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EVALUATION OF ECOSYSTEM SERVICES IN MOUNTAIN PROTECTED AREAS:
A MULTI-METHOD COMPARATIVE STUDY

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ABSTRACT

Mountain regions are critical ecological, climatic and cultural keystones with far-reaching significance, representing biodiversity hotspots and supply areas for fundamental ecosystem services. Nonetheless, these areas are undergoing multiple threats caused by climate change and anthropogenic pressures, which severely impact their ecosystems, and their consequent capacity to provide ecosystem services. Ecosystem services (ES) are defined as the benefits provided by ecosystems, and are vital for human well-being, playing a pivotal role in shaping the relationship between humans and the natural world. The valuation of ES is gathering more interest over the years, also from policy and decision makers. Such valuation provides holistic inputs for management and decision-making, taking into consideration the intricate interconnected elements that constitute an ecosystem, and reconnecting the natural sphere with economy and society. Despite the growing importance of this topic, the evaluation of ES lacks a common methodology, resulting in a variety of approaches and leading to potential discrepancies in outcomes when evaluating the same ES. However, evaluation and mapping of ES represent a fundamental tool for conservation of fragile areas, such as mountain areas, providing a quantitative and spatial understanding of the heterogenous provision of these benefits across the areas. This study represents a multi-disciplinary approach to the valuation of ES in mountain protected areas, with particular regard to the climate regulation service and cultural ecosystem services. The focus is on two mountain protected areas located in different geographic areas: the Adamello Regional Park, an Alpine protected area located in the North-western Italy, and the Troodos National Forest Park, a Mediterranean mountain protected area located in the earth of Cyprus. Further, data on another Alpine study area – the Gran Paradiso National Park, Italy - were collected and analysed in the previous study of our laboratory and have been used in this thesis for carrying out comparisons between geographically similar areas.

An intensive literature research was conducted, analysing 956 papers regarding ecosystem services in mountain areas, and gathering information on input data, indicators and type of evaluation for each ecosystem service. This is presented in Annex I, being analysis carried out as a coauthor. The result of this review was that a multitude of diverse approaches can be used for valuating ES, ranging from direct and indirect measurements to economic valuations and social surveys. However, there is an urgent need for the understanding of the discrepancies that ensue

when different approaches are employed. The review thus underlines the need for implementing a common methodology for valuation of each ES.

The thesis then proceeds towards four specific research studies. In the first study, the focus was on quantifying the organic carbon (OC) stock, a crucial indicator for evaluating the climate regulation service. There is a current lack of data gathered on-field for the valuation of the OC stock in mountain protected areas, hence fieldwork activities were carried out to collect samples and information in three critical pools: soil, aboveground biomass, and litter. Metadata on environmental features were described in each plot, which allowed us to determine the correlations between OC stocks and the characteristics of the study areas. Hence, a quantification of the OC stock in the pools was carried out in the most representative habitats of the two study areas, the Adamello Regional Park, and the Troodos National Forest Park. Moreover, a description of the forest structure and biodiversity was undertaken, and soils were classified according to the soil World Reference Base (WRB) classification. Results highlighted the mosaic of carbon storage within pools, habitat type and soil type, with the coniferous forest as the most stocking habitats with highest OC levels. Correlations with environmental features such as elevation and forest structure were also described, improving the understanding of the complex process of carbon stock accumulation.

Given the various methods available to evaluate ES described earlier, and the need for comparisons to evaluate discrepancies, the second study aimed to compare three approaches to evaluate the climate regulation service. Field data from two Alpine protected areas were collected - one from the Adamello Regional Park, and the other from a previously studied area - the Gran Paradiso National Park (studied by our laboratory using a common protocol for quantifying carbon stocks). The objective of this study was to identify the differences between the approaches and the advantages and disadvantages of each. The three approaches considered were: a) collecting data through fieldwork, which was the method used in the first study; b) collecting data from the Italian Forest and Carbon Inventory (INFC), which used the same methodology as the fieldwork data collection, but at a regional rather than local scale; and c) using the TESSA toolkit, a widely used tool for rapid assessment of ES. Significant disparities were identified between TESSA and the other two methodologies, leading to results with TESSA that sometimes exceeded the other approaches twofold. As fieldwork data collection can require significant resources, we suggest a minimum number of plots to perform an efficient assessment of OC stocks, limiting the expenses in term of resources and time.

The third study aimed to explore the dynamics of forest cover change at the Adamello Regional Park. Given that forests were found to be the most stocking habitats in the first study, this demonstrated the importance of understanding the changes in forest cover in protected areas. Remote sensing is a powerful tool for analysing land cover change, providing a synoptic view of the study area, and enabling the quantitative analysis of changes in cover over time. Landsat data were collected at a ten-year interval between 1988 and 2022. The Google Earth Engine platform was used to analyse the data collected, and a supervised classification of the changes between forest and non-forest was conducted using the Random Forest algorithm. The results confirmed the ongoing trend in the alpine areas, in which we experience an increase in forested coverage, however the decade 2010-2022 resulted in a net loss of forest areas, probably due to an extreme storm that occurred in the area and biotic disturbances.

The fourth study concerned the evaluation of cultural ecosystem services at the Adamello Regional Park and the Gran Paradiso National Park. First, 33 semi-structured interviews were carried out with park managers and municipality representatives, to detect their perception of potential threats to the areas, and their perception of ES. Tourism emerged as a potential threat. We found a common agreement both on the potentiality of tourism for the economic development of mountain areas, and on concerns regarding the dangers of mass tourism leading to the exploitation of mountain area resources. However, tourism is one of the important occupations in these alpine areas, and it is necessary to understand users' attitudes towards tourism, and their perception of the benefits provided by alpine protected areas. Hence, a total of 3399 questionnaires were administered in the two areas, in which socio-economic and other information was collected, along with their stakeholder categories, attitudes towards tourism, changes in attitudes due to the COVID-19 pandemic, and perception of 21 critical ES. Due to the large volume of data collected, this study was split into two papers, one referring to users' attitudes towards tourism, and the second, using these data to profile the perception of ES within different user categories. It was found in the first subchapter that the concerns of park managers and municipality representatives were confirmed: the majority of users were indeed one-day visitors, contributing to the phenomenon of mass tourism. Moreover, it was detected that generally senior-aged and repeat visitors were the ones with the longest stays, while younger-aged and first-time visitors were the ones with the shortest stays. Following this, in the second subchapter it emerged that the aesthetic value of landscape, nature observation, and biodiversity conservation were the most perceived ES in the areas. However, there was poor or limited perception of the fundamental regulating and provisioning services. Users that already acknowledged the concept of ES had the highest perception as demonstrated by a significant correlation between these categories - suggesting that, through knowledge, an improved awareness of the importance of ES can be promoted. Finally, some suggestions for the communication strategies for increasing ES perception were given, with the aim of engaging more users to increase their sense of attachment to mountain areas, thereby contributing to their conservation.

Finally, this study contributed to enhance the knowledge of ecosystem serviced in several ways. By measuring carbon levels in different habitats, this study improved our knowledge of carbon storage in mountain protected areas. Various approaches were compared to evaluate the climate regulation service, and the results showed the need for a standardised methodology to avoid biased outcomes. Forest contributed substantially to the provision of ES, and it was found that their coverage at the AD increased over the years, however the implications for the ES provision must be investigated. The study conducted a social evaluation of the ecosystem services provided by the Alpine areas, outlining future steps to enhance perceptions and communication targeting.

CHAPTER 1

General introduction

1. Mountain areas and vulnerabilities

Mountain's regions are crucial to biodiversity conservation, hosting half of the world's biodiversity hotspots (Butchart et al., 2010). In fact, due to their physical conditions related to slope and elevation, communities and abiotic conditions change rapidly over relatively short distances, creating a turnover of diverse habitats and contributing disproportionately to the global biodiversity (Quintero & Jetz, 2018); mountains cover only the 25% of Earth's land area, but are home to more than 85% of the world's species (Rahbek et al., 2019). Moreover, mountains provide a huge quantity of ecosystem services (Grêt-Regamey *et al.*, 2012b), such as climate regulation, natural hazards protection, soil erosion control, water regulation, and even cultural and recreational services (Schirpke *et al.*, 2021a). These areas are also fundamental for the survival and well-being of large human populations, providing a wide range of goods and services to both populations living inside and outside the mountains (MEA, 2005). As defined by the United Nations Conference on Environment and Development in 1992 (UN, 1992) "*Mountains are important sources of water, energy, minerals, forest and agricultural products and areas of recreation. They are storehouses of biological diversity, home to endangered species and an essential part of the global ecosystem. From the Andes to the Himalayas, and from Southeast Asia to East and Central Africa, there is serious ecological deterioration. Most mountain areas are experiencing environmental degradation*." Basic resources as food or freshwater are linked to mountain areas, and it is estimated that more than the 24% of worlds' lowland area will depend on mountains for the provision of water resources by 2050 (Viviroli *et al.*, 2020).

Nonetheless, mountains are found to be particularly vulnerable to climate change (Kohler & Maselli, 2009; Gonzalez *et al.*, 2010; Elkin *et al.*, 2013), and responses to changes are likely to be heterogeneously distributed. These areas are being subjected to accelerated warming with (Adler *et al.*, 2022), with an surface air temperature that resulted in a warming 0.3° C per decade (IPCC, 2018), with local warming rates depending on seasonality (Adler *et al.*, 2022). From the consequences of such accelerated warming, the melting of the cryosphere is one of the most known (Oerlemans, 2001; Laghari, 2013). The melting of cryosphere has impacts on water regimes, and it is forecasted with high confidence that these changes will continue occurring (IPCC, 2022), causing different impacts of the water availability, possibly causing tensions and conflicts for resources. Snow and ice in fact, represent a major input into rivers basins, and the decline of snowfall and glaciers are likely to have a huge impact on the freshwater availability, affecting both lowland and upland populated areas (Beniston & Stoffel, 2014; Sorg *et al.*, 2014). Changes in the precipitation regimes were forecasted, heterogeneously spread among mountain regions, having areas such as the European Alps in which an increase of the order of 5 to 20% over the 21st century is predicted, and areas where a decrease is forecasted, such as in the Mediterranean area (IPCC, 2022). Concerning the European Alps, the increase will not be evenly distributed throughout the year, but mostly related to natural extreme events, such as extreme rainfall events (Rajczak & Schär, 2017). Also, natural hazards processes are predicted to increase in terms of frequency and intensity with high confidence (Gariano & Guzzetti, 2016; IPCC, 2022), leading to adverse changes in mountain social and ecological systems (Schneiderbauer *et al.*, 2021).

Climate change is causing a shift in vegetation belts in mountain regions, leading to an upward shift in the spatial distribution of trees (Rosenzweig *et al.*, 2007; Gonzalez *et al.*, 2010; Steinbauer *et al.*, 2018; Hagedorn *et al.*, 2019). This leads to displacement of numerous species, altering the whole ecosystem and their capacity to provide ecosystem services. These forest dynamics have been exacerbated by the recent abandonment of agricultural lands in mountain areas (MacDonald *et al.*, 2000), reflecting the trend of the rural depopulation, and due to the disadvantages of such economic activities, which are no longer economically sustainable due to the low incomes and the enormous effort required. The agricultural and livestock activities undertaken in mountain grasslands had developed, over time, a semi-natural environment with a huge biodiversity associated. Grasslands and alpine meadows are fundamental habitats that act as biodiversity hotspots (Wilson *et al.*, 2012) and provide several ecosystem services. Hence, the substitution of grasslands areas into woody environments will lead to changes in the ES provided by these areas (Sala & Maestre, 2014), and represents a severe loss in natural capital (MacDonald *et al.*, 2000).

Moreover, the climate warming has impacts mountain areas also through biotic disturbances caused by insects and plants pathogens (Seidl *et al.*, 2017). As the temperature increases, ecosystems become less able to handle disturbance. It is estimated that between 2003 and 2012 biotic disturbances reduced substantially the provision of fundamental forest ecosystem services, affecting temperate forests even more that wildfires (Harvey *et al.*, 2023). One example related to the Alps, one area investigated in this study, is the spruce bark beetle (*Ips* *typhographus*), that is currently being an important threat to forests, particularly for Norway spruce forests (Wermelinger, 2004; Nardi *et al.*, 2022).

Finally, humans' activities subject mountains to strong disturbances, changing and degrading ecosystems. European mountains are subjected to medium to high human influences (Rodríguez-Rodríguez & Bomhard, 2012). Over the past hundreds of years, human activities have reshaped landscapes and modified the ecosystems, causing deforestation (Darby, 1955; Kaplan *et al.*, 2009), habitat fragmentation (Wulder *et al.*, 2006), loss in soil quality (Newmark, 1998; Zheng *et al.*, 2017), and loss in biodiversity (Chettri & Sharma, 2016; Liedtke *et al.*, 2020). Several drivers of change and disturbance are attributable to human activities in mountain areas, ranging from unsustainable tourism (Duan *et al.*, 2021), to habitat fragmentation (Hock *et al.*, 2019) and directs impacts on biodiversity. For all the mentioned reason, there is an urgent need for conservation of these fundamental regions, which on one hand are fundamental for the provision of several ecosystem services, and on the other hand are critically threatened.

2. Ecosystem services

The concept of ecosystem services (ES) has emerged as a fundamental topic in the fields of ecology and environmental science, highlighting the strong linkage between human survival and the health of ecosystems, and demonstrating the human existence depend on the benefits provided ecosystems (Costanza *et al.*, 1997; MEA, 2005). The Millennium Ecosystem Assessment (MEA), an international initiative that assessed the world's ecosystems and the impact of human activities, defined ecosystem services as "*the benefits that ecosystems provide for human well-being*". The assessment highlighted the deep human dependence on the wealth of ecosystems and the urgent need to preserve them through a sustainable use of ES. In the MEA, ecosystem services were classified into four main categories: provisioning, regulating, supporting and cultural. Provisioning services are those associated with material outputs from ecosystems, such as food, fibre, genetic resources and freshwater. Regulating services, refer to the services in which the ecosystem acts as a regulator, e.g., climate regulation, erosion control, protection against natural hazards. Supporting services are those ecosystem services that underpin the existence of the other categories, such as nutrient cycling or primary production. Eventually, cultural services relate to the social sphere, including the recreational, spiritual, inspirational and aesthetic values of ecosystems.

After the MEA 2005, another international initiative - The Economics of Ecosystems and Biodiversity (TEEB, 2010) - highlighted linkage between ecosystem services and economy. The innovative aspect of the concept of ES lies in its role as a bridge between the economy and the environment, connecting human societies (Daily & Matson, 2008), the conservation of natural capital, and embodying the interaction between nature and humans. In fact, the concept of ecosystem services is critically dependent on the concept of natural capital, defined as *the stock of resources provided by an ecosystem*. The term "capital" reconnects the environmental sphere with the economic sphere, where the value of ecosystems has often been overlooked or even neglected (Tallis & Kareiva, 2005). The natural capital, in order to provide benefits, must interact with other capitals relying on human beings, namely human capital, built capital and social capital (Costanza *et al.*, 2017).

As our world is facing complex environmental challenges such as climate change, habitat degradation and biodiversity loss, understanding and valuing ecosystem services has become essential for sustainable development and informed decision-making. The MEA estimated that around 60% of ecosystem services are already degraded or subject to inappropriate use (MEA, 2005), and over the years there has been a decline in the ecosystems' capacity to provide most of the ecosystem services (IPBES, 2019) (Fig.1.1). Global changes are projected to progressively cause a loss of ecosystem services (Masson-Delmotte *et al.*, 2021). Hence, the valuation of ecosystem services results a critical tool for understanding the processes ongoing in the ecosystems and to undertake adaptative and informed changes, that fundamental for ensuring the supply of these services and the health of ecosystems. It enables us to make informed decisions that balance economic development with conservation of the natural world, ultimately ensuring a sustainable future.

Figure 1.1. Global trends of the capacity of ecosystems to provide contributions to good quality of life from 1970 to present. Source: IPBES global assessment 2020

2.1. Ecosystem services in mountain areas

Mountainous areas are one of the most important regions for the supply of ecosystem services (Grêt-Regamey *et al.*, 2012a), but to multiple drives of disturbance threatens the health of these environments, such as climate change effect, infrastructure development, habitat fragmentation and mass tourism (Kohler & Maselli, 2009; Hock *et al.*, 2019). All categories of ecosystem services are provided by these heterogeneous areas, and they are therefore a fundamental element in supporting human existence. In terms of regulating ecosystem services, mountains are responsible for climate regulation, through the sequestration of carbon from the atmosphere (Canedoli *et al.*, 2020), soil erosion control (Dai *et al.*, 2020), protection against natural hazards (Sebald *et al.*, 2019), and water regulation (Roa-García *et al.*, 2011). Mountains are the supply area for a wide range of provisioning services, providing materials such as food, fresh water, raw materials and, timber (Ngwenya *et al.*, 2019). Finally, cultural ecosystem services are also provided to a large extent by mountain areas; indeed, mountains are the destination of many tourists, demonstrating the elevated demand for cultural ecosystem services (Scolozzi *et al.*, 2015; Schirpke *et al.*, 2016). Recreational, aesthetic, and nature observation values are highly valued cultural ecosystem services in mountainous regions. However, mental well-being, inspirational, and spiritual values are also present in these areas. However, services in mountain areas are unevenly distributed, highlighting the need for evaluating and mapping them. This will ensure a coherent mountain management plan that aligns with the distribution of ecosystem services. Finally, the demand for ecosystem services has risen exponentially, causing a mismatch between the supply capacity and demand. Protecting mountain areas is not only essential for preserving unique ecosystems and biodiversity but also for sustaining human well-being, ensuring the provision of fundamental ecosystem services to populations.

2.2. Evaluation of ecosystem services and their importance in the management of protected areas

Ecosystem services are an efficient tool for giving a holistic description of the interconnections between processes that occur in an ecosystem. Through the evaluation of ecosystem services and the adoption of a common approach, an integrative assessment of the benefits provided by an ecosystem can be carried out. Revealing explicitly the trade-offs between the ecosystem services lead to a comprehensive view of the impacts of human activities on ecosystems and, through informed management, there is the possibility to target strategies that allow to ensure the provision of such ES. Evaluation means assigning a "value" to a particular object or process under study, and the particular concept of "value" can be linked to multiple spheres, from ecology to economy and society. It is critical to recognise that economic and ecological valuations may be contrasting at time, since ecosystem function and processes have an intrinsic value, that often cannot be economically represented (Farber *et al.*, 2002). Scholars have assigned multiple terms to distinguish the diverse methodological approaches (Cheng, 2019), and in the case of this thesis we will address to the term of evaluation, referring to the process of assigning an ecological and social value to some ES, rather than to a specific economic quantification, which would fall under the term of valuation. However, it is essential to express explicitly the value of ecosystem services, especially for those services that decision-making has neglected and overlooked due to difficulties in quantifying and economically valuing them, such as regulating and supporting services. These are extremely important for life on Earth, but their valuation is more difficult than that of provisioning services, being the latter materials and their value have already been reflected in the market transactions (Sutherland *et al.*, 2018). Hence, processes related to non-material benefits - such as air purification, primary production, soil erosion control, nutrient cycling – have been often neglected in the economic accounting and decision making (Costanza *et al.*, 1998). In addition, cultural ecosystem services have also been overlooked in decision and policy making (Mengist *et al.*, 2020a), being linked to social and non-use values.

Valuations of ecosystem services can come with multiple dimension, namely biophysical, economic and socio-cultural (Boyd *et al.*, 2015). Biophysical values are obtained from the quantification of ES performance, both through direct and indirect measures (e.g., tons of carbon stocked in soil), but result in values that can be defined, measured and modelled. Economic valuations are referred to the price of market of the services, or eliciting the valued from the willingness to pay for non-material benefits (Ghermandi *et al.*, 2010), since several ecosystem services do not have a market price and issues in the accounting exist (Boyd & Banzhaf, 2007). However, these economic valuations must be considered as underestimations, and the actual market value may be larger than estimated (Costanza *et al.*, 1997). Social values refer mostly to material a non-material values that people perceive and feel connected to. These values are generally measured through surveys among users and express the perception of a group of people regarding ES. These values are even more difficult to include in monetary transactions, but their understanding is fundamental for creating a linkage between ecology, economic and societies. Chan et al. (2011) demonstrated that cultural ecosystem services arise a “sense of attachment” in people, that may lead to public engagement for conservation actions. For instance, through the understanding of users’ perception of ES in a particular area there may be the possibility of developing targeted projects that help to develop public awareness, and raising a sensibility towards these environments, fostering a greater sense of responsibility and support for conservation (Daniel *et al.*, 2012). Another issue emerging with evaluations is the need for standardized evaluations and shared indicators. Previous studies demonstrated that some ES are more valued than others (Mengist *et al.*, 2020b), such as cultural and provision ecosystem services, whereas regulation and supporting ES resulted to be the least studies. Over the years ecosystem services have gained interest from a broad audience (Costanza *et al.*, 2014), however there is an urgent need for a standardization of the methodologies and the indicators for the evaluation of ES (Tallis & Polasky, 2009) In fact, there is no common agreement on which indicators, approaches and input data shall be used for the evaluation of each ES, and this leads to a non-standardized valuations, that often cannot be compared (Canedoli, 2023).

Mountain protected areas have a fundamental in protecting the ES provision (Schirpke *et al.*, 2021b), and quite recently, managers needed to shift from fighting only internal problems related to the protected area, to preserving areas from external problems mostly related to climate change, beyond the existing internal problems and pressures (Catalan *et al.*, 2017). Over the years, there is an increasing interest in valuing ES for policy and decision making (Guerry *et al.*, 2015), and many protected areas have adopted ES assessments to monitor the status of the area and implement their management strategies. Evaluating ES helps to assess the potential economic risk of degrading the capacity to provide ES, guiding management towards economic and environmental decisions that favour the maintenance of ES. Firstly, evaluations help to assess the current status of the area, establish a baseline against which to monitor trends in change, predict future ES supply capacity or examine changes that have occurred in the past. Mapping ES is a fundamental tool for geo-referencing the results of assessments, providing a spatial description of the supply of ES, which is heterogeneously distributed across the many habitats of mountain areas. Moreover, for protected areas ES evaluation helps in anticipating social, economic and ecological impacts of management strategies (Schirpke *et al.*, 2017), and leads to a social inclusion of stakeholder (Young *et al.*, 2013), which were subjected to the effects of management approaches, but often neglected in the decisional process. Finally, evaluation allows for adaptive management strategies, where decisions can be adjusted based on changing ecosystem conditions and values.

