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# ECOSYSTEM SERVICES IN MOUNTAIN ENVIRONMENTS: BENEFITS AND THREATS

## *Servicios ecosistémicos en áreas de montaña: beneficios y amenazas*

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**ABSTRACT:** Mountain areas have a substantial impact on climate dynamics and are one of the most critical water sources. Mountains were key in human evolution throughout history and supplied essential biotic and abiotic ecosystem services (ES), key for human living. This perspective article will study the importance of mountains to ES supply and the impacts of the different drivers of change, namely habitat change, climate change, overexploitation, pollution, and invasive species. Mountain areas have a high capacity to supply an important number of regulating (global and local climate regulation, air quality regulation, natural hazards regulation, pollination), provisioning (crops, livestock, wild food and fish, biomass for energy and timber, freshwater renewable energy – hydropower, wind, solar and geothermal – and mineral resources) and cultural (recreation and tourism, landscape aesthetics and inspiration, cultural heritage and cultural diversity and knowledge systems). However, changes imposed by habitat change, climate change, overexploitation, pollution, and invasive species can increase the tradeoffs between ES and trigger environmental degradation. Overall, there is a need to balance mountain ES exploitation and reduce the effects of the different drivers of change.

**KEYWORDS:** Mountains; biotic; abiotic; ecosystem services; drivers of change.

**RESUMEN:** Las áreas de montaña tienen un impacto importante en las dinámicas climáticas y son una de las fuentes de agua con condiciones más críticas. Las montañas fueron claves en la evolución histórica del ser humano y suministraron servicios ecosistémicos (SE) bióticos y abióticos esenciales para la vida humana. Este artículo de perspectiva estudiará la importancia de las montañas para el suministro de SE y los impactos de los diferentes factores de cambio, a saber, cambios en el hábitat, el cambio climático, la sobreexplotación, la contaminación y las especies invasoras. Las zonas de montaña tienen una gran capacidad para suministrar un número importante de recursos reguladores (regulación del clima global y local, regulación de la calidad del aire, regulación de los riesgos naturales, polinización), de aprovisionamiento (cultivos, ganado, alimentos y pesca silvestre, biomasa para energía y madera, energía renovable de agua dulce -hidroeléctrica, eólica, solar y geotérmica- y recursos minerales) y culturales (ocio y turismo, estética e inspiración del paisaje, patrimonio cultural y diversidad cultural y sistemas de conocimiento). Sin embargo, los cambios impuestos por la modificación del hábitat, el cambio climático, la sobreexplotación, la contaminación y las especies invasoras pueden aumentar los intercambios entre los SE y desencadenar la degradación del medio ambiente. En general, es necesario equilibrar la utilización de los SE de montaña y reducir los efectos de los distintos factores de cambio.

**PALABRAS CLAVE:** Montañas; biótico; abiótico; servicios ecosistémicos; factores de cambio.

## 1. Introduction

Mountain areas occupy 40,957,238 km$^2$, approximately 30.55% of the global land area. For Kapos (2000), they are defined according to the slope, elevation and local relief. However, despite these factors being important, the definition of a mountain is not simple. For instance, absolute elevation is not the best criterion. The degree that slope change in space (ruggedness) is also important (UNEP-WMC, 2002). Kapos *et al.* (2002) created criteria to define mountains based on altitude and slope. They divided mountain environments in different classes Class 1: elevation ≥ 4 500 m; Class 2: elevation 3 500–4 500 m; Class 3: elevation 2 500–3 500 m; Class 4: elevation 1 500–2 500 m and slope ≥ 2°; Class 5: elevation 1 000–1 500 m and slope ≥ 5° or LER > 300 m; Class 6: elevation 300–1 000 m and LER > 300 m (Kapos *et al.,* 2002; https://www.fao.org/mountain-partnership/about/definitions/en/).

A good discussion about the challenges in the definition of mountain environments was conducted by Körner *et al.* (2011). Elevation cannot be the unique criterion for defining mountains since flat areas (plateaus) are located at altitudes around 2000 m (e.g., Central Asia). Also, mountains cannot be defined only by climate. A similar climate is observed in Antarctic and Arctic lowlands. The most common feature in mountain areas is the steepness and ruggedness (Körner *et al.,* 2011). Recently Körner *et al.* (2021) discussed the different mountain definitions and their consequences in identifying the area occupied. However, to use a standard definition, we consider a mountain as a *"landform that rises prominently above its surroundings, generally exhibiting steep slopes, a relatively confined summit area, and considerable local relief. Mountains generally are understood to be larger than hills, but the term has no standardized geological meaning. Very rarely do mountains occur individually. In most cases, they are found in elongated ranges or chains. When an array of such ranges is linked together, it constitutes a mountain belt"* (https://www.britannica.com/science/mountain-landform). Mountain areas play an essential role in shaping climate and the origin of the large majority of rivers. Also, they have an important influence in the surrounding areas through nutrient runoff and biotic interaction. Mountains are also hotspots and cradles for biodiversity and provide many ecosystem services (ES) essential for humans. Between 400-900 million humans live or depend partly or entirely on mountains (Sayre *et al.,* 2018; Rahbek *et al.,* 2019a; Perrigo *et al.,* 2020). Although mountains are harsh environments, there are multiple records that they have been occupied since pre-historical times and served as an important source of resources and shelter for the humans in America (e.g., Arkush & Arkush, 2021), Africa (e.g., Phillips *et al.,* 2019), Asia (e.g., Heydari-Guran & Ghasidian, 2020), Europe (e.g., Mazzucco *et al.,* 2019), and Oceania (Slack *et al.,* 2018). In several mountain areas, humans developed strategies to adapt to rough environments (e.g., terraces) (e.g., Lasanta *et al.,* 2017).

