mention that increasing the resilience of mountain grasslands against new climate challenges requires promoting collaborative research, involving a variety of regional experts, data sharing, and policy exchange. This can facilitate innovation, improve understanding of climate change effects, and support the development of conservation strategies at a large scale.

3.6. Limitations and future perspective

While this study attempts to offer a comprehensive analysis of the global mountain grasslands and related threats, it is important to recognize the presence of limitations. For instance, the use of satellite data, despite its extensive coverage, may present constraints due to spatial resolution and potential inaccuracies in interpreting specific ecosystem features. Additionally, projections of future scenarios such as those related to soil erosion by water are intrinsically susceptible to uncertainties arising from climate models and long-term forecasting. Future research efforts could enhance mapping techniques by integrating higher resolution data, such as Sentinel 2, Landsat 8/9, or Unmanned Aerial Vehicles (UAV) and in-field surveys in selected sites. Then, the implementation of advanced machine learning algorithms could allow improved accuracy in the identification of areas vulnerable to challenges such as soil erosion and drought in mountain grasslands. Finally, integrating in the analysis specific socio-economic factors and engaging local communities would enrich discussions on sustainable practices, preserving the cultural significance of these landscapes.

4. Conclusion

This study analyzes mountain grasslands and their associated ecosystem services in the context of climate change. They are areas of high landscape and social value, often more vulnerable due to unsustainable management practices or from traditional pastures abandonment. We first employed satellite-based remote sensing to shed light on the global distribution of mountain grasslands. Then, we delved into two significant climate change impacts: water-induced soil erosion and drought. For soil erosion analysis, we relied on open-access data and focused on climate condition changes (2015 vs. 2070-RCP8.5) while maintaining consistent land use. Despite possible limitations, our findings reveal that, in the current scenario, 14.5% of global mountain grasslands face a high risk of erosion (>10 Mg/ha/yr). South America stands as the most affected continent (53.2%), followed by Africa (17.0%), Asia (14.0%), and Europe (9.6%). In the future scenario, a projected +2.3% in water-induced erosion is estimated for global mountain grasslands. South America (+19.4%) and Africa (+10.0%) are expected to experience the most increases, while Asia may see a slight decrease (-2.6%). Furthermore, we assessed the severity of drought in European mountain grasslands during the extreme event of summer 2022 using a satellite-based Vegetation Health Index. A quarter of the area suffered from drought, with 5.7% experiencing severe or extreme severity. Southern Europe was the most affected zone, particularly Spain (80.0% of mountain grasslands affected), Bosnia and Herzegovina (72.9%), Montenegro (66.2%), Italy (48.3%), and Romania (32.5%). Finally, we explored strategies to enhance the resilience of mountain grasslands while preserving their critical ecosystem services. Our focus centered on NbS, including effective grassland management to mitigate erosion and the implementation of water ponding systems to address droughts. Recognizing mountain grasslands' importance in mitigating climate change is the first step to securing them for future generations. Crucial solutions involve targeted interventions addressing various climate change challenges, restoring degraded or abandoned valuable areas, and preserving the traditions that have maintained the balance between humans and nature for centuries.

CRediT authorship contribution statement

Eugenio Straffelini: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. **Jian Luo:** Data curation, Validation, Writing – review & editing. **Paolo Tarolli:** Conceptualization, Validation, Writing – review & editing, Funding acquisition, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by PHITO (Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunities) Horizon EU project n. 101084332; this manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them. The work was also supported by the Start-up funding from Inner Mongolia University (21800-5223728).

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