3. Thesis outline

Mountains are under diverse threats that will impact their capacity of supplying ecosystem services. The evaluation of ecosystem services is proved to be an efficient tool in understanding the processes in ecosystems, and to aid managers and decision makers to undertake strategies towards the protection of ES. Mountain protected areas are critical areas due to the huge biodiversity hosted within their boundaries, and the several ES provided. In this study, we aimed to evaluate some critical ecosystem services in mountain protected areas, and explore different approaches for the evaluation of ES, trying to identify possible discrepancies. Furthermore, the thesis highlights the significance of forests in these areas in providing ecosystem services (ES). Consequently, an essential question was raised regarding the changes in forest cover over time in the study area and the impact on the provision of ES.

This thesis addresses some of these identified gaps by contributing to the current lack of knowledge regarding the following topics: i) evaluation of the climate regulation service using in situ collected data that quantify of the organic carbon stock in Alpine and Mediterranean mountain areas, ii) how different methodologies can result in diverse outcomes for the evaluation of the climate regulation service and the management implications, iii) the forest cover dynamics of the last 35 years in an alpine protected area, iv) the perception of ecosystem services and the attitudes of visitors of alpine protected areas.

This thesis is arranged into 6 chapters, including 2 subchapters due to the huge amount of data collected in cultural ecosystem services evaluation. This introduction (**Chapter 1**) that provided an overview of the current knowledge of the ES and is followed by a collection of papers (two of which in preparation, and three already published, under review or submitted). In the last chapter, a synthesis and analysis of the overall outcomes is provided.

The beginning of this project relies on a literature review present in **Annex I**, in which I have collaborated for the data analysis and was the starting point for my PhD project. The focus was on the indicators existing for the evaluation of ecosystem services in mountain areas, having as time span 2015-2020, and analysing 965 papers. It resulted that, even for the same ecosystem service, there are often a multitude of evaluations which do not share the same indicators, input data and output data, leading to difficulties in the comparisons of results and to a global exchange of information regarding ES. From this, it emerged the idea of this thesis on the evaluation of cultural ecosystem services on alpine protected areas, and of one of the most valued regulating ES - the climate regulation service - using different approaches and comparing the outcomes in different study areas, to detect and spatial variability in the outcomes.

In **Chapter 2** we undertook the evaluation of the climate regulation service, using the organic carbon (OC) stock as indicator. For clarity reasons, the chapter includes both the study at the Adamello regional Park, an Alpine protected area located in Italy, and the Troodos National Forest Park, a Mediterranean mountain protected area situated in Cyprus. The chapters were merged to avoid repetitions, as they share the same protocol. The first draft of this project only included alpine protected areas due to possible comparisons, and the second study area should have been located in the Indian Himalayas (Great Himalayas National Park) but due to the travel limitations cause by the COVID-19 pandemic, and the limited possibilities for fieldwork data collection, we changed the project towards mountain regions and we collected data were no other data on soil OC stock was ever collected, the Troodos massif. We collected data on soil, aboveground biomass and litter through fieldwork activities, investigating 114 plots at the Adamello Regional Park and 23 plots at the Troodos National Forest Park. We gathered information of environmental features of each plot, to determine correlations with the carbon storage. We collected environmental DNA samples from each soil layer to study soil biodiversity in different habitats. However, the results will not be presented in this thesis due to delays in the analysis process.

Then, since the OC stock is one of the most used indicators for the climate regulation service, but is estimated using a multitude of approaches, we carried out a comparison of three diverse approaches in **Chapter 3**. The focus was on determining the difference between these approaches in terms of effort in the data collection and the accuracy of the outcomes. Being that the data collected in Chapter 2 were specifically related to the areas investigated, we used these as the reference base to determine the magnitude of the variations in the outcomes using a national inventory of carbon stock (INFC 2005) and TESSA Toolkit, a tool used for the quick assessment of ES, that relies on the IPCC tables.

Due to the importance of forest in the provision of ES, particularly the climate regulation service, studied in Chapter 2 and Chapter 3, we wanted to assess the changes in their extent from the institution of the protected area, to understand the forest cover dynamics occurring within the study area and to understand if these are leading to an improvement of ecosystem services. This study was carried out during the period at the Azim Premji University, where I had the possibility of learning how to use the Google Earth Engine platform to undertake land cover classification, since this was one of research topics of the university's team. Hence, **Chapter 4** includes the forest-non forest classification at the Adamello regional Park, focusing on the decadal changes from 1988 to 2022. Analyses of the relevant environmental features related to trends in forest cover were undertaken to provide insights into explanations of the changes that have occurred over the years of the study. This chapter was not specifically related to the valuation of an ecosystem service, but was the direct result of the previous chapters, since by studying the environments that provide ES and their land cover dynamics, it was possible to understand what happened in the past, and to give informed suggestions to mitigate and preserve the supply of ES.

Eventually, due to the huge importance of Alps as a tourist destination, **Chapter 5** includes the analysis of 3399 questionnaires administered to visitors of the Adamello Regional Park and the Gran Paradiso National Park, and 33 semi-structured interviews to managers and municipalities' representatives. This part of the thesis encompasses **Subchapter 5.1**, in which we addressed to the attitudes of visitors of PAs, the issues of mass tourism and managers' perception regarding tourism, whereas **Subchapter 5.2** focuses on the perception of ES and their prior knowledge, and from the outcomes we provided suggestions for managers and stakeholders for communication strategies and management insights. We split the chapter since there was a huge amount of data, and for clarity purposes we preferred to focus on one topic at a time, although the data used in subchapter 5.1 were fundamental for the understanding of ES and their perception and were included as variables in the analyses.

Eventually, in **Chapter 6** we presented conclusions regarding the results obtained, and future perspectives for the ecosystem services evaluation were provided.

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CHAPTER 2

THE EVALUATION OF THE ORGANIC CARBON STOCK IN MOUNTAINOUS PROTECTED AREAS

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In preparation

Abstract

Ecosystem services (ES) are essential for human well-being. There is limited research on the quantification of climate regulation service provision through measurements in situ in the Alpine and Mediterranean mountainous environments. Organic carbon (OC) serves as a commonly used indicator for this valuation. In this study, we aimed to quantify the OC stock in three pools, namely soil, Above Ground Biomass (AGB) and litter, in two study areas situated in mountain regions: the Adamello Regional Park (AD), an Alpine protected area located in the North-western part of Italy, and the Troodos National Forest Park (TRD), a Mediterranean protected area located in Cyprus. A fieldwork data collection was conducted in the most representative habitats of the areas, at the AD these were represented by Norway spruce forests, grasslands, larch forest, mixed coniferous forest, mixed deciduous forest and chestnut forests, whereas at the TRD there were Pallas pine forest (*Pinus nigra subsp. pallasiana*), Pallas pine forest and low forest vegetation with *Quercus alnifolia*, *Pinus brutia* forest with low forest vegetation with *Quercus alnifolia*, pure *Pinus brutia*, and mixed forest with Pallas pine, *Pinus brutia* and *Quercus alnifolia*. A total of 137 plots were studied, of which 114 at the AD and 23 at the TRD. For each, metadata on the environmental features were collected, and sampling involved measures of the Diameter at Breast Height and height of each tree, and collection of soil samples at standard depth layers, and litter by horizons. At the AD we found that soil was the most stocking pool 8.7 kg/m^2 and mixed coniferous forest was the habitat that stocked the highest quantities of OC (10.4 kg/m^2 in soil, 9.7 kg/m^2 in AGB and 1.5 kg/m^2 in litter). Elevation resulted to be significantly correlated with OC stock in soil and litter, whereas the basal area with AGB OC stock. At the TRD it resulted that AGB was the pool that stocked most of the OC (7.6 kg/m^2), with the mixed habitat of *Pinus brutia* with *Quercus alnifolia* as the most stocking in OC for soil (4.6 kg/m^2), pure *Pinus brutia* for the AGB (10.4 kg/m^2) and the mixed forest of all the three species for litter (1.5 kg/m^2). It was found that OC stock in litter was positively correlated with elevation and tree basal area, whereas a correlation between soil and AGB stock was found. Further research must be carried out to determine the cause-effect relationship of these correlations, and to investigate the linkages between OC stock and other environmental features, such as rainfall regimes and temperature. Such investigations will aid in determining the key factors influencing OC stock in the studied areas, to better understand the provision of this ES, and facilitate the development of forecast models.

1. Introduction

Mountains cover the 30% of the world's land area and encompass the 23% of the land forests, providing habitat to biodiversity (Zhang & Wang, 2023; Zhang *et al.*, 2023). They also play a crucial role in the provision of a multitude of fundamental ES, such as water regulation, erosion control, natural hazard protection, habitat provision and cultural ecosystem services (Gret-Regamey *et al.*, 2008; Grêt-Regamey *et al.*, 2012; Crouzat *et al.*, 2022). Mountain regions also have a huge capacity of storing carbon dioxide, providing an essential ecosystem service (ES): the climate regulation service. The interest regarding the valuation of such fundamental ES is growing, being included in many monitoring and management plans, and environmental certifications (Seifert-Granzin, 2011; Goetz *et al.*, 2022). However, the effects of climate change are likely to cause a loss of carbon storage capacity (Sjögersten *et al.*, 2011), even in areas in which the vegetation may increase (Jones *et al.*, 2003). Other climate-change related dynamics are expected to affect the mountain regions in the coming years, including the upward shift of the vegetation belts (Lenoir *et al.*, 2008; Cazzolla Gatti *et al.*, 2019), or the enhanced soil respiration rates due to global warming (Zhang *et al.*, 2023). Nonetheless, these changes are not uniformly spread across the mountain regions and still many uncertainties exist concerning how these changes will affect the OC stock. This can be addressed both to the complexity of carbon storage dynamics (Hilton & West, 2020) and to the lack of site-level measurements (Bangroo *et al.*, 2017). It is important to investigate these areas to quantify the current carbon stock values accurately, understand the relationship between carbon storage and the environment, establish a baseline for monitoring, inform conservation strategies, and allocate resources to prioritize habitats needing urgent conservation action. This thesis adopts the term "habitat" in alignment with the General Habitat Categories (GHC) classification introduced by Bunce *et al*. (2011). The GHC classification is rooted in the plant life forms of Raunkanier and based on the dominant layer of the vegetation, emphasizing the concept that habitat structure is intricately linked to the environment. Most of the habitats studied belong to the TRS (Vegetated tree/shrub) or the HER (vegetated herbaceous) category, due to the percentage in the vegetation coverage. Consequently, this thesis interprets habitat in accordance with the prevailing forest type in the study area, treating the two terms interchangeably, and assigning to the habitat the name of the forest/vegetation type accordingly to the national geoportals. It is acknowledged that this choice may not be optimal, but it is informed by the fact that the majority of habitat maps used in this study primarily rely on vegetation cover for delineation.

Little information is available regarding the quantification with site-level measurements of the OC stock alpine habitats (Canedoli *et al.*, 2020), and even less is known about Eastern Mediterranean mountain areas (Evrendilek *et al.*, 2006), in which most of the literature focused on agricultural areas rather than mountain forests. Accurate measurements can help in monitoring over time, and guide policies and strategies towards the mitigation of climate change. The changes predicted for the Cyprus Island are related to a higher temperature rise inland areas, particularly the Troodos Massif, and a reduction in precipitations that varies from 6% to 18% from 2021 to 2050 (Giannakopoulos *et al.*, 2010). These changes may affect the carbon stock process, probably towards a decrease in the carbon stock in Mediterranean areas. This underlines the critical importance of studying these areas to understand which are the current carbon stocks, and inform managers with precise data, in order to develop mitigation and management strategies focused on the safeguard of these areas.

This research was undertaken in two mountain protected areas, situated in two different geographical areas: one is located in the Alps (Adamello Regional Park, Italy) and the other in a Middle Eastern Mediterranean Island (Troodos National Forest Park, Cyprus). We aimed to (1) provide a quantification of the OC stock in three carbon pools - soil, litter and aboveground biomass (AGB), (2) to establish correlations between the environmental features and carbon stock among the diverse pools and habitats. The in-situ valuations provided by this study may be used for the monitoring and forecast of OC dynamics, setting a baseline of the current status of the carbon storage and its distribution within multiple habitats, correlated to the study areas' environmental features.

2. Materials and methods

2.1.Study areas

2.1.1. The Adamello Regional Park

The Adamello Regional Park (AD) (Fig.2.1) was established in 1983 through regional law no. 79/1983. It is located in the northern Italy, in the Rhaetian Alps within the Lombardy region. Its elevation spans from 390 to 3,539 m.a.s.l, and the Adamello peak is its highest point. It covers an area of 51,000 hectares, the park borders the Trentino Alto-Adige region to the east and is situated between two National Parks: the Adamello-Brenta National Park and the Stelvio

National Park. The park's diverse vegetation cover reflects its wide elevation range, having broadleaf forests in lower altitudes, and coniferous forests and shrublands above 2,000 m.a.s.l. The park hosts a rich variety of plant species, particularly in the alpine grasslands, situates in the highest elevations of the area. It is home to a diverse array of wildlife and numerous pristine mountain lakes and rivers are located within its boundaries. The forest coverage in the Camonica Valley, which is the area covered by the AD, has been significantly influenced by the historical use of timber resources for human livelihood, economic development, and conflicts, including world wars. Different management strategies were adopted over time depending on the owner of the area, such as the Venetian Republic until 1800 or the subsequent French dominion. During the world wars in 1900, forests were intensively used, which reduced the effectiveness of previous management strategies. However, in the 1930s, huge afforestation strategies were undertaken during the Fascist period, mostly favouring coniferous species such as *Picea abies* and *Larix decidua*. After the mid-1900s, a policy regarding forest conservation and development was established. This was accompanied by an increase in industrial and tertiary sector activities, which resulted in the gradual abandonment of land in mountainous areas (Agnoletti, 2007). Nowadays there are many regulations regarding the forest management, particularly the PA is divided into three areas (northern, central and southern) in which diverse managers are present. Within the PA’s boundaries the active management of the forest is promoted through Forestry Consortium, to whom the PA assigned the management, whereas the landowners are responsible of the forest management through forestry settlement plans. Civic use is a real right of collective use that belongs to those who make up a given community, and the entire PA is subjected to right of Civic use (Ducoli, 2012).

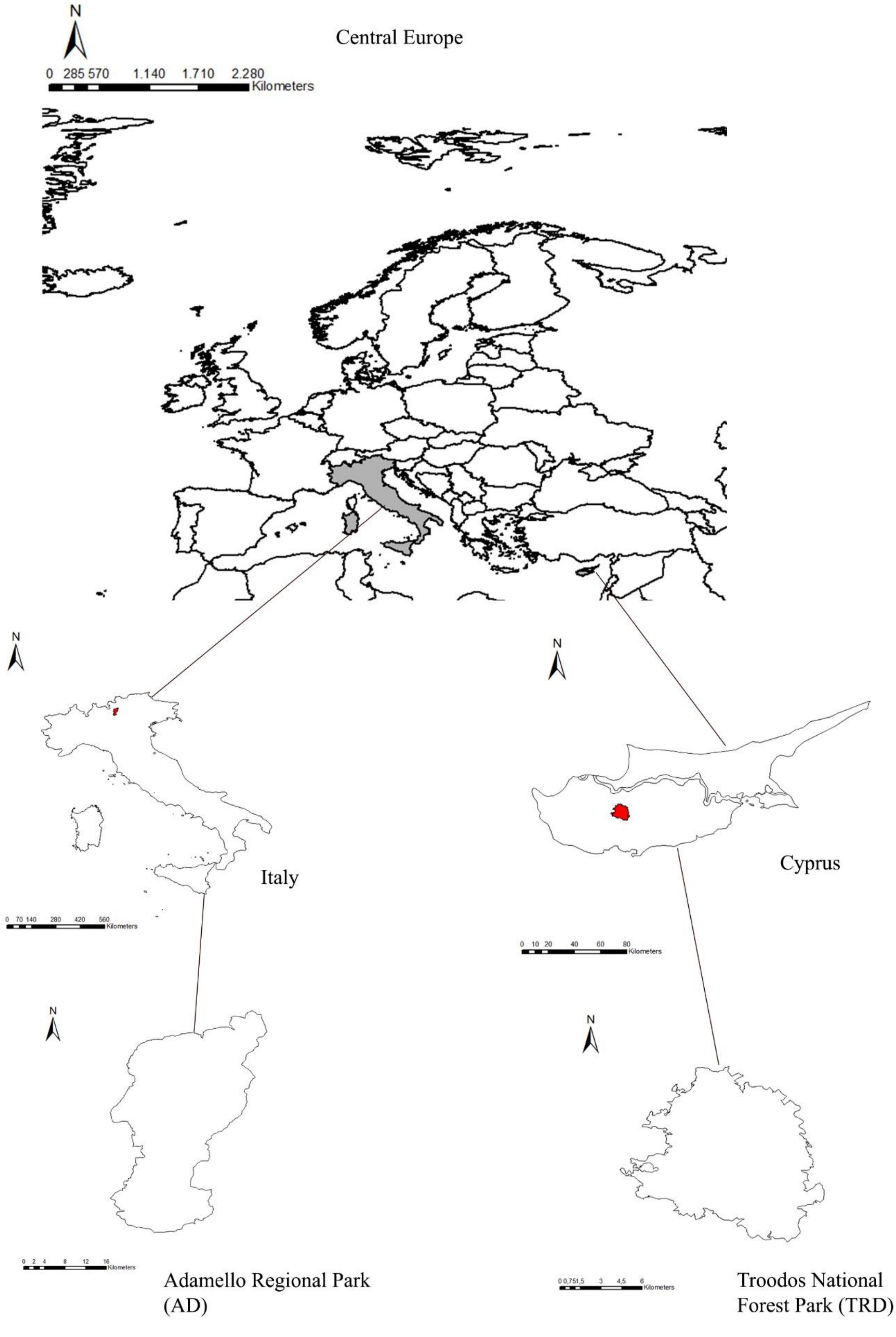
N
Central Europe
0 285 570 1.140 1.710 2.280
Kilometers
N
Italy
0 70 140 280 420 560
Kilometers
N
Cyprus
0 10 20 40 60 80
Kilometers
N
0 2 4 8 12 16
Kilometers
Adamello Regional Park
(AD)
N
Troodos National
Forest Park (TRD)

Figure 2.1. Location of the study areas, on the left the Adamello regional Park, on the right the Troodos National Forest Park. Source: Natural Earth Data (https://www.naturalearthdata.com/features/)

2.1.2. The Troodos National Forest Park

The Troodos National Forest Park (TRD) (Fig.1) *was* instituted *in* 1992 and designated also as UNESCO Global Geopark due to its geological features. It is located in Cyprus, in the eastern Mediterranean, and it covers an area of 9147 hectares. Its elevation ranges from 700 to 1952 m.a.s.l, with its highest peak at the Mount Olympus. Being a Mediterranean mountain area, during summer the lower elevation of the park can often exceed 30°C, whereas during winter the Troodos mountains is subjected to snowfall, and temperatures can drop significantly due to its elevation. The remarkable vegetation at the Troodos mountains is composed of *Pinus nigra* (subsp. *pallasiana*), at the highest elevations, *Pinus brutia*, *Cedrus brevifolia, Cupressus sempervivens, Juniperus foetidissima* and *Platanus orientalis.* Concerning the tall shrubs, it is noteworthy the *Quercus alnifolia* (Golden Oak), an endemic species restricted on Troodos mountain range. Cyprus underwent during 1800 to intensive land clearing for crop production, and currently, apart from *Quercus alnifolia*, which is an endemic low shrub, Cyprus no longer sustains oak forest, except for small and isolated trees. During the late 1800, Cyprus underwent to the British control, its forests were highly reduced and degraded. However, British authorities instituted the Department of Forestry, and undertook reforestation activities using native species. After World War II there was a massive timber harvesting, but during 1950s the Department of Forestry launched a massive reforestation effort, especially including indigenous Pines, as the *Pinus brutia*. Currently, the forest area of Cyprus is mostly confined in higher elevations and in the Troodos National Forest Parks. Most of Cyprus' forests are managed by the Turkish Cypriot and Greek Forestry Department, and private landowners (Ciesla, 2004).

2.2. Sampling and laboratory analyses

2.2.1. Habitat selection

Concerning the AD, the vegetation cover map was obtained from the forestry plan (PIF) of the area with respect to the year 2018. The map was compared with the forest map provided by the Lombardy region and the maps shared the same information. The map represented the vegetation attitudes according to the geoportal of Lombardy Region ("Geoportale della Regione Lombardia"), fort clarity purposes the vegetation cover were merged into main categories of vegetation types indicated by the forest types proposed by the Lombardy region, as follows: 1) spruce forest (composed mostly by *Picea abies* L.), 2) encompassing the categories of larch forest (composed of *Larix decidua* Mill.), 3) chestnut forest (composed mostly by *Castanea sativa*), and then the green alder shrubland (composed mostly by *Alnus viridis*), which differentiated a little from the Lombardy region due to the low presence of other Alnus, and then the mixed coniferous forest, mixed deciduous forest. Grasslands were not present in the forest map provided by the Park, but due to their extent and relevance for the topic, they were extracted from the DUSAF map provided by the Lombardy region in its Geoportal (https://www.geoportale.regione.lombardia.it/) . Concerning the TRD, the vegetation cover was obtained from the Natura 2000 map of 2017 (Tzirkalli *et al.* 2018) and provided by the Forestry Department of Troodos, the habitats selected were Pallas pine forest (cod. 9536), Mediterranean pine forest (cod. 9540, 9390*), and a mixed category containing *Quercus alnifolia* (cod. 9390).

Soil and litter samples were collected during the summers of 2021 and 2022 at the AD, and during autumn 2023 at the TRD. Plots had a standard dimension (30 × 30 m), and a stratified random sampling design distributed across the most representative habitats of the study areas was undertaken (Fig.S1, S2). A total of 114 plots were investigated at the AD and 23 at the TRD. The habitats of the study were identified through the maps provided by the parks, and only the most spatially extensive habitats were chosen for this study, keeping as a threshold a minimum of 5% of coverage on the total area of the park (Table 2.1, Table 2.2). The primary types of Troodos were Pallas pine forest (N) (*Pinus nigra* subsp. *pallasiana*), Pallas pine forest and low forest vegetation with *Quercus alnifolia* (NQ), *Pinus brutia* forest (B), *Pinus brutia* mixed with *Quercus alnifolia* (BQ), and the mixed forest of the three species (NBQ). The parks also contain rocky environments and aquatic environments, but for the purposes of the study, these were not encompassed due to the scarce presence of soil and their limited spatial extension.