It is well known that, mountains provide a multitude of ES (e.g., carbon sequestration, air quality purification, water provisioning, food, recreation) (e.g., Grêt-Regamey *et al.,* 2012; Liu *et al.,* 2019; Grêt-Regamey & Weibel, 2020). However, they are among the most fragile ecosystems, and several reports highlighted that they are extremely vulnerable to climate change (e.g., Iglesias *et al.,* 2018). Some biophysical systems started a process of adaptation, as highlighted in Vij *et al.* (2021). For instance, according to the latest IPCC (2021) report, mountain glaciers retreat has been unprecedented in the last 2000 years. Also, the changes in snow cover and the earlier onset of spring melt is changing rivers streamflow seasonality, ecosystem dynamics and water supply in low altitude areas. Permafrost and mountain glaciers are expected to melt for decades or hundreds of years. The permafrost degradation and glacier melting in mountain areas increase slopes instability, and the formation of glacial lakes increases the risk of landslides and glacial lakes outburst floods. Precipitation extremes are expected to rise in all the scenarios in mountain regions, triggering floods and landslides. The temperature changes are also expected to affect mountain habitats, and in recent decades a tremendous change in species abundance and composition has been identified.

Human pressures in mountains and profound socio-economic changes are affecting ecosystems equilibrium. Activities such as mining (e.g., Bokar *et al.,* 2020), massive tourism (e.g., Nepal *et al.,* 2020), intensive agriculture expansion (e.g., Peters *et al.,* 2019) have a dramatic impact on the ecosystems. On the other hand, mountain areas are suffering from rural exodus in several regions of the world. The abandonment of these areas is changing unprecedently semi-natural habitats created by millennial human activities. Although some benefits from this dynamic are recognised (e.g., rewilding, biodiversity conservation), negative implications occur as well (e.g., loss of semi-natural grassland ecosystems, wildfire risk increase) (e.g., Hinojosa *et al.,* 2019; García-Ruiz *et al.,* 2020). These socio-economic and environmental changes have a substantial implication on ES supply (Pereira, 2020). Therefore, it is critical to understand and identify the biotic and abiotic ES supplied by mountain areas and the drivers of change that can affect their quantity and quality. This perspective article aims to assess the regulating, provisioning and cultural ES supplied in mountain areas and the effects of a changing environment.

## 2. Regulating Ecosystem Services

Mountains have a different climate from the surrounding land. The altitude and the complex topography affect weather, climate, plant and animal distribution, even at small scales (e.g., Jähnig *et al.,* 2020). Therefore, the biodiversity in these environments is high when compared to lowland areas. Even though mountains occupy approximately 30% of the terrestrial area, they host more than 85% of the diversity of mammals, birds and amphibians (Rahbek *et al.,* 2019b). This high biodiversity is only possible due to the habitat's quality and the presence of well preserved and forests. Several works found that mountain forests have a high capacity for carbon sequestration (global and local climate regulation) (e.g., Sil *et al.,* 2017; Stritih *et al.,* 2021) (Figure 1), and this can be different according to the slope aspect. For instance, Swetnam *et al.* (2017) found that in the Rocky Mountains (The USA), the carbon storage capacity was higher in the north-facing slopes than in the southern. Similar results were also identified by Fravolini *et al.* (2018) in the Mediterranean mountains. These differences can also be identified in different mountain ecosystems. For example, forests have a higher capacity than grasslands to store carbon (Yu *et al.,* 2020). Others found that the implementation of measures that reduce fire risk and increase