Table 2.1. Plots distribution at the Adamello Regional Park

HABITAT	NUMBER OF PLOTS
CHESTNUT FOREST	5
GRASSLAND	31
GREEN ALDER FOREST	15
LARCH FOREST	13
MIXED CONIFEROUS	14
MIXED DECIDUOUS	8

SPRUCE FORESTS	28

Table 2.2. Plots distribution and abbreviations at the Troodos National Forest Park

HABITAT	NUMBER
PINUS BRUTIA MIX QUERCUS ALNIFOLIA (BQ)	7
PINUS NIGRA FOREST (N)	7
PINUS NIGRA MIXED QUERCUS ALNIFOLIA (NQ)	3
PINUS NIGRA, PINUS BRUTIA, QUERCUS ALNIFOLIA (NBQ)	3
PINUS BRUTIA FOREST (B)	3

2.2.2. Soil and litter sampling and analyses

A total of 114 plots were investigated at the AD and 23 at the TRD. The number of plots was chosen accordingly with their geographical extent and the number of habitats present. We collected 337 soil samples and 180 litter samples at the AD, and 69 soil and 51 littler samples at the TRD. In each plot, three excavations (mini-pit) were performed, and soil samples were collected from depth layers (0–10 cm; 10–20 cm; 20–40 cm) in each mini-pit. A composite sample for each depth layer (≈100 g) was created. Sampling by layers allowed comparisons among different plots that might have different horizons. We collected a volumetric sample of soil were possible, to obtain data on the bulk density, being a fundamental factor for the quantification of the OC stock. Litter samples were collected by organic layer in a standard area (18x18cm) near each mini-pit, and a composite sample for each layer was created. Soil samples were analysed to determine physical-chemical characteristics, such as soil organic carbon (SOC), total nitrogen (TN), (Flash EA 1112 NCSoil, Thermo Fisher Scientific elemental analyzer, Pittsburgh, PA, USA), and pH in water (soil to water ratio of 1:2.5). Particle-size and distribution were also determined via sieving and sedimentation. Litter samples were analysed to determine dry biomass, organic matter, SOC and TN. Soil types were determined according to the World Reference Base (WRB) (2015).

The soil organic carbon stock in soil (SOC_{stock}) was quantified for each investigated depth as follows:

$$SOC_{stock} = SOC*BD*d*(100-Vrf)$$

Where SOC_{stock} is the value of soil organic carbon stock (kg m^{-2}), d is the layer thickness (m), SOC is the organic carbon content (g kg^{-1}), BD is bulk density (kg dm^{-3}), and Vrf is the rock fragment volume (%). BD was measured using samples gathered for each depth layer, where the Vrf allowed the sampling. The BD was calculated for each depth layer with data collected in situ for both the study areas, that allowed the creation of specific pedotransfer functions (Table 2.3). For the Troodos massif, a specific pedotransfer function was created for each habitat, since the data allowed this distinction, whereas for the Adamello we could not distinguish the habitat, but a pedotransfer function was created for each depth layer.

Table 2.3. Pedotransfer functions used for the estimation of the BD, where C(%) represented the percentage of organic carbon content, Vrf the rock fragment volume, and C:N the carbon-nitrogen ratio.

Adamello Regional Park	
Layer	**Pedotransfer function**
0-10 cm	1.0435*C(%)^2-0.255
10-20 cm	-0.183*ln(C(%))+1.0861
20-40 cm	-0.185*ln(C(%))+1.358
Troodos National Forest Park	
Habitat	**Pedotransfer function**
B, BQ	1.35-0.17*C(%)-0.011*Vrf+0.03*d
N pure	1.69-0.13*C(%)-0.014*Vrf-0.01
NBQ, NQ	1.14-0.12*C(%)+0.004*C:N-0.004

The organic carbon stock in litter $SOC_{stocklitter}$ was quantified as follows:

$SOC_{stocklitter} = (SOC/1000) \times OMB$

where $SOC_{stocklitter}$ is the of soil organic carbon stock in litter (kg m^{-2}), OMB is the organic matter biomass (kg m^{-2}), and SOC is organic carbon content (%) in the organic layers.

2.2.3. Above ground biomass

In each plot, the tree component of vegetation was investigated. The species of all trees observed were described, and their height and diameter at Breast Height were measured. Height measurements were obtained using the Forestry App MOTI. In cases where the apex was not visibly accessible, a lanyard was deployed and used for measurement, whereas DBH was measured per each tree, using a soft meter, at a standard height of 130 cm. Due to the abundance of green alder shrubland, which represented the fourth most extended habitat of the area, we collected data on the number of branches of the tall shrub, *Alnus viridis*. We then calculated indices of diversity and forest structure for tree species. Stem density (SD) was determined as the number of trees per hectare. It was calculated as following:

SD= *n* / A *10000

Where *n* is the number of stems in the plot and *A* is the plot total area (900 m^2). SD indicates the stem density (n° of trees/m^2) of the plot considered.

Tree basal area (BA) was measured as the cross-section of a tree's trunk at breast height (1.3 m) and then calculated for the entire plot and converted from cm to m^2. It was calculated as follows:

$$BA = \pi \times (DBH/200)^2$$

BA is the basal area (m^2), DBH is the Diameter at Breast Height (cm). The sum of the BA of each tree results in the total BA for the plot (m^2/plot). This value is then converted into square meters per hectare.

The relative dominance (RD) and the relative stem density (RSD) were calculated for all the trees measured in our area. Finally, the Shannon Index (HSH) and Evenness were calculated to detect the diversity of tree species.

We estimated the aboveground biomass (AGB) density of trunk and branches (dw1) (according to Tabacchi et al. 2011) for the Adamello using allometric equations specific to the site and species (Table S1), accordingly to the protocol for a previous study area, the Gran Paradiso National Park (Canedoli et al. 2020), in order to yield comparisons. Allometric equations are previsional models that result in the estimation of the dependent variable (y_0), which in this case was the phytomass (kg). The independent variables were measured during fieldwork activities and were DBH (cm) and H (m), where the DBH was more than 10 cm. The general model for the estimation of phytomass were, according to Tabacchi et al (2011):

1) $y_0=b_0+b_1d^2h$
2) $y_0=b_0+b_1d^2h+b_2d$

3) $y_0=b_0+b_1d^2h+b_2d^2$

where b_x represented specific coefficients (that depend on species, environmental variables and geographic area), *d* was the DBH, and *h* was the Height. Specifically, equation 1 concerned *Acer pseudoplatanus, Carpinus betulus, Fraxinus excelsior, Fraxinus ornus,* and *Salix caprea,* whereas equation 2 concerned *Castanea sativa, Larix decidua, Prunus avium*. The remaining species were related to equation 3, except for *Alnus viridis* which had a different general allometric equation being a shrub and having only a measurement of the branches. The coefficient for each species and the allometric equation were listed in Table S1.

Concerning Cyprus there was a lack of site and species specific allometric equations, and we relied on published allometric equations of the two studied species and in the neighbouring area of the study area, e.g. Turkey. However, for the latter the equations referred to the total AGB, including all the component of the trees, but for the purpose of the thesis were considered as an option, since no comparison between the Troodos and the Adamello was undertaken. From the AGB density, the AGB OC stock was obtained with the IPCC (2003) conversion coefficient. Data on deadwood were collect during fieldwork activities but were not used for the purpose of this thesis. The analysis of forest structure included an assessment of diversities within different forest type categories. Diameter classes were established, each named with the average number of the class (e.g., class 15 encompassed values $10 < d \leq 20$). Subsequently, the average number of trees per class was determined for each species within each forest type, and corresponding percentages were calculated. Additionally, ipsometric curves were constructed to illustrate the relationship between diameter and height for each plot and species. Using our data, the average diameter per species was derived for each plot, and the average height was estimated using the ipsometric equation specific to the species and plot.

Eventually, for the calculation of the Leaf Area Index (LAI), 10 photos were taken in each plot using a hemispherical camera—two at each corner, stepping approximately one meter inside the sampling area, and two at the centre. In forested habitats, the camera was positioned facing the sky, while in alder stands, marshes, and meadows, it was directed towards the ground. Eventually, the Leaf Area Index (LAI) was measured using the software CAN_EYE, which performs a supervised image indexing, classifying pixels belonging to vegetation, sky and ground, then calculating the overall LAI.

3. Analyses

Analysis of Variance (ANOVA) and Post Hoc tests (Tukey HSD, Fisher LSD) were performed to determine significant differences in the variance between habitat feature and OC stock. To determine the relationships between all the features we performed a Pearson Correlation Matrix for each PAs, to assess the presence of correlations between two variables at a time. Hence, we used a principal component analysis (PCA) to assess the relationship between carbon stock and the environmental values, measuring the linear relationship between multidimensional values. The results of the PCA were represented as bi-plots, where carbon stock and explanatory variables were projected on a bi-dimensional graph and defined by two canonical axes. The statistical analyses were performed using R studio and StatSoft Statistica.

4. Results

4.1. The Adamello Regional Park

4.1.1. Soil type, forest structure, and environmental features

Soil WRB classifications and their distribution varied among habitats (Fig. S.2.2). The habitat that resulted in the highest number of soil types was grassland, and we attribute this result to the heterogeneity of this habitat type, which encompass many varieties of grasslands according to the dominant species (Gentili, 2010). Most of the soils resulted to be Umbrisols (32%), Cambisols (28%) and Podzols (24%), whereas a small percentage of soils were Regosols (7%), and Phaeozem (4%), the remaining soils were Luvisol, Histosol, and Kastanozem (Table S.2.3).

Our finding indicate that pH values are significantly lower in spruce forest (4.3, $p<0.005$) when compared to grasslands (5.33), while the Leaf Area Index resulted to be significantly higher in grasslands (3.8, $p<0.05$) than in mixed deciduous forests (1.8). Forest stand structure was described to disentangle the diverse habitat types (Table S.2.4). Basal Area (BA) revealed a statistically significant difference between spruce forest (52.8 m^2 ha^{-1}, $p<0.001$) and mixed deciduous forest (24.58 m^2 ha^{-1}), as well as between spruce forest ($p< 0.05$) and larch forest (36.8 m^2 ha^{-1}). Moreover, mixed deciduous forest differed significantly in BA with mixed coniferous forest (52.46 m^2 ha^{-1}, $p<0.01$), and chestnut forest (52.16 m^2 ha^{-1}, $p<0.05$). Concerning the Stem Density (SD) we encountered statistically significant differences between the chestnut forest (1077 trees/ha, $p<0.005$) and larch forest (455 trees/ha). The SD may be lower in the mixed deciduous forest due to the fact that these forests are highly composed of trees that were not considered in the SD calculation, due to their small sizes of the trunk, such as *Corylus avellana*.

However, these counts were included in the study only for the description and discussion of the diversities within the habitats.

The analysis of the forest structure aimed to identify potential differences between forest types and reasons for addressing diversities in OC stock. The initially reported Mixed Deciduous Forest (Figure S.2.12) as *Fraxinus excelsior* forest was reclassified after thorough analysis of forest structure, considering the relative dominance of species and stem density. Consequently, it was identified as a Mixed Deciduous Forest. The most abundant species in this reclassified forest was *Fraxinus excelsior* (676 trees/ha), primarily in the lowest diameter category (<10 cm DBH), indicating an increase in new individuals. *Castanea sativa* also featured prominently in the same class. Analysis of the percentage of trees per diameter class revealed an uneven-aged structure, particularly for the most abundant species, with over 60% of individuals falling within the <10 cm diameter category (class 5).The Chestnut Forest (Fig. S.2.13) exhibited considerable heterogeneity in species composition, especially in the class of small trees. The most abundant species, *Castanea sativa*, demonstrated a more even-aged distribution with a peak in the smaller class, likely influenced by forest management and timber logging. However, when considering all tree species in this forest type, an uneven-aged structure became apparent, similar to the Mixed Deciduous Forest. The Coniferous Forests, characterized by fewer species, displayed a more even-aged structure. For instance, the Larch Forest (Fig. S.2.14) featured four species, with *Larix decidua* and *Picea abies* having comparable tree numbers. Analysis suggested a potential shift in the Larch Forest at the AD, where *Larix decidua*, with higher average diameter values, is possibly being replaced by expanding *Picea abies*. This transformation might lead to the development of a mixed coniferous forest over time. The Mixed Coniferous Forest (Fig. S.2.15), dominated by *Picea abies, Larix decidua,* and *Pinus sylvestris*, emerged as the forest type with the least species and the most even-aged structure, primarily due to the prevalence of Picea abies. Notably, the Spruce Forest (Fig. S.2.16) was predominantly composed of *Picea abies*, with a mix of coniferous and deciduous species, possibly indicating vegetation shifts. The overall structure of this forest type was characterized by an uneven-aged distribution, with *Picea abies* and *Larix decidua* having the majority of small trees. For a more comprehensive description of the forest composition, we present the average Diameter at Breast Height (DBH) and Height values (Table 2.5.1.) for each species within each forest type. Height values were derived using ipsometric equations (Figure S.2.17), which illustrate the relationship between diameter and height. These values underscore that, on average, *Castanea sativa* exhibited the highest DBH in deciduous forests, while *Fraxinus excelsior* was predominantly associated with smaller diameters. Furthermore, our analysis revealed that *Larix decidua* tended to have a smaller size in mixed coniferous forests, aligning with our earlier findings of this forest type being the most even-aged. Conversely, *Larix decidua* exhibited a larger size in spruce and larch forests, surpassing Picea abies in height. These findings are pivotal for a comprehensive understanding of the Organic Carbon (OC) stock.

Table 2.5.1. Average values for (DBH: Diameter at Breast Height) and H (Height), and their standard deviation (StDev) divided per habitat type.

Mixed deciduous	Average DBH	StDev DBH	Average H	StDev H
Castanea sativa	43.00	8.97	16.83	1.17
Fraxinus excelsior	23.66	7.51	13.63	4.10
Larix decidua	39.79	-	15.00	-
Picea abies	30.24	-	12.00	-
Prunus avium	36.22	-	17.70	-
Robinia pseudoacacia	35.44	-	19.69	-
Chestnut forest	**Average DBH**	**StDev DBH**	**Average H**	**StDev H**
Betula pendula	20.32	1.43	10.55	0.63
Carpinus betulus	16.87	-	7.00	-
Castanea sativa	41.69	11.65	12.83	4.74
Fraxinus excelsior	17.27	6.45	15.12	6.90
Fraxinus ornus	14.64	-	8.00	-
Larix decidua	28.33	-	11.00	-
Picea abies	25.43	9.25	6.68	2.38
Populus tremula	45.77	-	22.44	
Prunus avium	19.02	4.76	10.83	4.80
Tilia cordata	33.71	-	22.21	-
Larch forest	**Average DBH**	**StDev DBH**	**Average H**	**StDev H**
Betula pendula	19.42	-	8.50	
Larix decidua	38.32	9.47	13.94	5.78
Picea abies	24.77	5.00	10.44	5.58
Mixed coniferous	**Average DBH**	**StDev DBH**	**Average H**	**StDev H**
Larix decidua	32.62	7.67	20.69	13.58
Picea abies	33.15	9.01	19.91	12.11
Pinus sylvestris	31.69	-	27.63	
Spruce forest	**Average DBH**	**StDev DBH**	**Average H**	**StDev H**
Abies alba	34.84	-	23.03	-
Betula pendula	17.79	5.01	11.63	4.71

Castanea sativa	25.37	2.39	9.18	2.39
Larix decidua	39.04	10.41	21.34	10.41
Picea abies	36.54	9.12	18.39	9.12
Pinus nigra	35.73	1.24	13.02	1.24
Pinus sylvestris	26.99	-	12.60	-

4.1.2. Organic carbon stock in soil, litter and tree aboveground biomass

The organic carbon stock was assessed in the three selected pools. On average, 57% of the organic carbon was found in soil mineral layers (Fig.S.2.4), 4% in organic layers, and the remaining 34% in above-ground biomass. The soil, on average, stocked 8.7 kg/m^2, with mixed coniferous forest having the highest stock at 10.4 kg/m^2, followed by grasslands with 10.1 kg/m^2 (Table 2.5.2). Concerning litter (Fig.S.2.5), the average stock was 0.7 kg/m^2, with spruce forest having the highest stock with 2.0 kg/m^2. The AGB (Fig. S.2.6) had an average stock of 5.8 kg/m^2, with mixed coniferous forest again being the most stocking habitats with 9.7 kg/m^2, chestnut forest having an average stock of 8.3 kg/m^2 and spruce forest with 8.2 kg/m^2.

Table 2.5.2. Average OC stock per habitat and pool (kg/m^2)

Habitat	*Soil*	*AGB*	*Litter*
Mixed coniferous	10.4	9.7	1.5
Grassland	10.1	-	-
Spruce forest	9.5	8.2	2.0
Larch forest	8.8	5.9	0.7
Green Alder Shrubland	7.8	1.5	0.1
Mixed deciduous	6.8	7.9	0.3
Chestnut forest	6.5	8.3	0.5

4.1.3. Correlations with the environmental features

The ANOVA (Fisher LSD test) revealed significant disparities among the habitats studied concerning the OC stock. Differences in carbon stock within the first mineral soil layer (0-10 cm) were observed across almost all habitats. Chestnut forest exhibited statistically significant differences when compared to mixed coniferous forest ($p<0.05$), grasslands ($p<0.05$) and spruce forest ($p<0.05$). Grasslands were observed to differ significantly from green alder forest ($p<0.05$)

and mixed broadleaves ($p<0.05$). Lastly, spruce forest differed significantly from mixed deciduous forest ($p<0.05$). There were no significant differences found in the other depth layers across the habitats. However, the overall organic carbon (OC) stock showed a significant difference ($p<0.05$) between grasslands and mixed deciduous forests. Concerning soil OC stock and soil types, we found statistically significant differences within WRB classifications (Table S.2.3). Umbrisol differed significantly (10.37 kg/m^2, $p<0.05$) from Phaeozem (6.73 kg/m^2). Regosols (3.10 kg/m^2) resulted in significantly lower values compared to Umbrisols ($p <0.000$), Podzol (10.34 kg/m^2, $p<0.000$), Cambisol (8.85 kg/m^2,$p<0.001$) and Kastanozem (8.95 kg/m^2, $p<0.05$).

There was a significant variability in OC stocks between habitats with respect to organic layers. In fact, the results show that spruce forest ($p<0.005$) and mixed coniferous forest ($p<0.05$) had a significant difference when compared to all other habitats. No significant differences were found among the tree AGB OC stock, while the green alder shrubland significantly differed from all the remaining forested habitats ($p<0.05$).

A Pearson Correlation matrix was conducted to identify the correlations ($p<0.05$) between the variables studied. Forest habitats (Fig.2.3) were analysed separately due to the inclusion of variables related to forest structure and diversity. It emerged a positive correlation with the soil OC stock, and a negative correlation with AGB OC and litter OC stock. Litter OC stock showed a strong positive correlation with higher values in coniferous relative dominance, whereas a negative correlation was found with higher pH values. This remarks that higher OC stock is present in acidic habitats, such as coniferous forest. AGB OC stock was negatively correlated with pH and Leaf Area Index values. The latter is possibly due to the fact that the highest LAI values were associated with green alder shrublands, which had the lowest values in OC stock. Considering the totality of the habitats (Fig.2.4), elevation positively correlated with higher values of in OC stock, represented by mixed coniferous forests and grasslands, whereas we detected a positive correlation with pH values, which possibly resulted from to the pH range of grasslands (4 -7.6), being less acidic than coniferous forests.

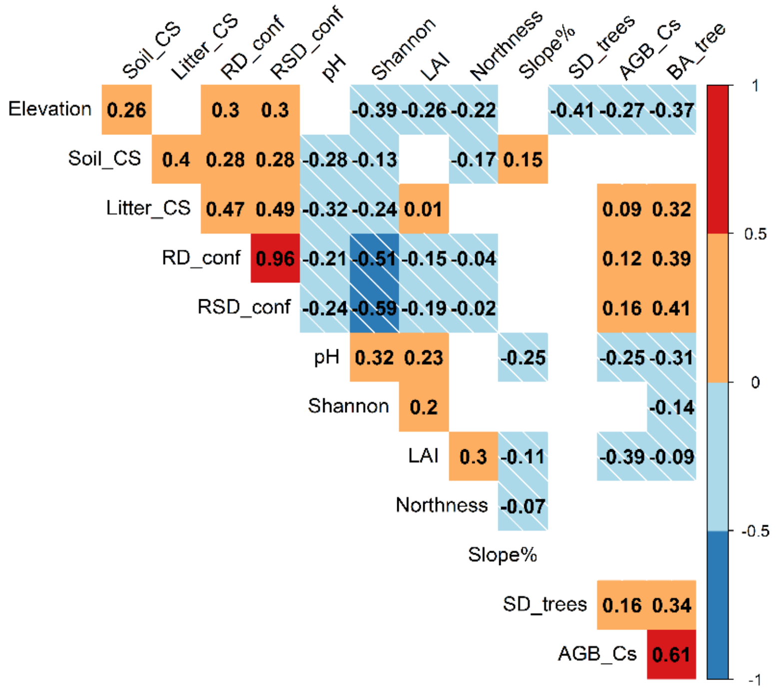

Figure 2.3. Pearson coefficient correlations in forested habitat showing variables that resulted to have p<0.05. Codes for the variables included (SD_trees: stem density, soil_cs: soil oc stock, litter_cs: litter oc stock, rd_conf: relative dominance coniferous trees, rsd_conf: relative stem density coniferous trees, agb_cs: aboveground biomass oc stock, BA_trees: basal area)

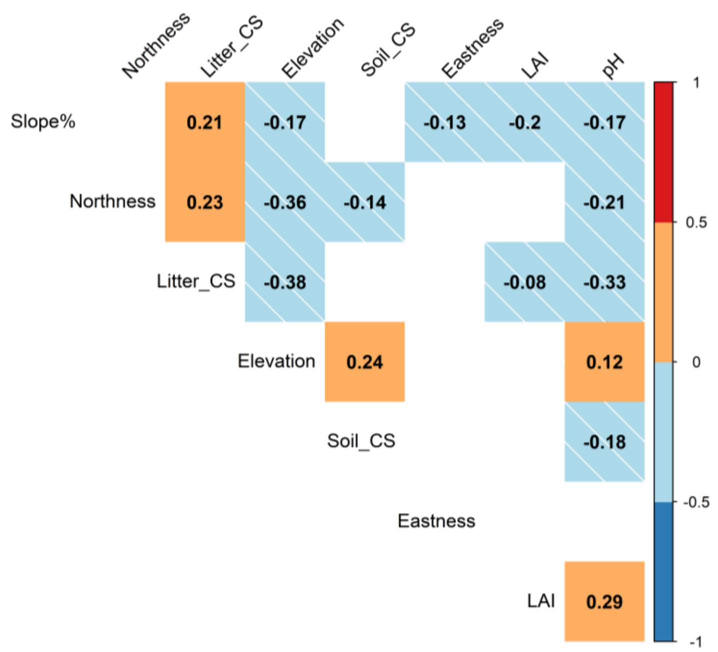

Figure 2.4. Pearson coefficient correlations in all the habitats filtered by statistically significant variables (p<0.05).

Principal component analysis (PCA) was used to disentangle the correlations between multiple factors, both environmental characteristics and OC stock. We performed two separate analyses for the totality of the habitats and forested habitats only, due to the forest diversity and structure variables. Concerning the forest habitats (Fig.2.5), our analysis explained the 50% of the variability, and it emerged a positive relationship between elevation, OC stock in soil, OC stock in litter and little correlation with higher slopes. A negative correlation was found with the previous cluster and higher Shannon index and pH, remarking the highest stocks in coniferous forests, which resulted in almost pure habitats with acidic soils. Finally, the AGB was positively correlated to the highest trees BA. Concerning forest and grasslands (Fig. S.2.7), we only detected a positive correlation between organic carbon stock in soil and higher values of LAI, and a negative correlation with slope, factors which generally associated with grasslands.

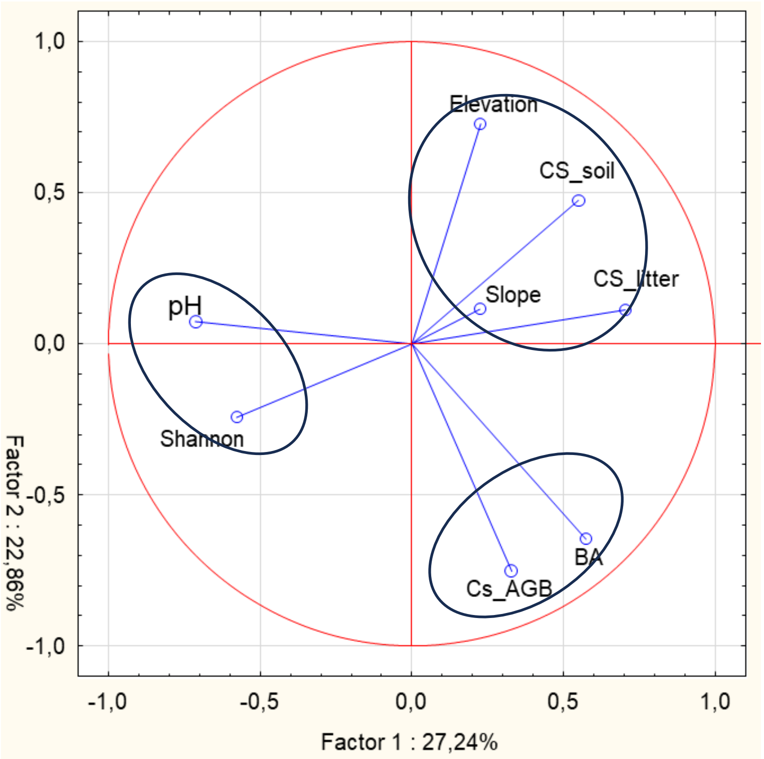

Figure 2.5. Principal component analysis of the variables related to forest habitats at the AD

4.2. The Troodos National Forest Park

4.2.1. Habitat type and forest structure

At the Troodos the soil types found were Cambisols (52%) and Regosols (47%). Cambisols were found mostly in forests with *Pinus nigra,* representing the 83% of pure *Pinus nigra* forest, 75% of

NQ forest, and 67% of NBQ forests, whereas pure *Pinus brutia* forest were found Regosols only (Fig. S8). The analysis of forest structure focused on the tree component, revealing that the majority of forest types exhibited an uneven-aged distribution. Notably, the B forest (Fig. S.2.18) emerged as the most evenly aged among them. The N forest (Fig.S.2.19) was predominantly characterized by small *Pinus nigra* trees, primarily falling within the first category of diameter classes, followed by the NQ forest type (Fig.S.2.20). The BQ forest (Fig. S.2.21) displayed a similarity to the B forest, featuring a more uniform age distribution, with a significant proportion of trees falling into medium diameter categories. Lastly, the NBQ forest (Fig. S.2.22) exhibited a composition dominated by *Pinus nigra* and an uneven-aged structure, with nearly 30% of the trees belonging to the smallest diameter category.

Environmental features were described for each habitat (Table S.2.5) and statistical analyses were conducted to identify notable differences between the habitats. We observed statistically significant differences in elevation range across all habitats, except for NBQ forest and NQ forest. In particular, there was a significant difference with $p<0.05$ between BQ (1085 m.a.s.l) forest and NBQ forest (1454 m.a.s.l), whereas for the remaining habitats, the difference was significant with a $p<0.001$. The results indicate that the elevation ranges were distinct among the habitats, except for the NBQ and NQ forests where overlapping elevation ranges could be hypothesised. Additionally, the BQ forest exhibited significant differences (41.3%, $p<0.05$) in slope percentages compared to the N forest (21%). Regarding the pH, we found that the N forest (6.75) differed significantly ($p<0.05$) from the BQ forest (7.09), and the B forest (7.13). Moreover, the B forest showed a notable difference ($p<0.05$) from the NBQ forest (6.56), and the BQ exhibited a strong significant difference ($p<0.01$) from the NBQ forest. Concerning the forest structure indices, no significant variations in stem density was observed among the habitats. However, we discovered a significant difference ($p<0.05$) in BA between BQ (26 m^2 /ha) and N forest (45.4 m^2/ha).

4.2.2. Carbon stock in soil, litter and vegetation

The pool that stocked most of the OC was AGB (Fig. S 2.10, Table 2.6), with an average of 7.6 kg/m^2 and resulting in the *Pinus brutia* (B) forest as the most stocking habitat in AGB (10.4 kg/m^2). On the other hand, the BQ forest had the lowest values, stocking on average of 6.1 kg/m^2. The soil (Fig. S.2.9) had an average stock of 4.0 kg/m^2, with the BQ forest as the most stocking habitat (4.6 kg/m^2), followed by the NBQ (4.3 kg/m^2) and N forest (4.0 kg/m^2). By contrast, we detected that the N forest resulted in the highest average litter OC stock (Fig. S.2.11) (1.4 kg/m^2), along with the NBQ forest (1.5 kg/m^2). The ANOVA (Fisher LSD Test) did not show any significant differences between the habitats for the OC stock in all the pools, nor within the layers separately. Also, the ANOVA between the soil types and OC stock showed no significant differences.

Table 2.6. Average values of the OC stock (kg/m^2) per habitat and pool at the Troodos National Forest Park

Habitat	*Soil*	*AGB*	*Litter*
BQ	4.6	6.1	0.9
NBQ	4.3	9.0	1.5
N	4.0	6.6	1.4
NQ	3.8	7.3	1.1
B	2.6	10.4	0.9

4.2.3. Correlations with the environmental features

The Pearson correlation matrix (Fig. 2.6) showed statistically significant ($p<0.05$) correlations between the environmental characteristics and the OC values. The litter OC stock was strongly positively correlated with the higher elevations and higher stem densities, while negatively correlated with sloping surfaces and higher soil pH. We also found a positive relationship between tree basal area and higher elevation, and this could be attributed to the Pinus nigra trees, which had the highest BA values, whereas the *Pinus brutia* trees generally had smaller stems. Soil carbon stock was positively correlated with AGB OC stock, BA and OC stocks in litter. Finally, the AGB OC stock was positively correlated with the Shannon index and the elevation, in fact we observed that the NBQ had the highest variance in the AGB OC stock, although the average values were lower than in the B forest. This result regarding the AGB could be influenced by the variance within the habitats and the different sampling effort per habitat, therefore further investigations must be carried out.

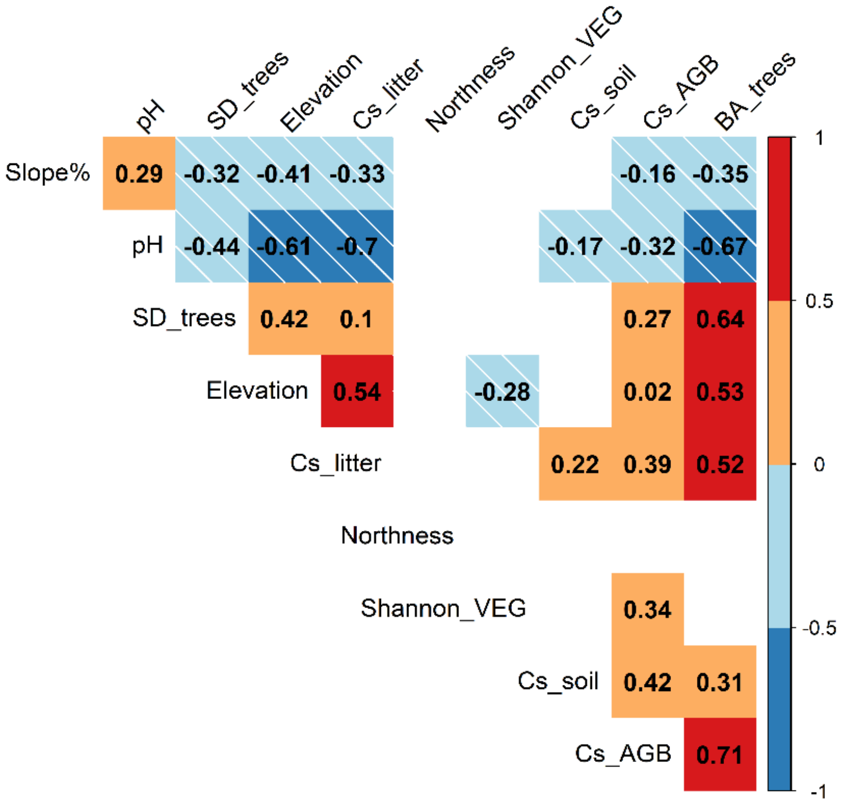

Figure 2.6. Pearson coefficient correlations in forested habitat (p<0.05). codes for the variables included (SD_trees: stem density, Cs_soil: soil oc stock, Cs:litter: litter oc stock, Cs_AGB: OC stock aboveground biomass; BA_trees: basal area)

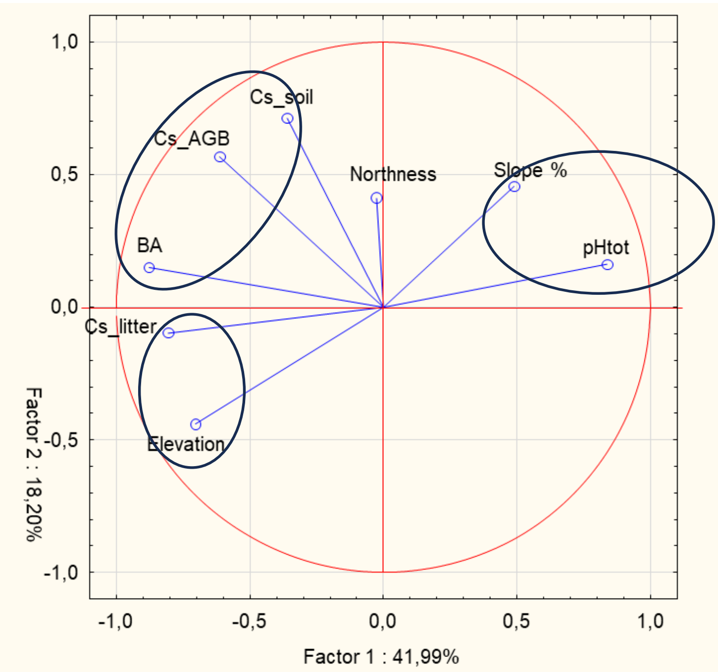

Figure 2.7. Principal component analysis using OC stock values and environmental features at the Troodos

A Principal component analysis (PCA, Fig.2.7) was undertaken to disentangle the correlations among all the variables and accounted for the 60% of the variability in our study area. Three clusters emerged. The first exhibited a positive correlation between AGB and soil OC stock, and the BA. The second cluster showed a positive correlation between elevation and litter OC stock, and a negative correlation with the third cluster, composed by the correlation of slope and pH.

5. Discussion

5.1.ADAMELLO REGIONAL PARK

5.1.1. Environmental features

Our findings revealed that the Adamello resulted in some recurrent soil types, which were Umbrisol, Cambisol and Podzols. We found that Umbrisols were represented in almost each habitat, with the exception of the Larch forest, that was mostly composed by Podzols and Kastanozem. Cambisols were highly present in chestnut forests and mixed deciduous forests. Regosols, which resulted in the lowest OC stocks in soils, were strongly related with green alder shrublands, that are generally situated on slopes and rocky surfaces, however in this habitat also soils such as Umbrisols and Podzols were found.

Forest structure varied considerably among the habitats, and we found the highest BA values in spruce forests, whereas the mixed deciduous forest resulted in the lowest BA. The latter is a habitat mostly composed of a mixture of *Fraxinus excelsior, Fraxinus ornus, Salix caprea, Castanea sativa, Acer pseudoplatanus* and *Corylus avellana.* We hypothesise that these differences may be due to the usage of the area, in terms of timber harvesting (Comunità montana dell Valle Camonica, 2018), and to the age of the forests. This result was also reported in the forest inventory of other regions (Sistema Informativo Forestale Regionale (SIFOR), 2020), however further investigation must be carried out the establish the causes. Moreover, in this study, tall shrubs were not included in the SD calculations, as we included plants with a diameter greater than 10 cm, but individuals were counted in order to have an overall description of each plot and to identify possible descriptive differences within the same habitat category. Hence, the mixed deciduous forest resulted in low values of stem density if compared to the other habitats, but it is important to underline that further studies on the abundance of shrubs and undergrowth should be undertaken to have a better characterisation of such a complex habitat. Larch forests resulted particularly poor in terms of number of trees, both for their intrinsic characteristics and because at the Adamello it turned out that larch forest was less abundant than the quantities described in the habitat map, and particularly sparse in tree coverage. This habitat on situ often resulted in a mixture with *Picea abies*, for this reason, according to the measured Relative Dominance, some habitats were reclassified from larch forests to mixed coniferous forest. Thus, we suggest that a new habitat classification must be carried out, in order to refer to a precise spatial distribution.

5.1.2. OC stock and correlation with environmental features

This study showed that coniferous forests were the forest habitat that stocked the highest amount of OC in all the three pools. At the Adamello Regional Park we found that the soil OC stock accounted the 61% of the total carbon stock, resulting in the highest stocking pool of the area, whereas AGB contained the 33% and litter the 5%. The mean values for OC stock were slightly higher than those reported in the National Inventory of Forest and Carbon (Gasparini & Tabacchi, 2011) concerning AGB and soil. We address this results to the different scale of the two studies: our was local and within a protected area, while the INFC study was regional, with fewer plots and including more heterogeneous habitats with different environmental conditions. Tree composition may affect soil carbon stock in forests (Duarte *et al.*, 2016), but we did not detect significant differences in the overall OC stock in soils, except for the first mineral layer. However, it resulted that the highest values were among coniferous forests habitats, as previously reported (Jandl *et al.*, 2021). After mixed coniferous forest, grasslands were the second habitat to stock the most OC in soil. Grasslands have been often overlooked in the OC assessments (Ward *et al.*, 2014), but they represent a fundamental and extended habitat in alpine environments, and showed a huge carbon stock within their soils. We obtained statistically significant differences in the OC stock in soils according to the soil type: Umbrisols, Podzols and Cambisols resulted in the highest stocks, and differed significantly from Regosols. This result suggests that concerning OC stock in soil, the habitat description that only relies on the vegetation coverage may be not efficient for understanding how the stock is spread, whereas a classification according to soil types may be more informative on the actual soil carbon stock (Canedoli *et al.*, 2023).

Coniferous forest stocked most of the AGB OC stock, followed by chestnut forests. In general, the values obtained were slightly higher than the INFC2005 (Gasparini & Tabacchi, 2011), apart from larch forest exhibited slightly lower values than the INFC, resulting in least stocking habitat within forested habitats. We address this result to the peculiarity of the study area, which, as stated previously, resulted in sparse larch forests with small stems. Through the analysis of the correlations, we found that the elevation positively correlated with the OC stock in soil. This result was already detected in Alpine environments (Prietzel & Christophel, 2014; Simon *et al.*, 2018; Canedoli *et al.*, 2023), and explainable with the decreasing temperature along the altitudinal gradient that reduces decomposition of organic matter, leading to greater OC stocks (Rodeghiero & Cescatti, 2005; Garten & Hanson, 2006; Tashi *et al.*, 2016). The OC stock in soil and litter was positively correlated with the lowest pH values, this result may be explained again by the reduced microbial activity related to more acidic pH (Liao *et al.*, 2016), and generally associated with coniferous forests. The AGB OC stock negatively correlated with higher altitudes, that at the AD are dominated by green alder shrublands and larch forests, while the highest stocks were found in intermediate elevations, in which spruce forest and mixed coniferous forest were present. The organic carbon (OC) stock values in the soils fell within the range reported by previous researchers. However, they were slightly lower than the average values found in studies conducted in the German Alps by Prietzel and Christophel (2014), where the average OC stock in soil was 109 Mg ha^{-1}, and in Trentino Alto Adige by Rodeghiero *et al*. (2009) (76 Mg ha^{-1}), reaching an average of 69 Mg ha^{-1} in our study (down to 30cm depth), similarly to the 70 Mg ha^{-1} identified in French soils by Arrouays (1999). Our values were also somewhat higher than other estimations, like those by Panagos et al. (2013b), who reported an average OC stock value of 59 Mg ha^{-1} for the entire country of Italy. The observed variation in soil carbon content, which can fluctuate even on a millimeter scale according to Schrumpf et al. (2008), primarily accounts for the noted discrepancy. Additionally, specific attributes of the study area, the historical context of the studied forests and their land use, the resolution of our study, and methodological factors contribute to this divergence. The average aboveground woody biomass (comprising stems and branches, excluding shrub biomass) measured at 81.4 Mg ha^{-1} closely aligns with comparable values reported in Germany (81.0 Mg ha^{-1}) by Baritz and Strich (2000) and in another Italian region, Trentino Alto Adige, where it amounted to 85.8 Mg ha^{-1} as documented by Rodeghiero et al. (2009).

5.2. TROODOS NATIONAL FOREST PARK

5.2.1. Environmental features

At the Troodos National Forest Park, it emerged that the vegetation belts were situated in distinct elevation ranges, with the exception of the mixed habitat. As for the previous study area, tall shrubs were not included in the calculation for the SD, but branches with a circumference greater than 10 cm were counted, particularly of *Quercus alnifolia,* which was a widespread species across the habitats. Hence, this count was used only for a classification of the habitats, in fact we divided habitats into pure pine forest and pine forests associated with *Q.alnifolia*. Also, the other structural indices did not result in significant differences, and this could be because of similarities in the age of forests (Ciesla, 2004), and the presence of the same recurring species in all the habitats. However, we detected that forests composed by *Pinus nigra* had generally higher BA values, as reported previously (Evrendilek *et al.*, 2006). Moreover, the special conditions on Troodos massif were created by the shade intolerance of *P.nigra* and the even-aged structure of the forest, thus small diameter trees were almost absent in the *P.nigra* forest (Raptis *et al.*, 2021). In addition, both *Pinus nigra* and *Pinus brutia* were planted and managed for timber provision, and the differences in within the habitats are few. British colonisation in 1878 caused severe forest degradation in Cyprus. However, in the 1950s, there was a major initiative to restore the forests through widespread planting of *Pinus brutia* trees (Walker, 1936; Ciesla, 2004). Differences between the two can be found in other environmental features, that were not measured directly in the study: the *Pinus nigra* is related to higher elevations and precipitation regimes (800-1000 mm annually), whereas *Pinus brutia* is located at lower elevations and reduced precipitation regimes (450-800 mm annually) (Ciesla, 2004).

5.2.2. OC stock and correlation with environmental features

In this study area, we found that the AGB was the pool that stocked most OC, and soil stocked amounts that were, in some cases, half of the AGB stock. Comparisons with other studies in the Cyprus region posed challenges, given that Cyprus is still in the early phases of ES assessment, as highlighted by Vogiatzakis et al. (2020). Additionally, most data in the area are derived from indirect measurements, such as the TESSA Toolkit (Manolaki & Vogiatzakis, 2017). Despite these challenges, our study identified similarities in aboveground biomass (AGB) with Kounnamas & Andreou (2022), who estimated a carbon storage of 73.18 Mg ha^{-1} in plants. In our investigation, we found an average AGB of 76 Mg ha^{-1}. It's crucial to note that our focus was solely on AGB of tree-dominated species, excluding the shrub component (*Quercus alnifolia*). In contrast, the previous study considered the total AGB, encompassing shrublands, wetlands, and grasslands even though an average value of 73 Mg ha^{-1} was found for all the tree dominated habitats in their study. Therefore, further studies are imperative to elucidate and address any discrepancies. A study conducted on the Mediterranean side of Turkey by Evrendilek et al. (2006), which shared similar vegetation characteristics, highlighted an average organic carbon (OC) stock value of 83 Mg ha^{-1} in the aboveground biomass of coniferous forests. Notably, the average OC stock in the soil far exceeded the values observed in the Troodos region, reaching an average of 118 Mg ha^{-1} in *Pinus brutia* forest. This value was more than double the 40 Mg ha^{-1} recorded in the Troodos, underscoring a substantial disparity in soil organic carbon content between the two regions.