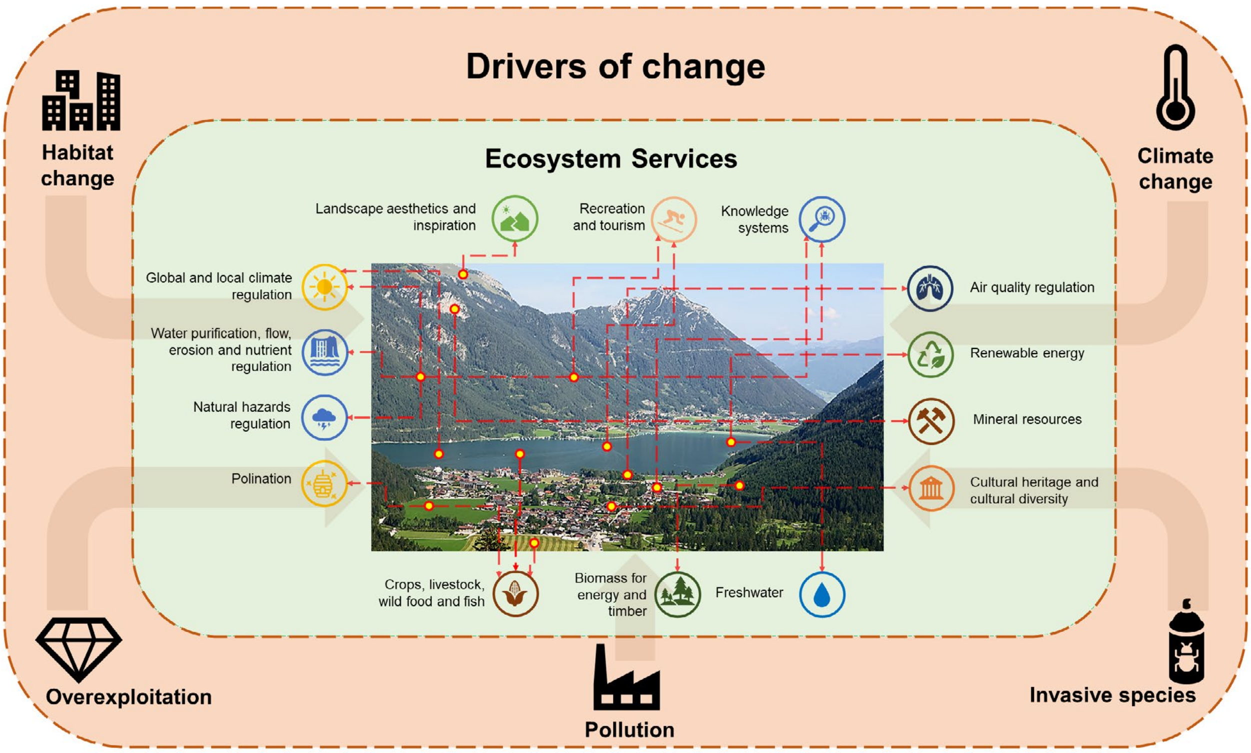


Figure 1. Mountain ecosystem services supply and the impact of the different drivers of change.
*Figura 1. Oferta de servicios ecosistémicos de montaña e impacto de los diferentes impulsores de cambio.*

biodiversity in mountain areas of Gerês-Xurés (Portugal and Spain) would be key for carbon sequestration in the long term (Pais *et al.,* 2020). On the other hand, Seidl *et al.* (2019) identified that unmanaged forests in the Alps have a high capacity for carbon sequestration and, therefore, climate regulation. Mountains with high biodiversity and forest cover have a high capacity for local and global climate regulation.

Vegetation can capture particulate matter (10 and 2.5 mm) and pollutants from the atmosphere (Pereira *et al.,* 2022) (Figure 1). Therefore it is expected that forest mountain areas located near cities can reduce air pollution. Most of the studies carried out were focused on urban trees or urban forests (e.g., Yli-Pelkonen *et al.,* 2017; Nowak *et al.,* 2018). Few studies were conducted in green areas located in mountain environments using measured data or models (Mengist *et al.,* 2020). However, Ji-Young *et al.* (2017) found that in the Gongju City (Korea), the surrounding forests located had a high capacity to capture pollutants. Evergreen coniferous had a high capacity to remove pollutants than evergreen forests. More studies have been developed about the social perception of the role of mountain forests in air purification. However, the results are not conclusive, and some showed that this ES is highly valued (e.g., He *et al.,* 2018; Pedraza *et al.,* 2020), while others are not (Paudyal *et al.,* 2018).

Mountain forests can filter and regulate water flow (e.g., Locatelli *et al.,* 2017; Ngwenya *et al.,* 2019; Ma *et al.,* 2021), controlling the water quality and quantity that reach the water bodies (Figure 1). They reduce the sediment transport significantly and sustain the fragile mountain soils. Forests are a key for mountains soil conservation, as observed in several works (e.g., Sheng *et al.,* 2017; Xiao *et al.,* 2017). This high capacity to retain water and regulate flow is key to reducing peak flow and decreasing the probability of flash floods and landslides after high-intensity precipitation events (e.g., Paudyal *et al.,* 2018; Costache *et al.,* 2020; Huber *et al.,* 2020). Forested catchments can reduce the flood peak from 3 to 70%, especially in small and medium-sized floods (Wahren *et al.,* 2012). Also, in natural forests, surface microrelief contributes to increasing water retention and decreasing runoff (Valtera & Schaetzl, 2017). Mountain areas are also known to host a high diversity of pollinators (e.g., Naeem *et al.,* 2020; Baumann *et al.,* 2021), essential to agricultural production and the function of rural communities.

## 3. Ecosystem Services Provisioning

Mountain supply a vast array of food, such as mushrooms, cash crops, berries, vegetables, spices and medicinal plants (McLellan & Brown, 2017; Ulloa-Muñoz *et al.,* 2020) (Figure 1). Other animal-based products are produced from these areas, such as meat, oils, fats, milk, cheese, fish, and shellfish (Martins & Ferreira, 2017). Numerous works highlight the high capacity of mountain areas for crops, livestock, wild food, and fish supply (e.g., Kokkoris *et al.,* 2018; Faccione *et al.,* 2019). Also, they provide a basic income to mountain communities as observed elsewhere (e.g., Shrestha *et al.,* 2019). Due to the high diversity and food quality, several certification schemes were developed to label mountain regional products and increase consumer trust. This is key to improving mountain rural areas' livelihood and sustainability (Mazzocchi & Sali, 2022). Timber and biomass for energy are also important ES supplied by mountains (e.g., Gurung *et al.,* 2021) (Figure 1). In several areas is still one of the most important sources of local communities' income and is highly valued in the Alps (Gori *et al.,* 2018), Carpathians (Melnykovych *et al.,* 2018), Himalayas (Gentle & Marseni, 2012) and Africa - Burundi (Ndayizeye *et al.,* 2020). Mountains are environments that have the highest capacity to provide freshwater. They act as natural water towers and supply approximately 60 to 80% of world freshwater (https://www.fao.org/mountain-partnership/our-work/focusareas/water/en/). Mountains as water towers are critical in semi-arid and arid areas and have an essential role in supplying water for agriculture, industry, and the growing urban population (Viviroli & Weingartner, 2008). For instance, approximately 1.5 billion people living in lowlands depend on mountain freshwater (Viviroli *et al.,* 2020).