This could be due to the fact that soil carbon stock is strongly related to temperature and precipitation regimes (Olaya-Abril *et al.*, 2017), however, despite being in a Mediterranean island, the Troodos mountains are characterised by the highest mean values for annual precipitations (1000 mm) (Nikolakis, 2007). However, no statistically significant difference was detected among the pools, this could be attributed to the fact that, although there are differences in the environmental features (such as elevation and precipitation regimes), these habitats share many similarities as they are composed of coniferous trees with recurrent species. Additionally, the area size is smaller compared to the previous study area, resulting in less variation than the previous study area that included broadleaves and grasslands. Furthermore, as there is no allometric equation available for *Q.alnifolia,* it is plausible to suggest that this might result in some variances across mixed habitats compared to pure ones. Despite this, we found some differences that were interesting to further investigate. Litter OC stock was higher in habitats in which *Pinus nigra* was present, and might be related to the characteristics of the needle or the seasonality (Taskinsu-Meydan et al. 2010) , since fieldwork activities were conducted during late October and during a particularly cold and rainy year, hence further investigations must be carried out to understand the reasons of this discrepancies. This toughness results from a higher content of lignin and other complex organic compounds, that reduce the degradation by microbes and environmental features. On the contrary, we found that the highest AGB stocks were related to habitats composed of *Pinus brutia* and *Pinus nigra* with *Q.alnifolia* (NBQ). This result must be further investigated, adding other field measurement, since it emerged that AGB had a huge variability both in the mixed habitat and the pure *Pinus brutia* forest (B). These habitats were investigated with fewer plots than the Pure *P. nigra* (N), which was mapped as the most extended habitat in the study area and exhibited less variance within its AGB OC stock. In the map provided by the park, these habitats were not present, however during the fieldwork activities these were found recurrently, hence, our sampling design was readapted to have an assessment of their characteristics and carbon storage capacity. From the analyses of the correlations, it emerged that OC stock in litter was strongly related to elevation and to lower pH, and this again could be attributed to the presence of the *Pinus nigra* at the highest altitudes (Ciesla, 2004). In this case we did not find any correlation with elevation for the OC stock in soil, and this might be due to the reduced elevation range if compared to an alpine area.

6. Conclusion

In this study, we assessed the carbon stock of two mountain protected areas, determining the distribution among habitat types and carbon pools. Alpine and Mediterranean mountain areas are environmentally diverse areas, and through the correlation with environmental features, it was possible to give insights on how these and the carbon stock correlated. These assessments not only help us quantify the carbon stored within these ecosystems but also provide fundamental information on areas that are highly vulnerable to the climate change. Understanding the dynamics of carbon storage in these environments enables us to implement targeted conservation and management strategies. By safeguarding these environments, we can simultaneously protect biodiversity, preserve natural heritage, and contribute significantly to global carbon sequestration efforts. Further studies should be carried out to determine the hierarchical relevance of the correlations found and their cause-effect relationships, to implement the knowledge on such a complex process and develop models on carbon stock distribution.

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Supplementary materials

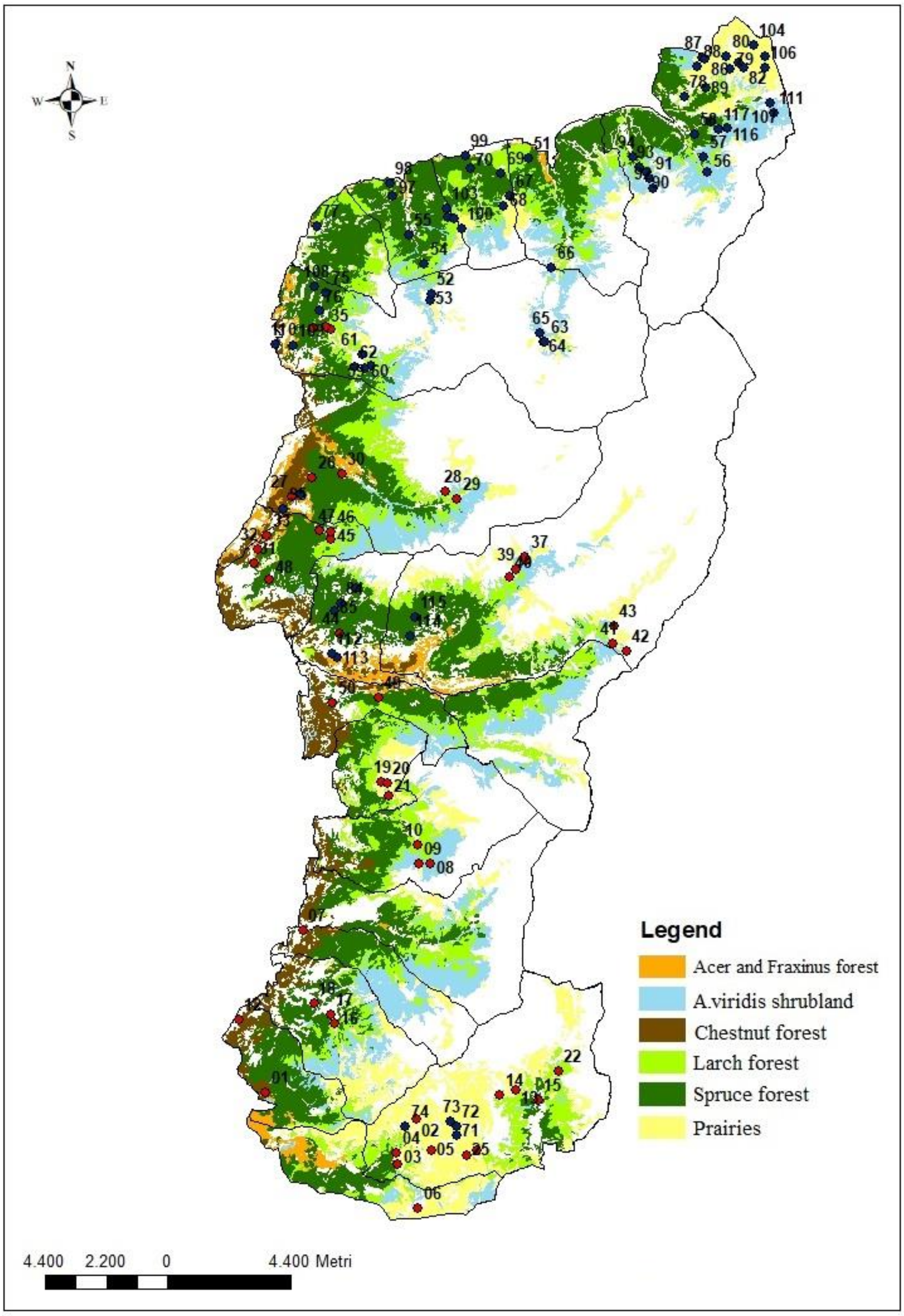


Figure S.2. 1. Habitat map of the Adamello Regional Park, showing the most representative habitats and plots (red: 2021, blue:2022). Mixed coniferous and broadleaves forest were not indicated in the map and classification was carried out using in-situ data.

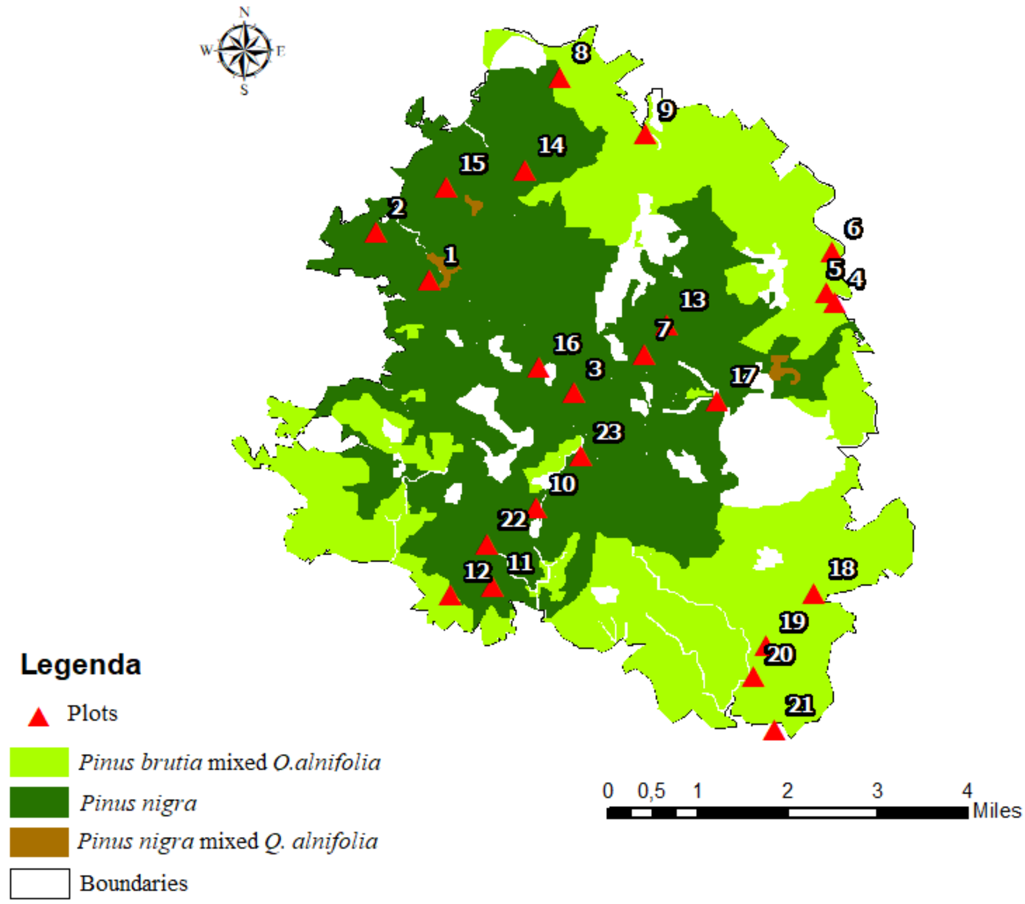


Figure S. 2. 2. Troodos habitat map provided by the Park

Table S. 2.1. Allometric equations used for the estimation of the biomasses in this study, where W1 is the phytomass of stem and branches (kg), M is the total AGB phytomass (kg), DBH is the Diameter at Breast Height (cm), and H is the height of the tree (m).

Species	Allometric equation	Source
Picea abies	$W1 = 2.5338 + 9.5351 * 10^{-3} DBH^2 h + 6.2893 * 10^{-3} DBH\ h^2$	Gasparini et al., 2006
Larix decidua	$W1 = 1.7603 * 10 + 1.9161 * 10^{-2} DBH^2 h - 1.8211\ DBH$	Gasparini et al., 2006
Abies alba	$W1 = 9.8961 * 10^{-1} + 1.3980 * 10^{-2} DBH^2 h + 1.4895 * 10^{-2}\ DBH^2$	Gasparini et al., 2006
Pinus nigra	$W1 = -3.5712 + 1.4429 * 10^{-2} DBH^2 h + 6.8047 * 10^{-2}\ DBH^2$	Gasparini et al., 2006

Pinus sylvestris	$W1 = -7.3626 * 10^{-1} + 1.8465 * 10^{-2} DBH^2 h$	Gasparini et al., 2006
Salix caprea	$W1 = 8.9159 * 10^{-1} + 1.6329 * 10^{-2} DBH^2 h$	Tabacchi et al., 2011
Salix glabra	$W1 = 2.1616 * 10^{-1} + 1.4282 * 10^{-2} DBH^2 h + 4.4323 * 10^{-2} DBH^2$	Gasparini et al., 2006
Salix appendiculata	$W1 = 2.1616 * 10^{-1} + 1.4282 * 10^{-2} DBH^2 h + 4.4323 * 10^{-2} DBH^2$	Gasparini et al., 2006
Acer pseudoplatanus	$W1 = 8.6876 * 10^{-1} + 2.0421 * 10^{-2} DBH^2 h$	Tabacchi et al., 2011
Fraxinus ornus	$W1 = -6.5463 * 10^{-1} + 2.5364 * 10^{-2} DBH^2 h$	Tabacchi et al., 2011
Fraxinus excelsior	$W1 = -6.5463 * 10^{-1} + 2.5364 * 10^{-2} DBH^2 h$	Tabacchi et al., 2011
Betula pendula	$W1 = 2.1616 * 10^{-1} + 1.4282 * 10^{-2} DBH^2 h + 4.4323 * 10^{-2} DBH^2$	Gasparini et al., 2006
Castanea sativa	$W1 = -9.5407 * 10^{-1} + 1.8335 * 10^{-2} DBH^2 h + 1.9237 * 10^{-1}\ DBH$	Tabacchi et al., 2011
Prunus avium	$W1 = -9.1098 + 7.3484 * 10^{-3} DBH^2 h + 2.3666\ DBH$	Tabacchi et al., 2011
Laburnum anagyroides	$W1 = -4.6965 + 1.2034 * 10^{-2} * DBH^2 h + 2.1771 * 10^{-1} DBH^2$	Gasparini et al., 2006
Quercus spp	$W1 = -4.6965 + 1.2034 * 10^{-2} * DBH^2 h + 2.1771 * 10^{-1} DBH^2$	Gasparini et al., 2006
Quercus rubra	$W1 = -4.6965 + 1.2034 * 10^{-2} * DBH^2 h + 2.1771 * 10^{-1} DBH^2$	Gasparini et al., 2006
Fagus sylvatica	$W1 = -3.7197 + 1.9559 * 10^{-2} DBH^2 h + 8.8089 * 10^{-2}\ DBH^2$	Gasparini et al., 2006
Carpinus betulus	$W1 = -1.0514 + 2.3952 * 10^{-2} DBH^2 h$	Tabacchi et al., 2011

Alnus viridis	$W1(g)=44.06*DHB^{2,395}$	He et al., 2018

Table S.2.2. Classification of soil types at the AD and their representativeness in terms of total number of plots and percentage on the overall study.

Soil WRB	Count	Percentage
Cambisol	32	28
Histosol	1	1
Kastanozem	3	3
Luvisol	1	1
Phaeozem	5	4
Podzol	27	24
Regosol	8	7
Umbrisol	37	32

Table S. 2. 3. Values of the OC stock in soils at the AD according to soil types

Soil Type	Average	Min	Max	StdDev
Cambisol	8.85	2.26	17.94	3.40
Histosol	5.54	5.54	5.54	0.00
Kastanozem	8.95	7.96	9.51	0.86
Luvisol	7.96	7.96	7.96	0.00
Phaeozem	6.73	2.59	9.17	2.71
Podzol	10.34	3.66	20.80	4.36
Regosol	3.10	0.22	5.95	1.76
Umbrisol	10.37	1.63	17.38	4.24

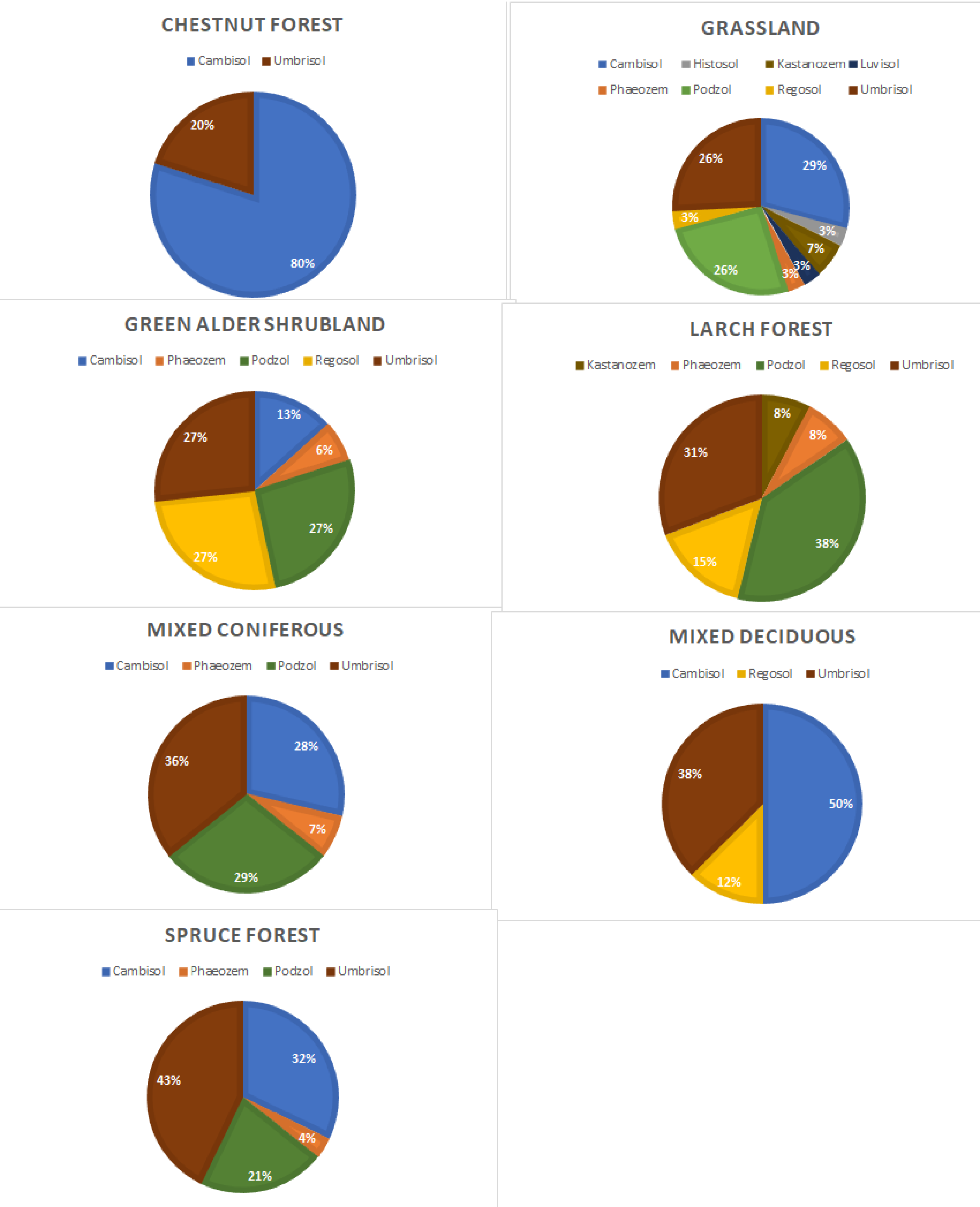


Figure S.2.3. Distribution of soil classifications among the habitats at the AD

Table S.2.4. Environmental features for the AD

Elevation		Average	Min	Max	StdDev
	Green Alder Shrubland	1888	1573	2354	186.8
	Chestnut forest	732	481	942	188.0
	Larch forest	1754	1510	2035	156.8
	Mixed coniferous	1528	991	2047	327.0
	Mixed broadleaves	1188	882	1827	383.0
	Spruce forest	1342	818	1790	243.3
	Grassland	2042	1643	2407	192.2
Slope (%)		Average	Min	Max	StdDev
	Green Alder Shrubland	37.9	10.0	74.0	19.8
	Chestnut forest	60.2	30.0	80.0	19.0
	Larch forest	37.2	20.0	60.0	13.3
	Mixed coniferous	49.1	12.0	109.0	23.3
	Mixed broadleaves	47.1	27.0	75.0	17.0
	Spruce forest	46.1	3.0	80.0	17.6
	Grassland	35.6	0.0	80.0	18.5
pH		Average	Min	Max	StdDev
	Green Alder Shrubland	4.4	3.5	7.3	0.9
	Chestnut forest	5.0	4.0	7.5	1.4
	Larch forest	4.7	3.6	6.8	1.0
	Mixed coniferous	4.7	3.8	6.9	0.9
	Mixed broadleaves	5.0	3.8	7.1	1.2

	Spruce forest	4.3	3.5	7.6	0.7
	Grassland	5.3	4.0	7.6	1.1
Basal Area (m2/ha)		Average	Min	Max	StdDev
	Chestnut forest	52.16	21.21	67.04	19.2
	Larch forest	36.83	6.13	64.91	16.8
	Mixed coniferous	52.46	8.57	113.77	28.2
	Mixed broadleaves	24.58	0.84	65.85	23.7
	Spruce forest	52.89	32.68	89.85	16.1
Stem Density (trees/ha)		Average	Min	Max	StdDev
	Chestnut forest	1077.8	822.2	1711.1	368.2
	Larch forest	454.7	122.2	1188.9	287.6
	Mixed coniferous	666.7	233.3	1222.2	312.5
	Mixed broadleaves	651.4	100.0	1555.6	458.4
	Spruce forest	723.8	188.9	2011.1	468.0
Shannon Index		Average	Min	Max	
	Green Alder Shrubland	0.5	0.0	2.5	0.6
	Chestnut forest	2.0	1.5	2.6	0.4
	Larch forest	0.8	0.0	1.5	0.5
	Mixed coniferous	1.0	0.6	1.9	0.4
	Mixed broadleaves	1.6	1.1	2.4	0.5
	Spruce forest	0.7	0.0	2.1	0.5

Leaf Area Index		Average	Min	Max	StdDev
	Green Alder Shrubland	2.9	0.9	8.5	2.3
	Chestnut forest	3.4	1.1	4.6	1.4
	Larch forest	2.2	1.1	3.7	1.0
	Mixed coniferous	2.1	1.0	5.0	1.4
	Mixed broadleaves	1.8	1.0	3.4	1.0
	Spruce forest	2.6	0.8	5.5	1.4
	Grassland	3.1	1.0	7.4	1.5

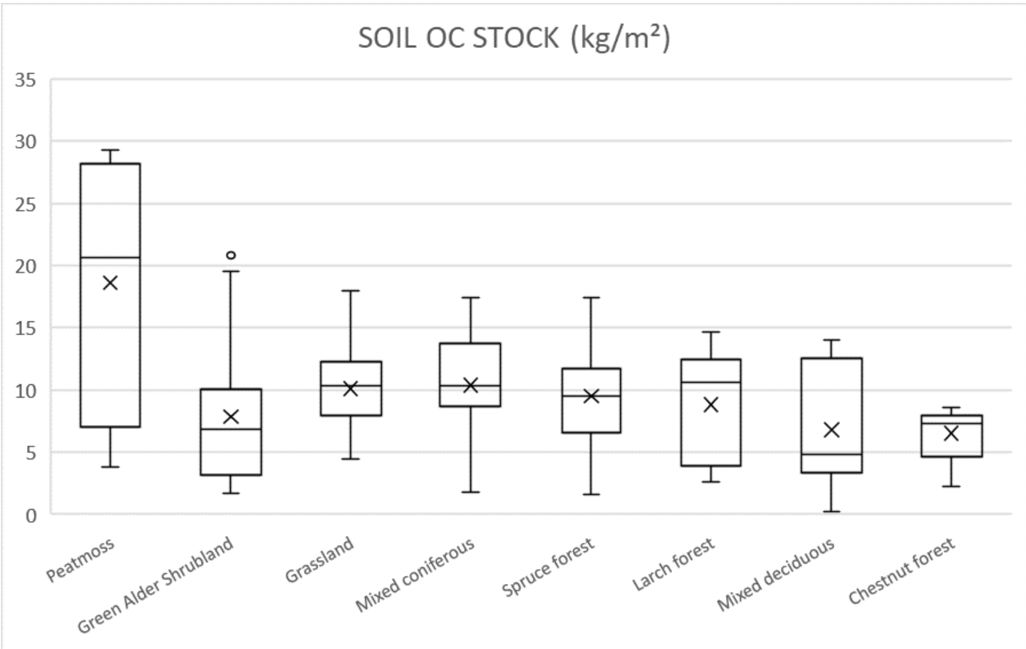


Figure S.2.4. Box plot of soil OC stock (kg/m^2) distribution among habitats at the Adamello Regional Park

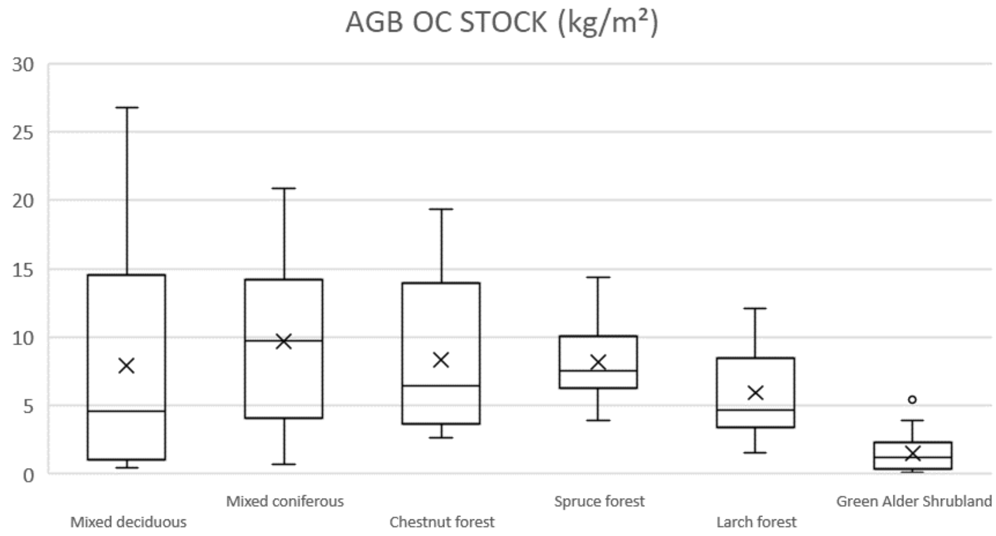


Figure S.2.5. Box plot of AGB OC stock (kg/m2) distribution among habitats at the Adamello Regional Park

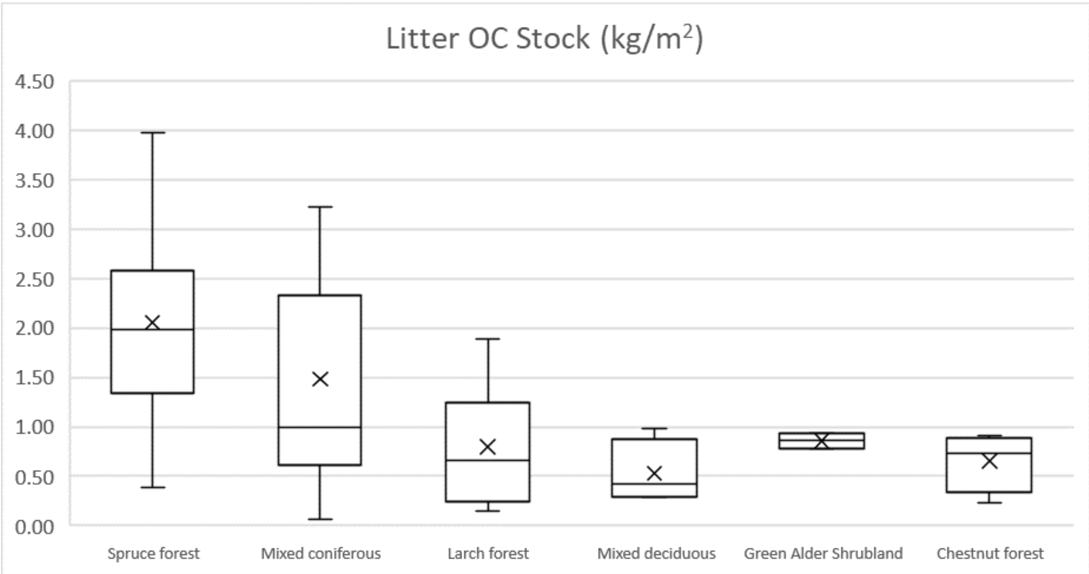


Figure S.2.6. Box plot of litter OC stock (kg/m2) distribution among habitats at the Adamello Regional Park

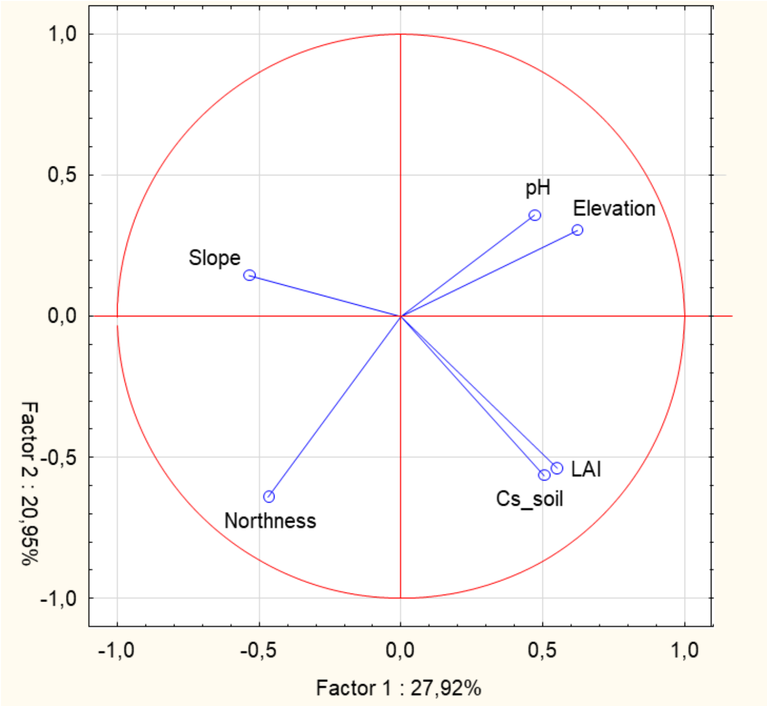


Figure S.2.7. PCA of the variables related to forests and grasslands at the Adamello Regional Park

Table S.2.5. Environmental features at the Troodos National Forest Park

Elevation	Average	Min	Max	StdDev
Pinus brutia forest	881	739	1006	134
Pinus brutia mix *Quercus alnifolia*	1085	870	1324	144
Pinus nigra and *Pinus brutia* and *Quercus alnifolia* mixed forest	1454	1304	1605	151
Pinus nigra forest	1713	1598	1883	100
Pinus nigra mix *Quercus alnifolia*	1387	1337	1458	63
Slope (%)	Average	Min	Max	StdDev
Pinus brutia forest	24.00	7.00	40.00	16.52
Pinus brutia mix *Quercus alnifolia*	41.29	5.00	70.00	22.46
Pinus nigra and *Pinus brutia* and *Quercus alnifolia* mixed forest	25.33	14.00	32.00	9.87
Pinus nigra forest	21.57	10.00	32.00	8.24

Pinus nigra mix *Quercus alnifolia*	33.33	25.00	45.00	10.41
pH	Average	Min	Max	StdDev
Pinus brutia forest	7.13	6.93	7.25	0.17
Pinus brutia mix *Quercus alnifolia*	7.09	6.84	7.26	0.16
Pinus nigra and *Pinus brutia* and *Quercus alnifolia* mixed forest	6.56	6.29	6.86	0.29
Pinus nigra forest	6.75	6.20	7.29	0.33
Pinus nigra mix *Quercus alnifolia*	6.72	6.59	6.93	0.19
Basal Area (m2/ha)	Average	Min	Max	StdDev
Pinus brutia forest	32.06	17.03	45.52	14.31
Pinus brutia mix *Quercus alnifolia*	26.05	13.11	36.60	9.58
Pinus nigra and *Pinus brutia* and *Quercus alnifolia* mixed forest	45.74	16.86	84.12	34.62
Pinus nigra forest	45.40	30.77	63.40	11.68
Pinus nigra mix *Quercus alnifolia*	42.48	25.42	52.63	14.86
Stem Density (trees/ha)	Average	Min	Max	StdDev
Pinus brutia forest	270.37	188.89	400.00	113.49
Pinus brutia mix *Quercus alnifolia*	338.10	133.33	833.33	226.34
Pinus nigra and *Pinus brutia* and *Quercus alnifolia* mixed forest	496.30	188.89	800.00	305.57
Pinus nigra forest	561.90	122.22	1144.44	331.65
Pinus nigra mix *Quercus alnifolia*	362.96	155.56	544.44	195.74
Shannon Index	Average	Min	Max	StdDev
Pinus brutia forest	0.34	0.04	0.53	0.26
Pinus brutia mix *Quercus alnifolia*	0.41	0.22	0.52	0.11
Pinus nigra and *Pinus brutia* and *Quercus alnifolia* mixed forest	0.60	0.44	0.71	0.14

Pinus nigra forest	0.16	0.00	0.29	0.11
Pinus nigra mix *Quercus alnifolia*	0.44	0.29	0.52	0.13

Figure S.2.8. Soil types (WRB) per habitat (%) at the TRD

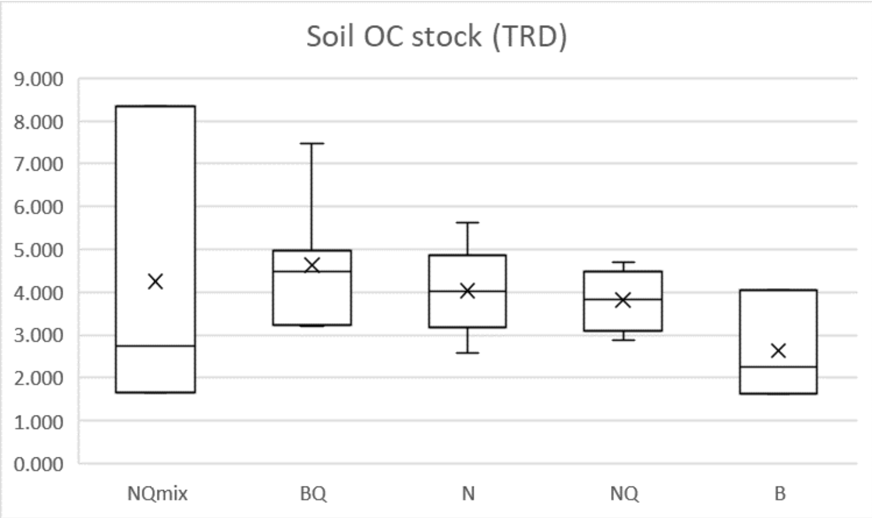


Figure S.2.9. Box plot of soil OC stock (kg/m2) distribution among habitats at the Troodos National Forest Park

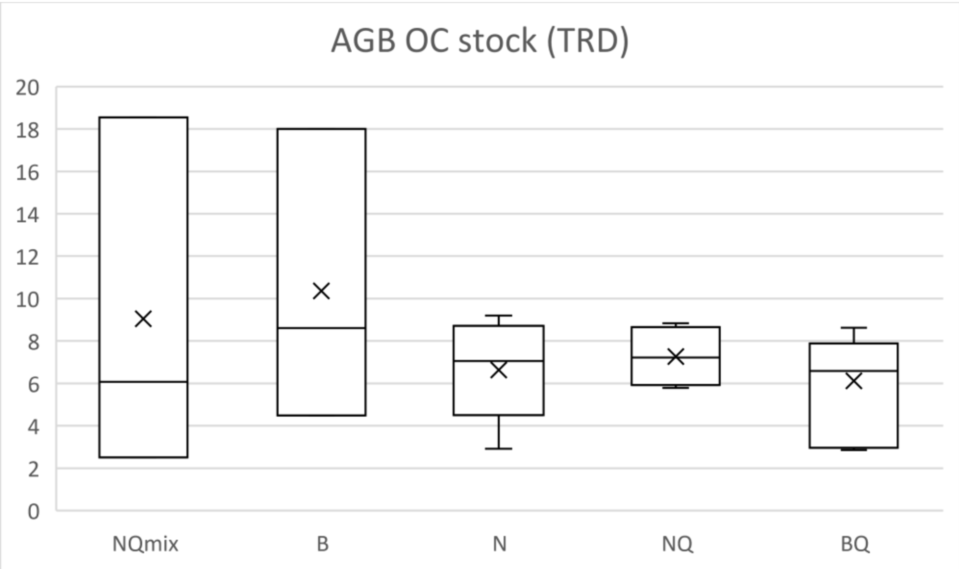


Figure S.2.10. Box plot of AGB OC stock (kg/m2) distribution among habitats at the Troodos National Forest Park

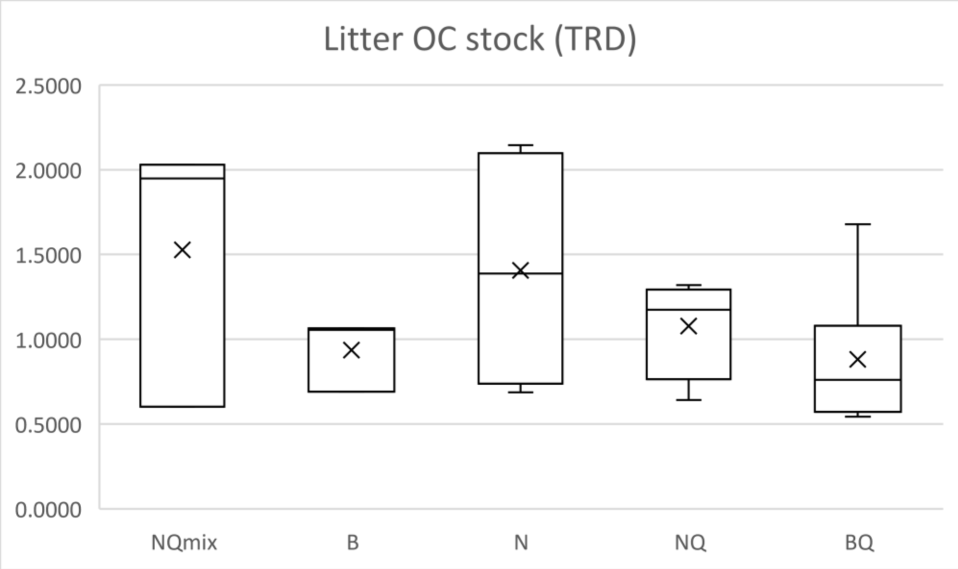


Figure S.2.11. Box plot of litter OC stock (kg/m2) distribution among habitats at the Troodos National Forest Park

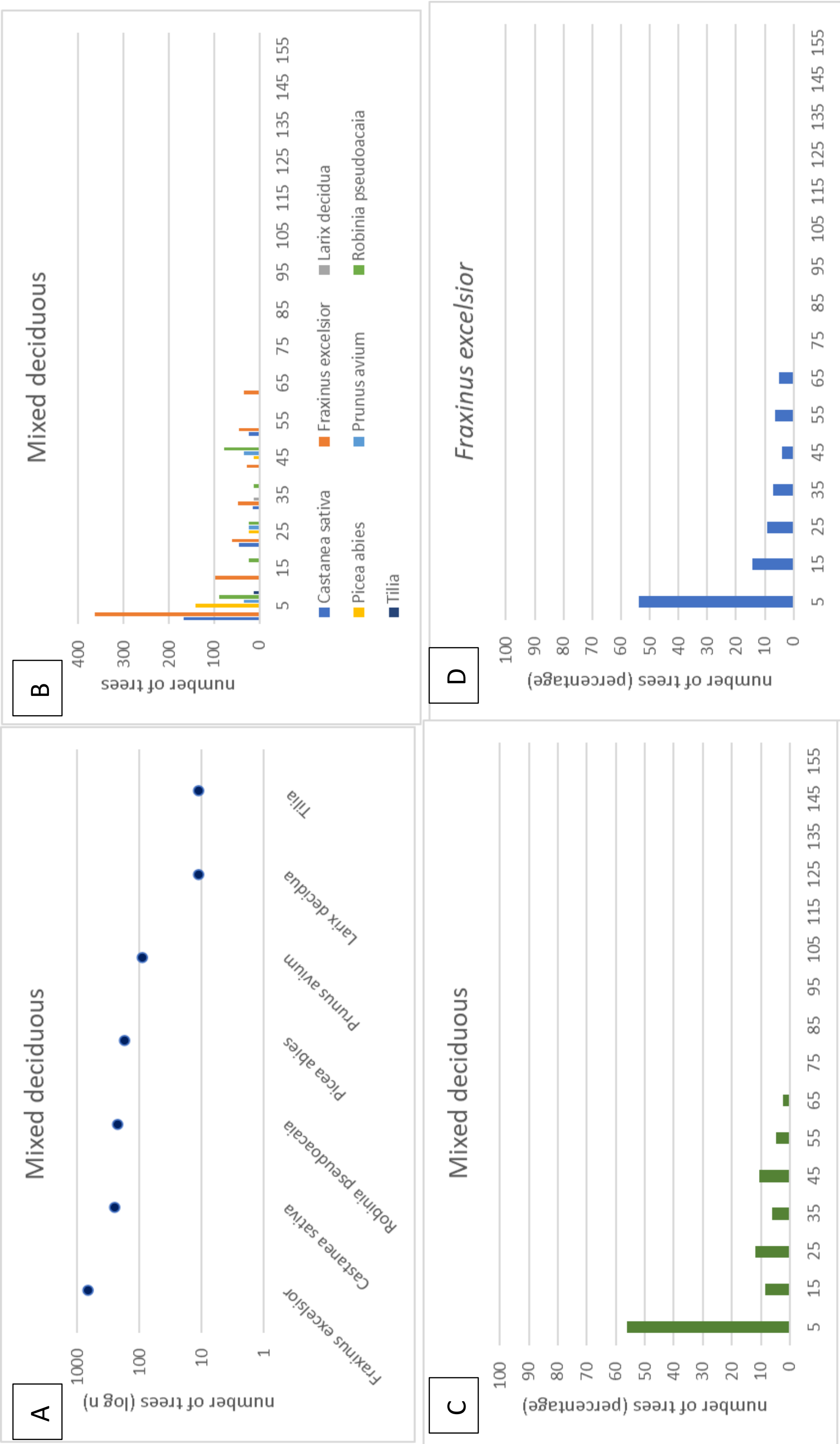


Figure S.2.12. Results of the forest structure analysis for the Mixed deciduous forest, indicating the number of trees per species (A), number of trees per species and diameter class (B), percentage of trees per diameter class (C) for all the trees in the habitat, and percentage of trees per diameter class for the most abundant specie (D).

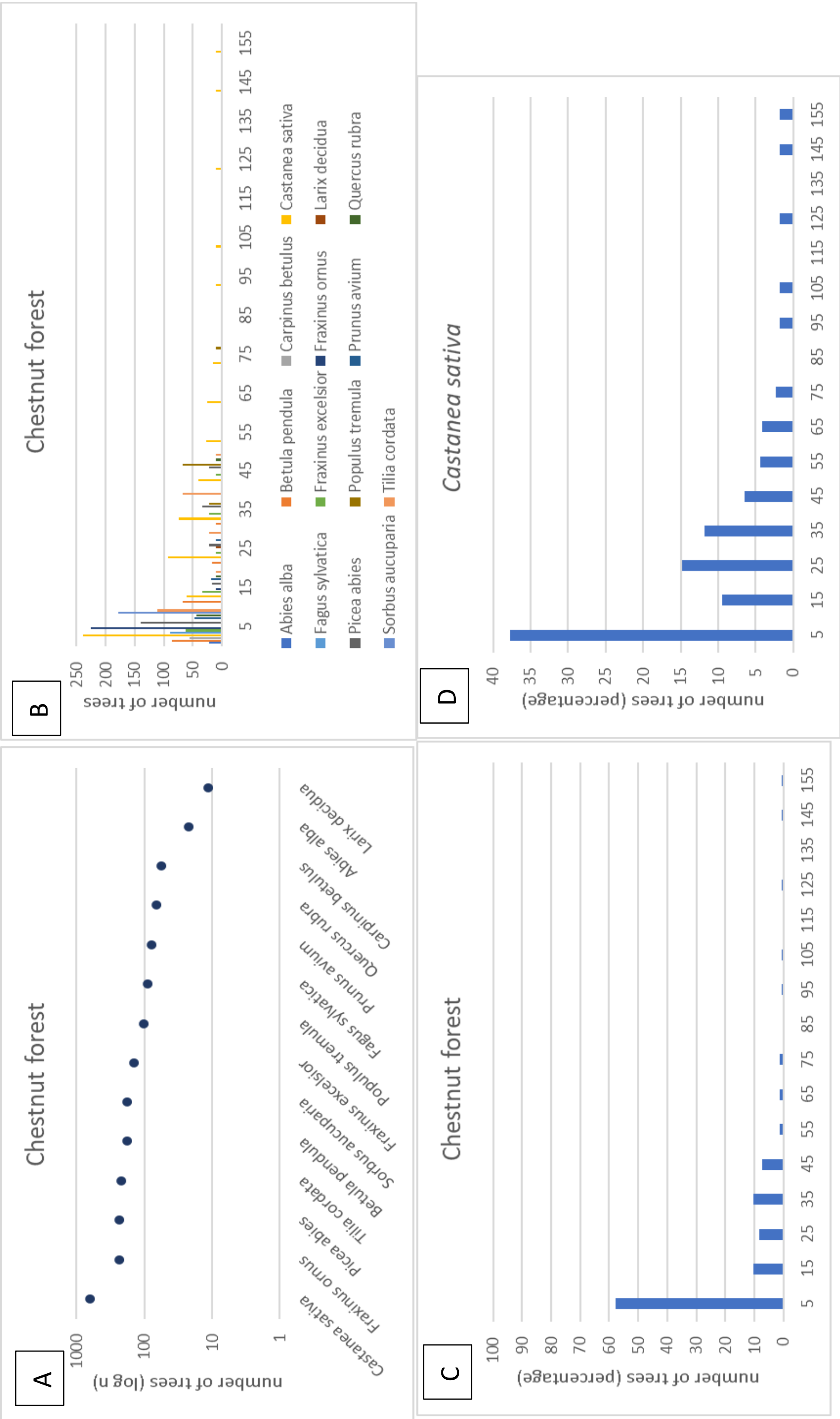


Figure S.2.13. Results of the forest structure analysis for the Chestnut forest, indicating the number of trees per species (A), number of trees per species and diameter class (B), percentage of trees per diameter class (C) for all the trees in the habitat, and percentage of trees per diameter class for the most abundant specie (D).