The high presence of water and sloped terrain make mountains key environments for producing hydropower energy. Since ancestral times, humans used water energy (e.g., water mill) to mill cereals and represented an important energy source for rural communities (e.g., Serrano & González-Amuchastegui, 2020) (Figure 1). Nowadays, hydropower supplies more than 16% of the total electricity production. This energy type is the primary renewable energy resource and is expected to increase in the future (Bilgili *et al.,* 2018; IEA, 2019). Mountains also have a high potential to supply wind energy. The wind blows with high velocity in high altitude and high roughness areas (e.g., mountain corridors), therefore, several wind farms were established (e.g., Ólafsdóttir & Sæþórsdóttir, 2019; Cunden *et al.,* 2020) (Figure 1). After hydropower, wind energy is the energy that contributes the most to renewables production (IEA, 2019). Several projects have been developed in mountain areas to produce solar energy (e.g., Karpić *et al.,* 2019; Kahl *et al.,* 2019), which are an option to be considered in the context of the rising energy demand. For instance, solar energy production in the mountains can be 20% higher than at sea level (https://www.fao.org/mountain-partnership/our-work/focusareas/renewableenergy/en/). Solar energy is the highest contributor to renewables production after hydropower and wind energy (IEA, 2019) (Figure 1). Finally, in mountainous volcanic areas, there is a great potential for the production of geothermal energy (Figure 1). Worldwide, there are several areas where this type of energy is extensively explored, such as in Iceland (e.g., Spittler *et al.,* 2020), New Zealand (e.g., Kumar *et al.,* 2021), United States (e.g., Neves *et al.,* 2021), Japan (Taghizadeh-Hesary *et al.,* 2020) and Italy (Pellizzone *et al.,* 2017). There is an increasing trend of geothermal exploitation (https://www.irena.org/geothermal). Geothermal energy, after hydropower, wind energy and solar energy, is the one that contributes more to the total renewable energy production (IEA, 2019).

Since historical times, mountain areas have been an essential source of mineral resources such as bronze, iron and gold (e.g., Mariet *et al.,* 2018; Tolksdorf *et al.,* 2020) (Figure 1). More recently, other vital minerals were exploited in the mountains, which are the primary resources for many countries such as diamonds, coal and other raw materials (e.g., Lithium, Tungsten, Cobalt) (e.g., Redondo-Vega *et al.,* 2017; Ahiakwo *et al.,* 2018; He *et al.,* 2020). According to OECD (2015), due to human demand, mineral resources are expected to increase.

## 4. Cultural Ecosystem Services

Mountains are essential areas for recreation and tourism during the different seasons and attract between 15 to 20% of global tourists (https://www.fao.org/mountain-partnership/our-work/focusareas/sustainable-tourism/en/). These activities are vital to the economy of several communities is expected to increase in the future (World Tourism Organization, 2018). For instance, mountains during the winter have a high capacity for skiing activities (e.g., snowboard, skating) during the winter and walking, trekking, biking, rock climbing, paragliding, rafting in spring, summer and autumn (e.g., Mutana & Mukwada 2018; Noome & Fitchett, 2019) (Figure 1). In several mountain environments (e.g., Pyrenees), it is also popular to pick berries and mushrooms (e.g., Melnykovych *et al.,* 2018; Fuste-Forne, 2020). Mountain areas are also well known for their high landscape aesthetic value (Hermes *et al.,* 2018) and are a popular place for sight-seeing, photography or wild animal watching (e.g., Larm *et al.,* 2018; Ito, 2021) (Figure 1). For instance, several mountain areas are considered sacred areas for many indigenous cultures in the Himalayas (Brandt *et al.,* 2013), Andean (Reinhard, 1985), Mongolia (Sneath, 2014), Japan (McGuire, 2013), North America (Shipek, 1985) and Norway (Myrvoll, 2017), therefore with a very high value for spirituality. Since ancestral times, for protection or the abundance of resources, numerous civilizations were developed in mountain areas, some of them reaching a high stage of development (e.g., Incas) (e.g., Gonzales & Bauer, 2021). Mountain areas are rich in many archaeological sites that are part of our cultural heritage and diversity (e.g., Giannakopoulou & Kaliampakos, 2020) (Figure 1). In Europe, one of the good examples is the agricultural terraces that are good evidence of human adaptation to harsh environments for food production (Brown *et al.,* 2021). Important archaeological sites classified as UNESCO heritage sites are located in mountain areas, such as Historic Sanctuary of Machu Picchu (Peru), Phnom Kulen (Cambodia), Prehistoric Rock Art Sites in the Côa Valley and Siega Verde (Portugal), Sacri Monti of Piedmont and Lombardy (Italy) and Archaeological Site of Delphi (Greece) (https://whc.unesco.org/en/list/). Finally, mountain areas are excellent laboratories to develop cutting edge research and to understand important phenomena such as climate change (e.g., glacier dynamics, Bach *et al.,* 2018; vegetation processes, García-Ruiz *et al.,* 2015), pre-historical human development (e.g., Dreslerová et al., 2020), the interaction between past climate change and human expansion, i.e., agriculture and mining (e.g., lake sediments/pollen, Rey et al., 2017), land degradation (e.g., overgrazing, Umuhoza *et al.,* 2021) or land abandonment (e.g., rural exodus/vegetation encroachment, Nadal-Romero *et al.,* 2021) (Figure 1).