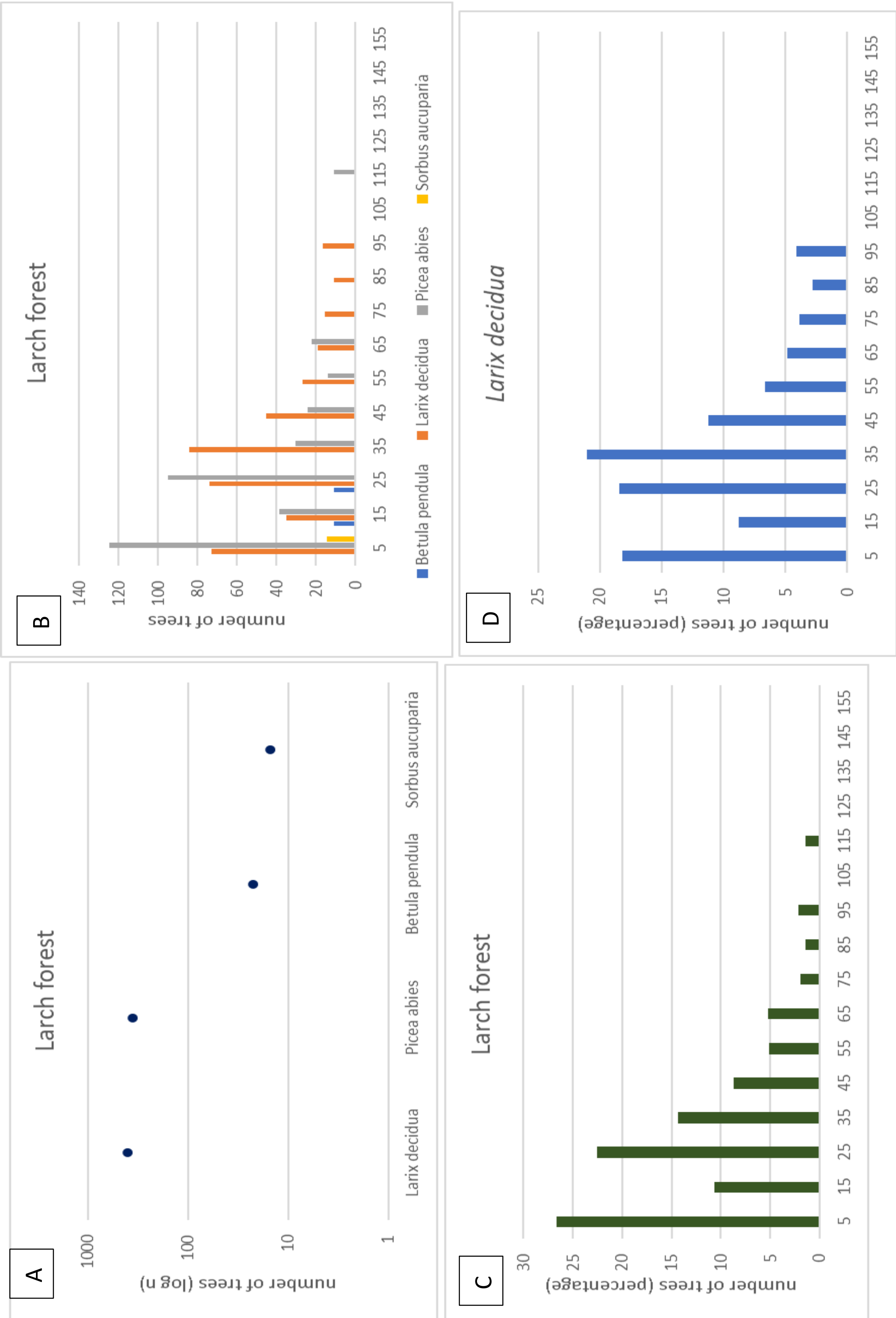


Figure S.2.14. Results of the forest structure analysis for the Larch forest, indicating the number of trees per species (A), number of trees per species and diameter class (B), percentage of trees per diameter class (C) for all the trees in the habitat, and percentage of trees per diameter class for the most abundant specie (D).

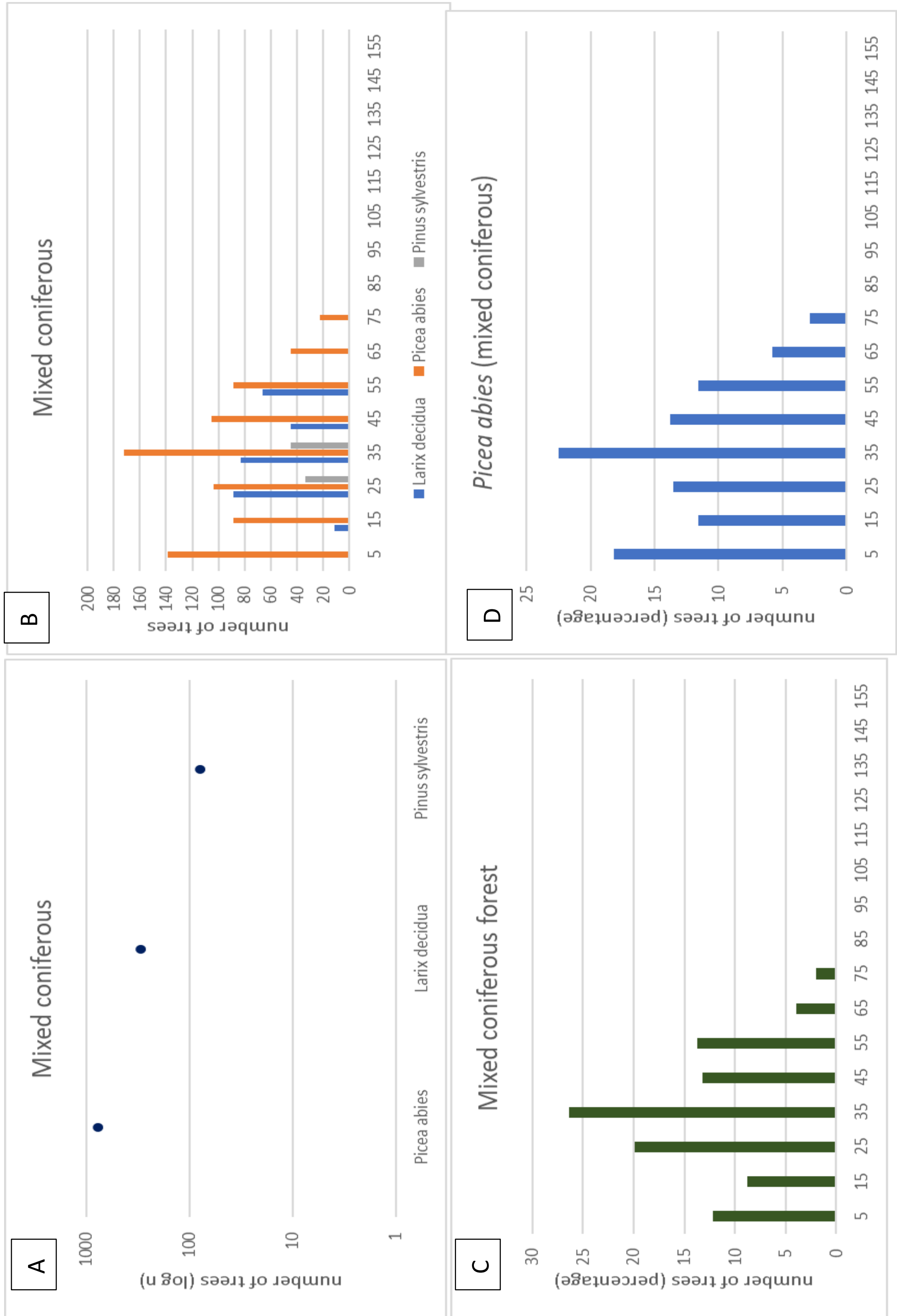


Figure S.2.15. Results of the forest structure analysis for the Mixed coniferous forest, indicating the number of trees per species (A), number of trees per species and diameter class (B), percentage of trees per diameter class (C) for all the trees in the habitat, and percentage of trees per diameter class for the most abundant specie (D).

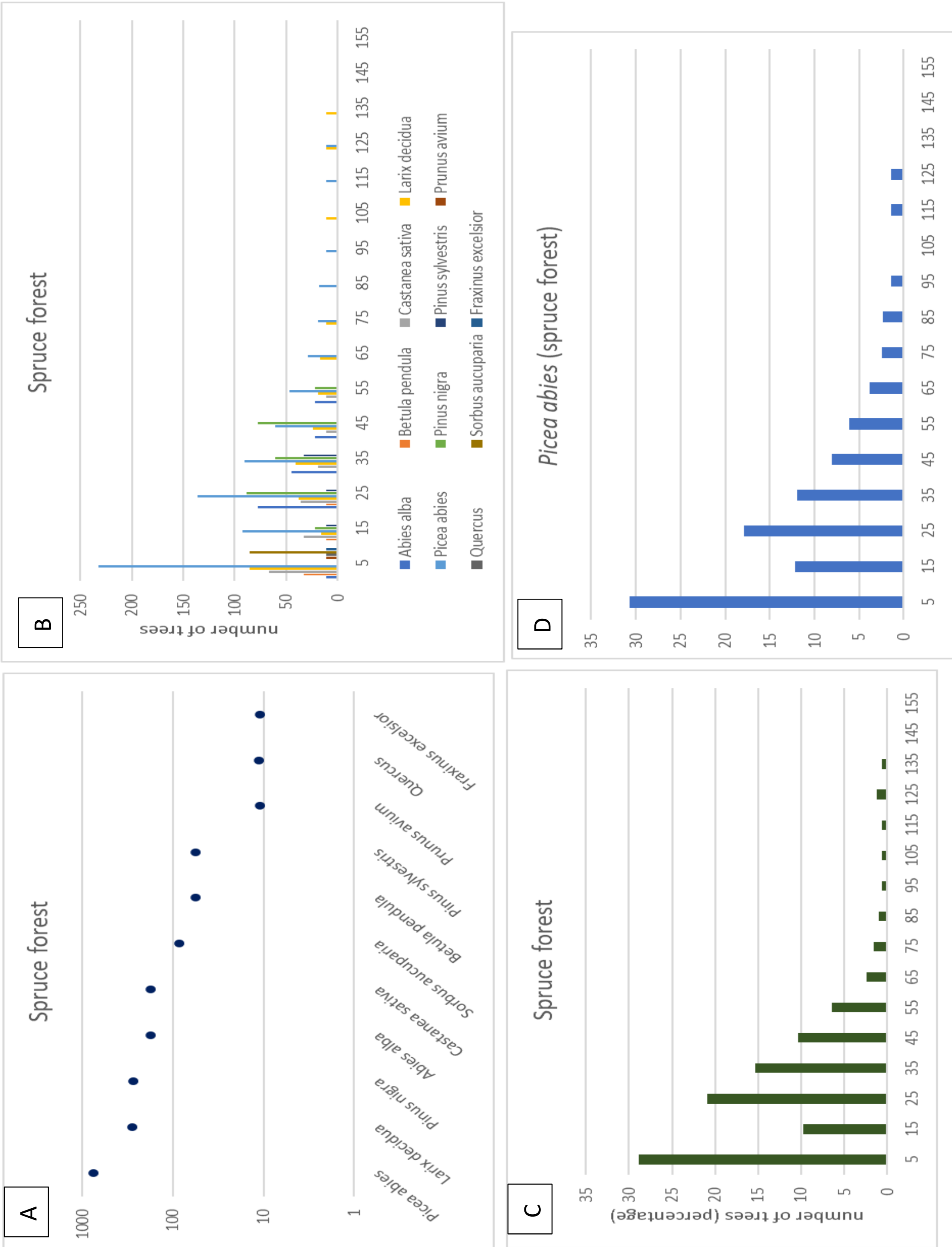
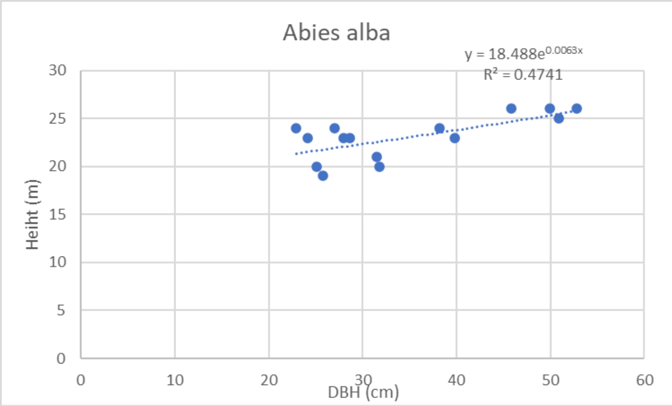
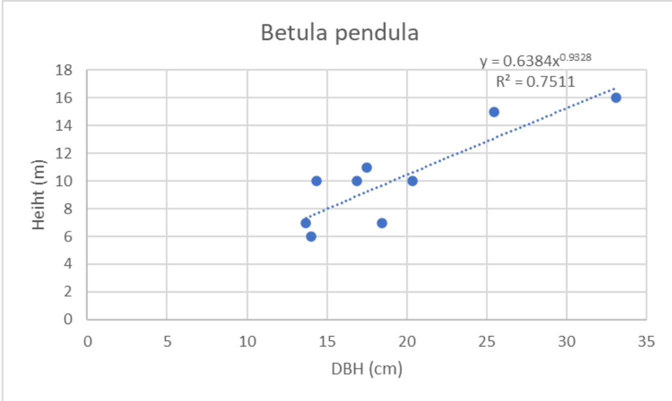
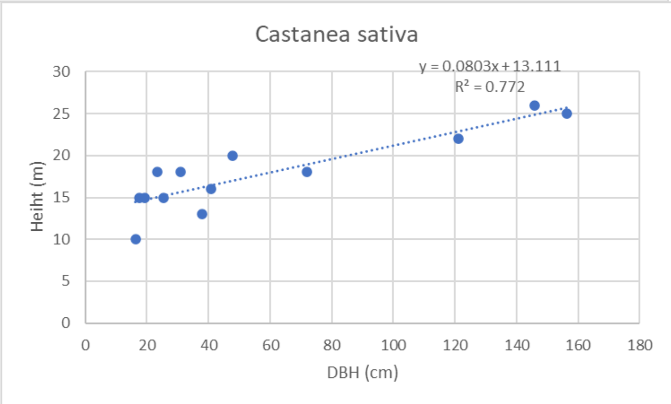
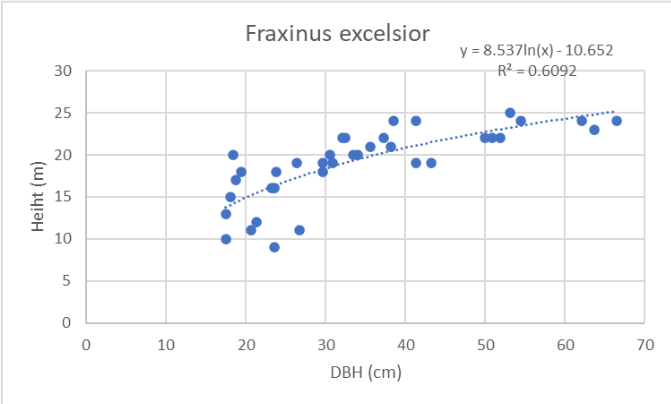


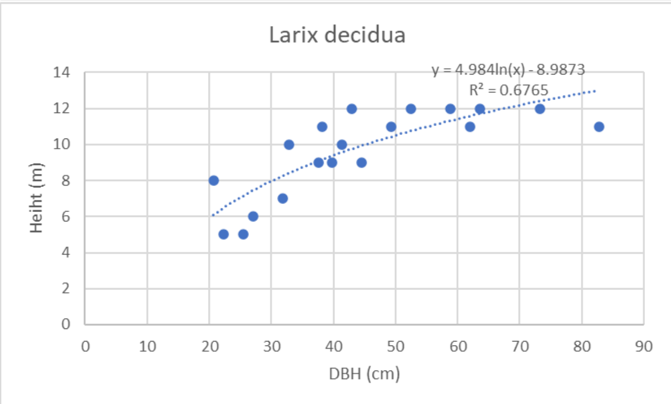
Figure S.2.16. Results of the forest structure analysis for the Spruce forest, indicating the number of trees per species (A), number of trees per species and diameter class (B), percentage of trees per diameter class (C) for all the trees in the habitat, and percentage of trees per diameter class for the most abundant specie (D).

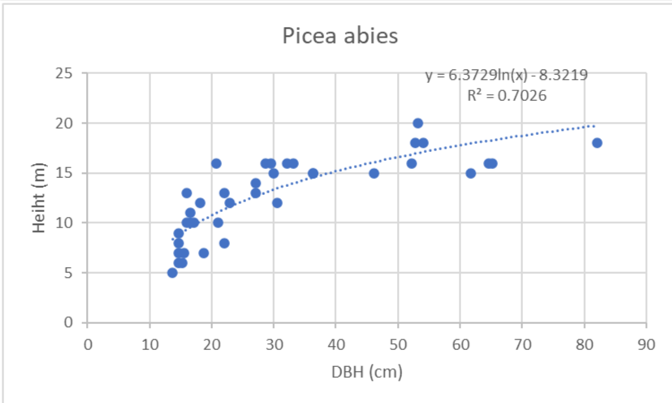

Abies alba
y = 18.488e^0.0063x
R² = 0.4741
Heiht (m)
DBH (cm)


Betula pendula
y = 0.6384x^0.9328
R² = 0.7511
Heiht (m)
DBH (cm)


Castanea sativa
y = 0.0803x + 13.111
R² = 0.772
Heiht (m)
DBH (cm)


Fraxinus excelsior
y = 8.537ln(x) - 10.652
R² = 0.6092
Heiht (m)
DBH (cm)


Larix decidua
y = 4.984ln(x) - 8.9873
R² = 0.6765
Heiht (m)
DBH (cm)


Picea abies
y = 6.3729ln(x) - 8.3219
R² = 0.7026
Heiht (m)
DBH (cm)

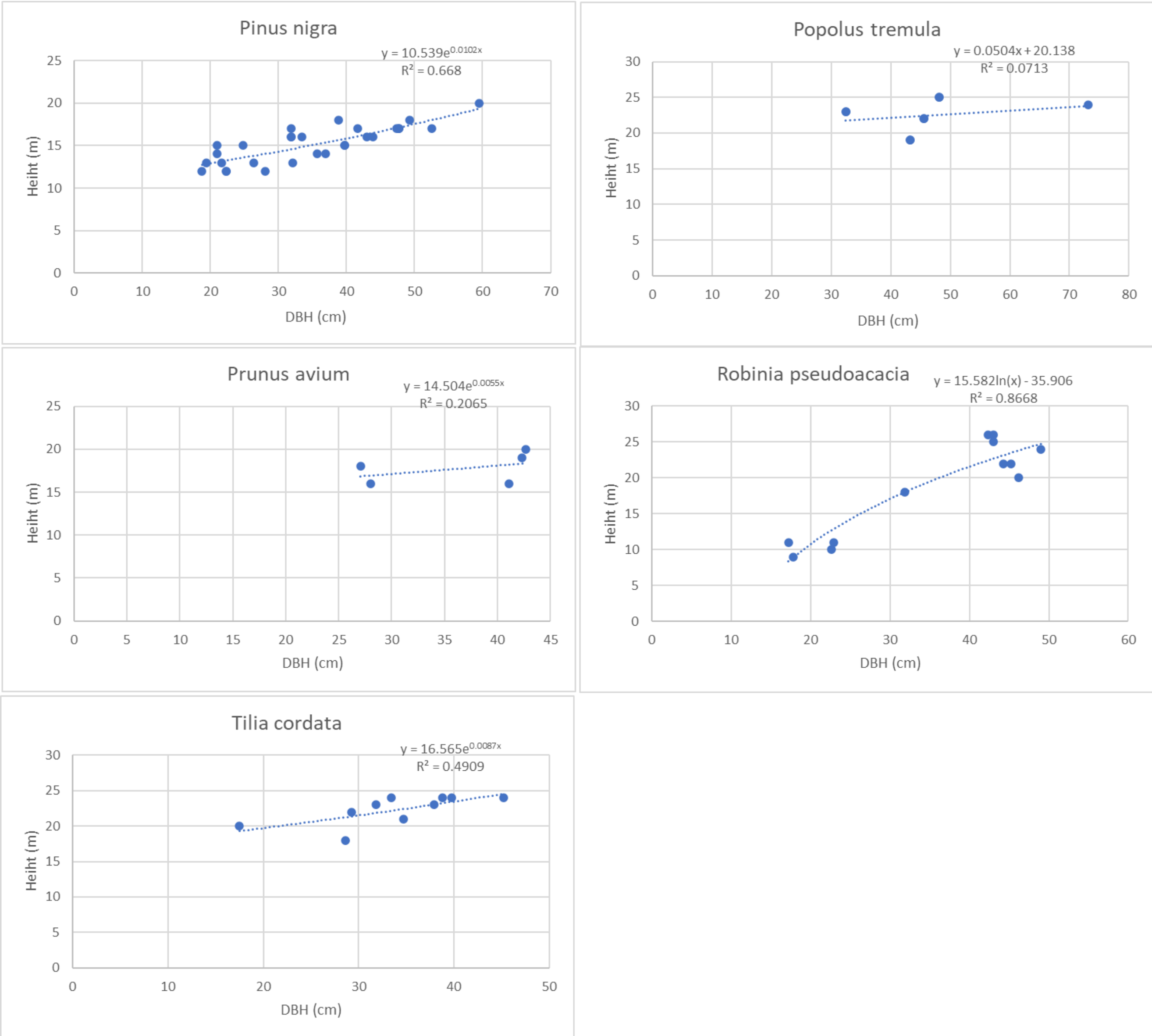


Figure S.2.17. Examples of ipsometric curves for the estimation of height of the most representative species of the AD. Carpinus betulus, Fraxinus ornus and Quecus rubra were not reported due to the few individuals for the construction of a regression.