## 5. Drivers of change impacts on ecosystem services

Drivers of change are defined as any action from humans (e.g., land-use change, political decisions) or natural (e.g., earthquakes, volcanic eruptions) origin that can affect directly or indirectly the ecosystems dynamic. These disturbances can positively or negatively impact the ecosystems (Mikša *et al.,* 2020; Pereira, 2020). Mountains are subjected to several drivers of change that can dramatically alter ecosystems and their capacity to supply ES in quality and quantity, such as habitat change, climate change, overexploitation, pollution and invasive species. These drivers of change can act alone or combined, increasing the capacity to change the ecosystems (Pereira, 2020).

### *5.1. Habitat change*

Habitat change has been dramatic in some mountain environments and occurs in different forms (e.g., urban and agricultural expansion/land abandonment) (Figure 1). The drivers of change imposed by recreation and tourism are changing mountains dramatically (e.g., land-use change, habitat fragmentation, conflicts with wildlife, noise, air and soil pollution, greenhouse gas emissions, land degradation, i.e., erosion). This has been observed in the Alps (e.g.; Orsi *et al.,* 2020), Pyrenees (e.g., Badoque *et al.,* 2017), Himalayas (e.g., Yang *et al.,* 2021), Tatra mountains (Fidelus-Orzechowska *et al.,* 2021), to mention some. For instance, Skiing resorts development has a detrimental impact on soil properties, vegetation distribution, biodiversity (Hudek *et al.,* 2020), geomorphological features (Wrońska-Wałach *et al.,* 2019) and wildlife (Stott *et al.,* 2019). Another popular activity that is changing mountain habitats is mountaineering (e.g., climbing, trekking, hiking, biking) (Apollo, 2021). Several works highlighted that the climbers, hikers and bikers are altering land relief and soil (e.g., soil erosion), vegetation and grazers behaviour, animal feeding grounds, and increasing trail degradation, litter and excrement pollution (e.g., Apollo & Andreychouk, 2020; Evju *et al.,* 2021). Although recreation and tourism activities are beneficial for local economies, retain people in rural areas and favour the development of outdoor activities important for human wellbeing (Hanna *et al.,* 2019), there are important tradeoffs associated with the loss of regulating ES, such as global and local climate regulation (Delgado *et al.,* 2007), air quality regulation, water purification, flow and nutrient regulation (e.g., Ristic *et al.,* 2012), natural hazards regulation (Arnaud-Fassetta *et al.,* 2005) and pollination (e.g., grassland flora diversity, Bacchiocchi *et al.,* 2019). The expansion of ski resorts has a strong impact on the conversion of grasslands and agricultural areas to the urban fabric, decreasing the capacity of these ecosystems to supply biomass for energy and food (García-Ruiz & Lasanta, 1993; Theobald *et al.,* 1996), respectively. Also, negative impacts were identified on the local cultural activities (Pickering *et al.,* 2003).

In several mountains of the world, such as in the Peruvian Andes (Tovar *et al.,* 2013), Ethiopian highlands (Kidane *et al.,* 2012) or Thailand (Choenkwan *et al.,* 2014), the pressure for food security and increasing market demand, are increasing the agriculture area expansion. The agriculture intensification in mountain areas can be profitable in the short term regarding food production and can support recreation and tourism activities. Nevertheless, agriculture intensification may have negative impacts on the ecosystems capacity to regulate the climate and the air quality (e.g., Cai *et al.,* 2019), water purification, flow, erosion and nutrients (e.g., Rukundo *et al.,* 2018), natural hazards (e.g., Erena & Worku, 2018) and pollination (e.g., Ritten *et al.,* 2018). Although there has been observed a trend in the increase of mountain areas agriculture, others have been affected by land abandonment, a complex socio-ecological phenomenon observed in several mountain areas of Europe (Lasanta *et al.,* 2017) and Asia (Han & Song 2019). Land abandonment imposes an important disturbance in mountain ecosystems, which can have positive or negative impacts. Associated with land abandonment is the rewilding process that favours several regulating ES such as global and local climate regulation, through the increase of carbon sequestration (e.g., Bell *et al.,* 2020) and water purification, erosion and nutrient regulation (e.g., Lizaga *et al.,* 2018) and biomass for energy and timber (e.g., Pitman & Peace, 2021). As a consequence of vegetation encroachment, there is an increase in plant water consumption, evapotranspiration, consumption and storage. This reduces water flow and the quantity of water that reaches rivers (Khorchani *et al.,* 2021) and aquifers (Ouyang *et al.,* 2021). Afforestation reduces the probability of flash floods and landslides (e.g., Dittrich *et al.,* 2018; Hu *et al.,* 2021). On the other hand, land abandonment and vegetation encroachment increase the fuel available and risk wildfire occurrence (Palaiologou *et al.,* 2017). Regarding the impacts of land abandonment/afforestation on natural hazards regulation, there is an important tradeoff between flood/landslides mitigation and wildfire risk. To mitigate this, it is essential to establish fuel management policies (e.g., prescribed fires) to reduce fire risk without compromising flood regulation (Pereira *et al.,* 2021). Land abandonment decreases the capacity of mountain areas to provide food. In this process, traditions, cultural activities and landscapes are lost (e.g., Hanaček & Rodríguez-Labajos, 2018). For instance, one of the most evident impacts is the agricultural terraces destruction due to lack of maintenance (Stavi *et al.,* 2018). The destruction of these structures can trigger soil, water losses, floods and landslides (e.g., Moreno-de-las-Heras *et al.,* 2019).

Dam construction for hydropower production dramatically impacts freshwater habitats fragmentation, river ecological function and thermal regimes, nutrient and sediment flux and biodiversity loss (Vuong Pham *et al.,* 2019; Barbarossa *et al.,* 2020). Although these infrastructures increase the amount of energy produced from renewable resources, they have profound impacts on fish spawning migratory routes and affect the communities that depend on this resource for food supply (Dugan *et al.,* 2010). Also, wind farms imposed a high disruption in the environment, and several works highlight that they disturb the natural habitats strongly and negatively affect the different trophic levels (e.g., Thaker *et al.,* 2018; Fernández-Bellon *et al.,* 2019). These infrastructures have negative impacts on recreation and tourism (Ólafsdóttir & Sæþórsdóttir, 2019), landscape aesthetics, noise (Kalinauskas *et al.,* 2021) and cultural heritage (Nazir *et al.,* 2020). Finally, as the previous renewable energy resources, solar energy may impose a negative impact on habitats loss and reduce the habitats for pollinators (e.g., McCoshum & Geber, 2020) and landscape aesthetics (e.g., visual quality) (Dhar *et al.,* 2020).

### *5.2. Climate change*

Climate change (e.g., glacier melting, extreme events, and drought periods) negatively affects mountain ecosystems and their capacity to supply services (Figure 1). Although all ES are predicted to be affected, the most relevant impacts are expected in global and local climate regulation, natural hazards regulation, crops, wild food and fish provisioning, freshwater provisioning, renewable energy, recreation and tourism, landscape aesthetics and cultural heritage and cultural diversity (Palomo, 2017; Hua *et al.,* 2021).

Mountain ecosystems are highly vulnerable to small changes in the climate (e.g., Iglesias *et al.,* 2018) and, therefore, to ecosystem change (e.g., tree-line upward) (Cazzolla Gatti *et al.,* 2019). This will likely affect carbon sequestration (global and local climate regulation) (Hua *et al.,* 2021). As a consequence of glacier and permafrost melting and increase in extreme events, natural hazards (e.g., flash floods, landslides, rockfall) are expected to be more frequent and severe (e.g., Terzi *et al.,* 2019; Viani *et al.,* 2020). The increase of wildfires frequency can amplify the high vulnerability to natural hazards, severity and recurrence in a climate change context (e.g., Taboada *et al.,* 2017; Cassell *et al.,* 2019). High temperatures and the prevalence of long and frequent drought periods are expected to increase the vulnerability to wildfires. Severe and recurrent wildfires are the ones that impose more ecosystems damage and affect drastically the ecosystems capacity to recover. Therefore, the expected increase of severe wildfires may trigger other natural hazards such as flash floods (e.g., Nolan *et al.,* 2018; Coscarelli *et al.,* 2021).

The alteration of temperature and precipitation patterns due to climate change will affect the water availability (e.g., glacier melting, reduced snow cover, drought periods) for food production in mountain communities (e.g., Poudel & Duex, 2017), but also in lowland areas that depend on water from glacier and snow melting to irrigate their fields (Huss *et al.,* 2017). Also, climate change impact on ecosystems shift will affect the distribution of wild foods such as berries (Prevéy *et al.,* 2020) and mushrooms (Yang *et al.,* 2012). This impact on mushrooms productivity in some mountain ranges (e.g., Prades Mountains, Catalonia-Spain) will be negative (Karavani *et al.,* 2018). Climate change will also affect adversely mountain grasslands (e.g., afforestation) (Schirpke *et al.,* 2017). The sensitivity to climate change increases with the increasing altitude (Li *et al.,* 2019a), which will have implications on their capacity to supply food for cattle.

Climate change is also expected to negatively impact hydropower energy, mainly due to the snow and ice cover decrease and the reduced glacier volumes that will negatively affect runoff and energy production. These harmful impacts are mainly identified in dry areas, such as central Asia or the tropical Andes, where runoff volume depends on glacier melting (Huss *et al.,* 2017). Decreases in hydropower production were also observed in other regions such as California (Forrest *et al.,* 2018), Brazil (Oliveira *et al.,* 2017) or Portugal (Teotónio *et al.,* 2017). On the other hand, in regions where precipitation is expected to be high (e.g., Three Gorges Reservoir – China), hydropower energy will increase (Qin *et al.,* 2020).

Climate change has a negative and positive impact on mountain recreation and tourism. Winter sports will be negatively affected by the decreasing number of days with snow and ice cover (e.g., Fang *et al.,* 2021). Several solutions have been established to tackle this problem, such as show snowmaking. However, this solution increases energy and water demand (Rixen *et al.,* 2011) and has negative impacts on mountain ecosystems (Wrońska-Wałach *et al.,* 2019). Glacier tourism is also being affected since most mountain glaciers are disappearing, bringing substantial losses to this industry (Wang & Zhou, 2019). Other phenomena related to climate change, such as the wildfire risk increase, discourage tourists from travelling to these areas (Pereira *et al.,* 2021). However, mountain tourism can benefit during heatwave periods, where people can look for refuges in high altitude areas. Finally, climate change and the impacts on seasonality can affect the time when tourists visit mountain areas (Palomo, 2017).

The disappearance of mountain glaciers decreases landscape aesthetics since tourists highly appreciate this landscape, as observed in previous works (e.g., Welling *et al.,* 2020; Salim *et al.,* 2021). The increasing wildfire frequency will decrease temporarily landscape quality and the attractiveness of these areas to be visited (Pereira *et al.,* 2021). Around the world, several mountain landscapes are sacred for different communities located in the Meili Snow Mountains of Yunnan (China), Nepalese Himalaya, Peruvian Andes, Alaska or Canada. The loss of these glaciers will have a detrimental impact on the communities living in these areas (Allison, 2015; Thornton *et al.,* 2019).

### *5.3. Overexploitation*

Mountain environments are subjected to high overexploitation, threatening biodiversity and ES supply (Figure 1). For instance, hunting and poaching practices cause biodiversity loss in some mountainous areas (e.g., Adhikari *et al.,* 2021). The mineral resources demand increases the landslides, debris flow, collapse, and ground deformation and subsidence, with severe implications for the populations living in lowland areas (Shao, 2019). Mineral exploitation imposes a high degradation in the areas where they are established by removing soil and vegetation, drastically hampering these ecosystems' capacity to supply regulating, cultural and other provisioning services (e.g., food, freshwater). Overall, these activities impose a high ES value loss (Dawen *et al.,* 2018).

Overgrazing is another threat to regulating (e.g., global and local climate regulation, water purification, flow, erosion and nutrient regulation, pollination) and provisioning (e.g., food for livestock) ES (Figure 1). This has been identified in several mountain areas of Ethiopia (Mekonen, 2020), China (Hao *et al.,* 2018), Greece (Fetzel *et al.,* 2018) and Central Asia (Nowak *et al.,* 2020), to mention some. For instance, overgrazing reduces the grassland capacity to store carbon (e.g., Zhou *et al.,* 2020), grassland biodiversity (e.g., Nowak *et al.,* 2020), increases soil and nutrient loss (e.g., Zheng *et al.,* 2017; Li *et al.,* 2019b) and reduce pollinators abundance (Naeem *et al.,* 2019). Mountain Forest overexploitation (e.g., timber production) is also a reality in several environments (e.g., Payne *et al.,* 2020), imposing a degradation in the capacity of these ecosystems to regulate global and local climate, air quality (Rawat *et al.,* 2021), water purification, flow, erosion and nutrient regulation (e.g., Negash *et al.,* 2021), natural hazards and pollination. It also negatively impacts non-timber products (e.g., Soe & Yeo-Chang, 2019), landscape aesthetics, and cultural heritage (e.g., Zeb *et al.,* 2019) since several of these areas are considered sacred.

Agriculture intensification in mountain environments also implies a natural resources overexploitation (e.g., water), and it is responsible for soil quality degradation (e.g., von Westarp *et al.,* 2004), changes in pedogenesis process (Tang *et al.,* 2019), erosion (West *et al.,* 2015) and deforestation (Munwar & Udelhoven, 2020). Although agriculture intensification and resources overexploitation may have some short-term positive impact on food production, it has crucial tradeoffs related to global and local climate, air quality and regulation (Ali *et al.,* 2017), water purification, flow, erosion and nutrient regulation (Locatelli *et al.,* 2017), pollination (Christmann *et al.,* 2021), freshwater supply (Rolando *et al.,* 2017), recreation and tourism (Locatelli *et al.,* 2017), landscape aesthetics and cultural heritage (Albizua *et al.,* 2019). Mass tourism expansion increases overexploitation (e.g., Ganie *et al.,* 2019; Mateusz, 2021). For instance, unregulated tourism harms the overexploitation of medicinal plants (Ganie *et al.,* 2019), fuelwood (Laiolo *et al.,* 2004) and water (Singh *et al.,* 2020) in the Himalaya. In the Mediterranean mountains, mass tourism is causing an increase in groundwater exploitation (Pulido-Bosch *et al.,* 2020).

### 5.4. *Pollution*

Mining activities are responsible for high levels of soil and water resources pollution (in the site and off-site) in several mountains of the world, located in Asia (e.g., Wang *et al.,* 2019), North America (e.g., Lemly, 2019), Europe (e.g., Kupková *et al.,* 2018), Africa (e.g., Khelifi *et al.,* 2021) and Australia (e.g., Ali *et al.,* 2017) (Figure 1). The overexploitation of mineral resources is one of the most important causes of land degradation (Gabarrón *et al.,* 2019). Mining harms all the biotic ES 1) regulating (global and local climate; air quality; natural hazards; pollination) and 2) provisioning (crops, livestock, wild food and fish, biomass for energy and timber and freshwater) since mining exploitation involves vegetation and soil removal (e.g., Lee *et al.,* 2017; Rajan, 2019) and increase waterbodies pollution (e.g., Santana *et al.,* 2020). Also, the mining industry affected negatively cultural heritage in several countries (e.g., Ghana and Western Australia) (Apoh *et al.,* 2017). Paradox to the above mentioned, there is a growing interest in preserving old mines as part of cultural landscape and history in some regions (e.g., Pardo Abad *et al.,* 2017).

Agriculture intensification increases soil and water pollution (e.g., agrochemicals, microplastics) (Ennaji *et al.,* 2020; Feng *et al.,* 2021), and this has been observed in several mountain areas (e.g., Wu *et al.,* 2020; Li *et al.,* 2021). Although some benefits are obtained from crop production, agriculture intensification and the impacts on soil are decreasing their capacity to regulate nutrients, and there are high losses through overland flow (e.g., Strohmenger *et al.,* 2020). It is also well known that agrochemicals harm plants flowering and pollinators (e.g., Dupont *et al.,* 2018), reduce freshwater quality (e.g., Loecke *et al.,* 2017) and decrease the waterbodies capacity to supply fish due to diffuse pollution (e.g., Godinho *et al.,* 2019).

The development of tourist infrastructures in mountain areas increases the pollution and greenhouse gases emission (Jamnongchob *et al.,* 2017) due road development, traffic increase (Sundriyal *et al.,* 2018), infrastructure construction, waste production (Semernya *et al.,* 2017) and litter in wildland environments (Hu *et al.,* 2018). Although for the region, this can represent an increase in recreation and tourism activities. It will have important tradeoffs on other ES such as air quality regulation, pollination and freshwater supply (Sundriyal *et al.,* 2018; Kamel, 2020).

### 5.5. *Invasive species*

Invasive species in mountain environments are a consequence of multiple human impacts such as land-use change (e.g., plantations), nitrogen deposition and tourism development (e.g., infrastructure development) (Figure 1). Other aspects such as the herbivores abundance, pests and diseases, wildfires or landslides have implications on plants distribution. Climate change has direct (e.g., productivity, competitive balance, phenology) and indirect (e.g., changes in hydrological regime) impacts on plant distribution. Although the invasive species spread in mountain areas is not so easy as in other ecosystems due to climate conditions, when alien species pass this filter, it is complicated to manage and reverse their spread due to the complex topography. Invasive species in mountain environments is a global phenomenon and are mostly of agricultural origin (McDougall *et al.,* 2010, 2011; Kueffer *et al.,* 2013).

For instance, the proliferation of *Eucalyptus* spp. (a native specie from Australia) for timber production in several mountains of the world has dramatic impacts on the environment. This specie is planted in all the continents i.e., Africa (Piiroinen *et al.,* 2018), America (Durán *et al.,* 2017), Europe (Oliveira & Tome, 2017) and Asia (Chen *et al.,* 2021). *Eucalyptus* ssp. plantations are well known to have a high-water consumption than the native forests (White *et al.,* 2021), reduce biodiversity (Deus *et al.,* 2018), increase soil degradation (Banfield *et al.,* 2018) and the vulnerability to wildfire risk (Nunes, 2012). Rubber, palm oil plantations are other invasive species that cause high land degradation in mountain areas (e.g., Leite *et al.,* 2018; Vijith *et al.,* 2018).

Tourism development is an important cause of plant invasion. For example, hiking trails and roadsides are considered major paths of alien plants spread in mountain areas (Liedtke *et al.,* 2020). Also, the introduction of species of fish (Tiberti *et al.,* 2019) and herbivores (Martín-Esquivel *et al.,* 2020) in high lands dramatically impact native fauna. There are several examples where the introduction of non-native herbivores leads to a very high environmental degradation (e.g., sheep in Iceland, Barrio *et al.,* 2018).

Finally, climate change is expected to increase invasive species spread in mountain areas. However, this is a more serious problem in low land areas. Since mountain areas have a harsh climate, the alien species spread is difficult. However, climate change may favour the environmental conditions required for non-native species that affect high altitudes (Petitpierre *et al.,* 2016). In addition, as mentioned previously, with climate change, it is expected that wildfires will be more severe and frequent, increasing the risk for plant invasion, as observed in previous works (e.g., Reilly *et al.,* 2020).

Several studies have been developed about the impact of invasive species on ES (e.g., Vilà & Hulme, 2017; Rai & Singh, 2020). There are several tradeoffs involved in the impacts of invasive species in mountain environments. Forest plantations can have some benefits in the production of biomass for energy and timber. However, they have a low capacity to regulate global and local climate than native forests (Yu *et al.,* 2019). Therefore, the establishment of non-native species plantations cannot be considered an advantage. Plantations affect the capacity of the ecosystem dramatically to regulate water flow, erosion and nutrients – mainly in young plantations - (e.g., Liu *et al.,* 2017), pollination (Potts *et al.,* 2010), freshwater supply (León-Muñoz *et al.,* 2017) and recreation and tourism (Benra *et al.,* 2019). Climate change impact on invasive species is expected to affect native pollinators negatively (e.g., Schweiger *et al.,* 2010; Silva *et al.,* 2021).

## 6. Conclusion

Mountains ecosystems are key for human existence and provide many biotic and abiotic ES to the local communities and lowland inhabitants. Although these environments can be inhospitable and challenging to colonise, humans have developed strategies oaf adaptation and established flourishing civilisations in mountain areas throughout history. The ES supply by these environments is immense, though their exploitation can produce different tradeoffs. The excessive exploitation of one determined ES (e.g., mining) can trigger a cascade of adverse effects in all the other ES. Therefore, to maintain the continuous ES supply in quantity and quality, it is vital to rationalising all ES's exploitation to reach the necessary equilibrium in utilising mountain resources. Sustainable approaches are needed in the ES management in mountain environments. This is a challenge for our and future generations.

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