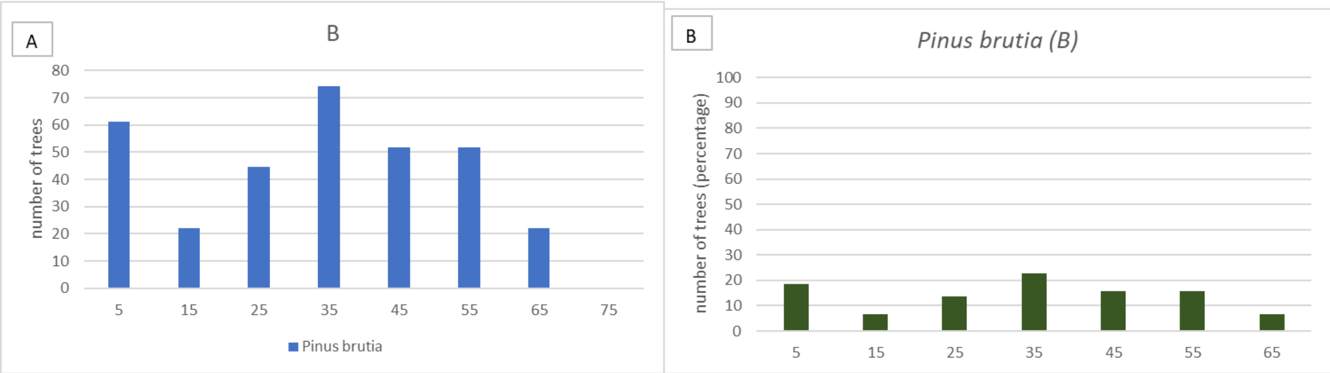


Figure S.2.18. Results of the forest structure analysis for the B, indicating the number of trees per species (A), and percentage of trees per diameter class for the most abundant specie (B).

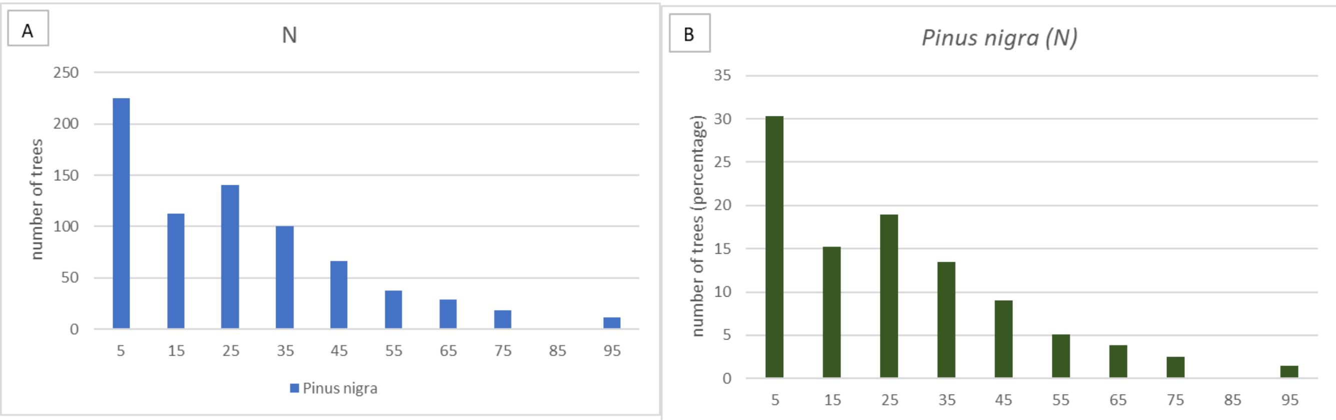


Figure S.2.19. Results of the forest structure analysis for the N, indicating the number of trees per species (A), and percentage of trees per diameter class for the most abundant specie (B).

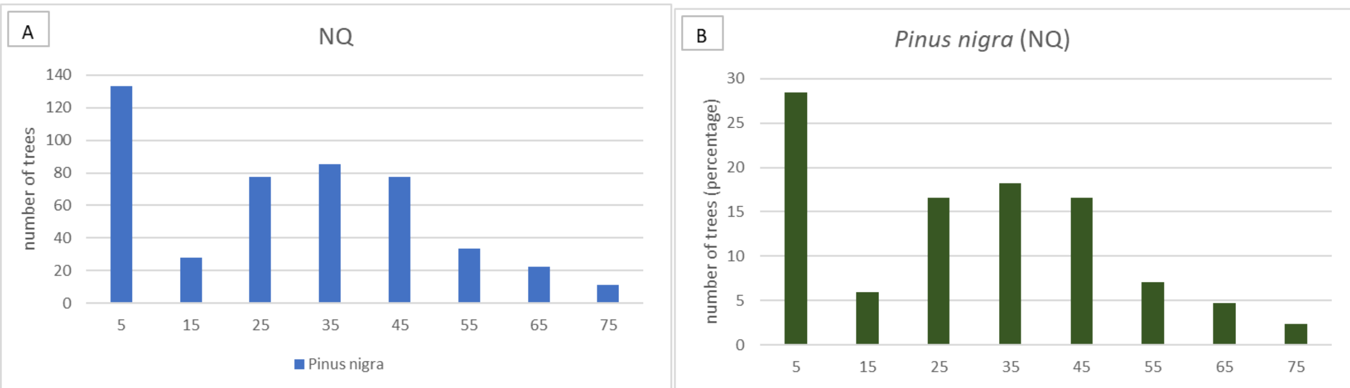


Figure S.2.20. Results of the forest structure analysis for the NQ, indicating the number of trees per species (A), and percentage of trees per diameter class for the most abundant specie (B).

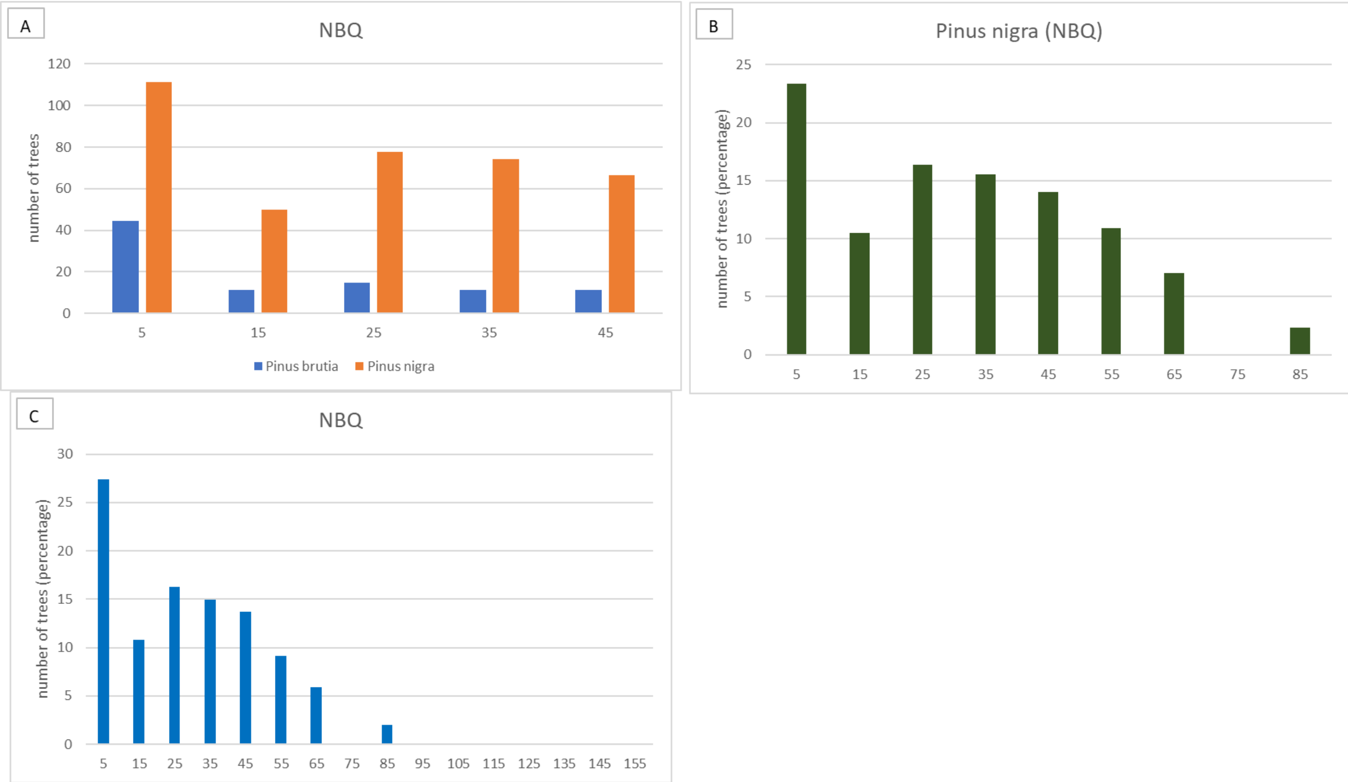


Figure S.2.21. Results of the forest structure analysis for the NBQ, indicating the number of trees per species (A), and percentage of trees per diameter class for the most abundant specie (B), and the percentage of all the species (C).

CHAPTER 3

THE EVALUATION OF THE CLIMATE REGULATION SERVICE IN TWO ALPINE AREAS USING DIFFERENT METHODOLOGIES: A COMPARISON BETWEEN FIELDWORK DATA, A NATIONAL INVENTORY AND THE TESSA TOOLKIT

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Under review

Nature Conservation Journal

Abstract

Alpine protected areas (PAs) provide a wide range of ecosystem services, with climate regulation being one of the most significant. There is an urgent need to correctly manage these areas in order to maximize biodiversity conservation and the supply of ecosystem services. To achieve efficient management and decision-making processes, it is crucial to first assess the current supply of ecosystem services and to have a basic reference for monitoring activities. Various approaches can be used to evaluate the climate regulation service, defined using organic carbon stock as the indicator. In this study we sought to use three of these approaches, namely fieldwork data collection, the national inventory and the TESSA toolkit, to evaluate the outcomes of each, and to consider the possible discrepancies. Our findings revealed that the TESSA toolkit was the approach which took least time and consumed the fewest resources, but that it overestimated organic carbon values in most situations. Fieldwork data collection was the most time and resource-intensive approach and it provided the highest level of accuracy in our results. The national inventory of forests and carbon yielded similar values to the fieldwork data, however the organic carbon stock in grasslands was not in the aims of the INFC, hence no data on grasslands were available. TESSA depicted qualitatively the same OC stock distribution across the habitats but yielded almost twice the amount for the OC stock in all the habitats. As a result, we propose different applications for these approaches, considering the advantages and disadvantages of each. Specifically, we suggest using the TESSA toolkit for preliminary screening of a study area to identify potential areas of ecosystem services supply, while more precise but demanding approaches should be employed for local studies.

1. Introduction

Protected Areas (PA) play a fundamental role in the supply of many Ecosystem Services (ES) (MEA, 2005; Eastwood *et al.*, 2016). ES are recognized as valuable conservation tools that support policy makers and managers in decision-making and monitoring activities (Goldman *et al.*, 2008; Goldman & Tallis, 2009; Duarte *et al.*, 2016). Due to their relevance, there is a growing demand for their evaluation, even within national and local policies. However, although ES were introduced to the public over two decades ago (Costanza *et al.*, 1997), still there is no common agreement on the indicators and the methodologies to be used for their evaluation (Bagstad *et al.*, 2013), leading to non-standardized descriptions (Boyd & Banzhaf, 2007; (Egoh *et al.*, 2012; Czúcz *et al.*, 2018) and to uncertainties regarding the magnitude of ES supply. Alpine areas are crucial for the provision of ES that support human wellbeing (Grêt-Regamey *et al.*, 2012a), but they are also highly vulnerable to the effects of climate change (IPCC, 2022). Hence, it is essential to understand how ES are provided by these areas and how to support and improve their supply. Among the multitude of the ES provided by alpine protected areas, we focused on the climate regulation service, due to its fundamental role in mitigating the effect of climate changes and the lack of a precise evaluation of it in alpine areas, particularly in soils (Canedoli *et al.*, 2020). Among the numerous indicators for estimating climate regulation, the organic carbon (OC) stock is the most used in the scientific community and the most fitting to the description of the climate regulation service (Canedoli *et al.*). Multiple approaches exist for the evaluation of OC stock, from fieldwork activities to remotely sensed data collection (Meersmans *et al.*, 2012). However, the choice of the approach to use relies on the scope of the study, the resolution desired, the study area's size and the available resources. Higher resolution studies are certainly fundamental for an appropriate description of the current status of an area, but these are generally time and resources consuming. In some cases, limited resources may hinder the choice of higher resolution for the studies (Peh *et al.*, 2013b) and cost-effective tools and more general but quick descriptions may be more suitable for the area management and monitoring (Manolaki & Vogiatzakis, 2017). Another key factor is the output resolution, which may vary, either depending on the extent of the study area or the peculiarity of the study (Waage & Stewart, 2008). We were interested in understanding how the methodologies chosen can affect the outputs in the OC stock evaluation, in order to achieve an accurate description of the OC stock and to better develop informed management strategies. We then considered that depending on the purpose of the OC stock evaluation and the study area, one methodology could be preferable to another to achieve the most suitable description within a specific time and budget. In this study, we aimed to i) identify the differences in the OC stock using diverse approaches on diverse habitats within the study areas, and ii) to reach conclusions about the effort for obtaining the outcomes for each approach. We evaluated the average OC stock in three carbon pools (aboveground biomass, soil, litter) across the most representative habitats of our study areas, located in the Italian Alps (Gran Paradiso National Park, Adamello Regional Park) using three different approaches: a) fieldwork data related to an ongoing research line of the laboratory of Ecology at the University of Milano Bicocca, concerning the evaluation of ES in protected areas in the Alps (Canedoli *et al.*, 2020; Rota *et al.*, 2020) , b) data from the Italian National Inventory of Forests and Carbon (INFC 2005) (Gasparini & Tabacchi, 2011), c) TESSA Toolkit (Peh *et al.*, 2013a), a widely used toolkit for the rapid assessment of ES. We aimed to investigate the differences between using these diverse approaches and to analyse the outcomes of each the methodologies, in order to provide recommendations for ES evaluation within the constraints of available resources and time, while achieving a proper description of the OC stock. We did not seek to evaluate which approach is superior in a general context, but rather to investigate the resolution of the results, also considering the effort required for obtaining them, aiming to elucidate advantages and disadvantages of each approach, and to provide an informed baseline for deciding on different approaches for future OC stock evaluations.

2. Materials and methods

2.1.Study areas

The study areas are two protected alpine areas in the North of Italy, the Adamello Regional Park (AD) and the Gran Paradiso National Park (GP) (Fig. 3.1). These specific PAs were selected due to their comparable environmental characteristics, including elevation range, vegetation cover, climate, and soil types. Moreover, both areas are included as part of a broader project on the assessment of ES within mountainous protected areas.

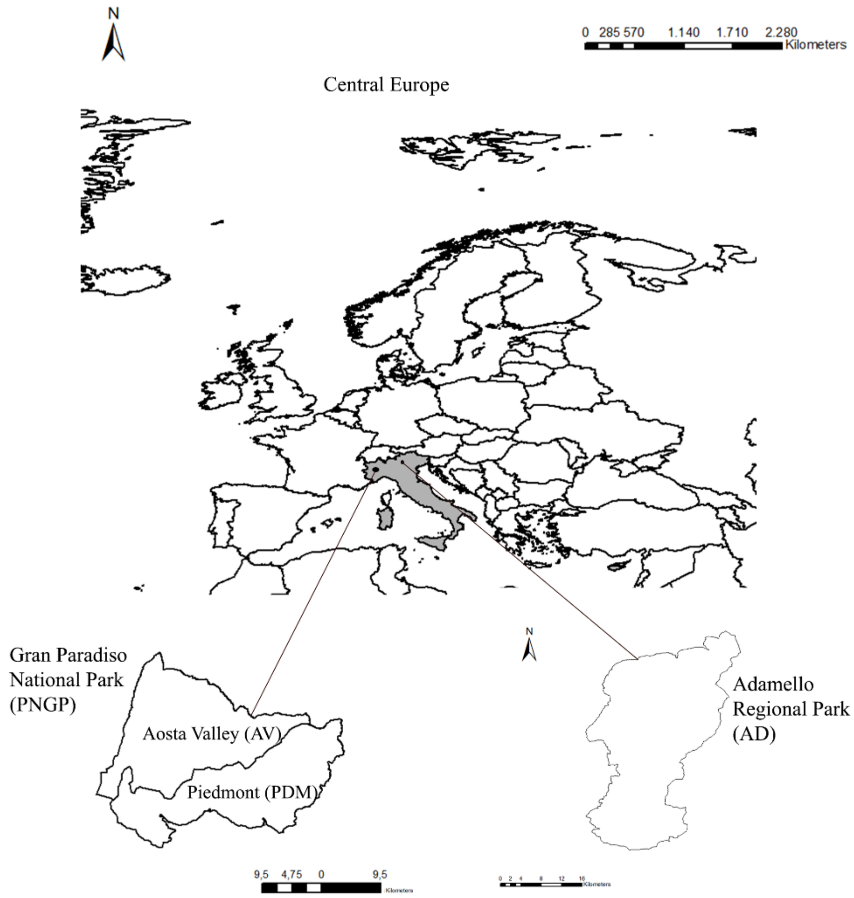

Figure 3.1. Map of the study areas, in the west the Gran Paradiso National Park, in the east, the Adamello Regional Park

2.1.1. Adamello Regional Park

The Adamello Regional Park (AD) was established in 1983 under regional law no. 79/1983. It is situated in northern Italy in the Rhaetian Alps, within the Lombardy region, with elevations ranging from 390 to 3,539 m.a.s.l, the peak of Adamello being its highest point. The park, covering an area of 51,000 hectares, is situated between two National Parks: the Adamello-Brenta National Park and the Stelvio National Park, and borders the Trentino Alto-Adige region to the east. The park displays a varied vegetation cover which mirrors its vast range in altitude. It hosts broadleaf forests in its lower altitudes and coniferous forests and alpine grasslands at an elevation beyond 2,000 m.a.s.l.

2.1.2. Gran Paradiso National Park

The Gran Paradiso National Park (GP), situated in the Graian Alps, and founded in 1922, is the oldest Italian National Park. Its history is related to the protection of the alpine ibex (*Capra ibex*) from extinction during the XX century and it was donated by the king to the Italian state by a Royal Decree. It is regulated under the Framework Law 394/91. Its area is approximately 70,000 ha, covering two regions – Piedmont and the Aosta Valley - and its elevation ranges from 800 m a.s.l. to 4061 m a.s.l., reached at the peak of the Gran Paradiso mountain. As with the AD, the vegetation cover is related to the elevation range, starting from broadleaf forests to coniferous forests and alpine grasslands. The most representative habitats in this study area are larch forest, spruce forest, alpine grasslands, mixed coniferous forest, chestnut forest and mixed deciduous forest.

In this study we will consider the GP as divided into two separate areas according to the regional boundaries, for the following reasons. Firstly, the INFC evaluated the OC stock using a regional approach, and since the GP covers two diverse regions, we will have diverse OC stock values for each pool and habitat. Moreover, the regions of the Aosta Valley (AV) and the Piedmont (PDM) have slightly different environmental characteristics, e.g., the rainfall regimes. Additionally, according to the IPCC ecological zones, the PDM region comprises warm temperate moist, cool temperate moist and warm temperate dry zones, whereas the AV is characterized by cool temperate moist and polar moist, even though the Park's area falls completely into the cool temperate mountain system, but these discrepancies may affect the INFC values. Consequently, we will treat the PDM and AV as separate entities throughout the study, except for visual representations.

2.2. Data collection

2.2.1. Fieldwork activities

The investigation of the GP took place between 2017 and 2020, while the study of the AD was conducted from 2021 to 2022. Data collection was done during the summer from June to August, due to the accessibility of the areas. First, we selected the most extended habitats of the study areas (Table 3.1), in order to yield a representative description of each PA, selecting only the habitats that covered at least 5% of the total area (see Chapter 2, cfr. Paragraph 2.2.1). The baselines for our selection were the habitat maps provided by the PAs. However, these were not homogeneous between the PAs and, for this study, we tried to create similar categories. For instance, at the GP there was a differentiation in the description of the grasslands, which involved discriminating between calcicolous and acidic grasslands, whereas at the AD, the maps did not include grasslands, thus we obtained these data from the LULC map of the Lombardy region. Nevertheless, during the fieldwork data collection and analysis, we took care to include in the habitat description only the habitats that reached 97% of relative dominance of the corresponding dominant species. The habitats chosen for both PAs were grasslands, mixed deciduous forests, chestnut forests, mixed coniferous forests, spruce forests (composed mostly by *Picea abies* L.), and larch forests (composed mostly of *Larix decidua* Mill.), while at the AD we also included the green alder shrublands (*Alnus viridis*). For the purposes of this study, we considered the habitats that had at least three plots sampled in the fieldwork campaigns.

A total of 258 plots were examined, with 49 plots in the PDM, 95 in AV and 114 at AD. Each plot was 30x30m in size, chosen through a stratified random sampling design.

Table 3.1. Description of the habitats sampled using the classification for TESSA, fieldwork and the INFC, and their extent in ha.

Ecological zone	**Type**	**Habitat type**	**INFC habitat**	**Area AD (ha)**	**Area AV (ha)**	**Area PDM (ha)**
Temperate mountain system	**Tree dominated habitat**	Chestnut forest	Chestnut forest	1674	-	236
		Larch forest	*Larix decidua* and *Pinus cembra* forest	5309	4244	2648
		Mixed deciduous	Other broadleaves	961	299	2006
		Mixed coniferous	Other coniferous	-	973	125
		Spruce forest	Spruce forest	9136	265	129

	Shrub dominated	*Alnus viridis* shrubland	-	4749	-	-
	Grass dominated	Grasslands	-	9136	7692	9392

Data on soil, tree aboveground biomass (AGB) and litter were collected according to Canedoli (Canedoli *et al.*, 2020). Mineral soil was collected at three standard depths (0-10 cm, 10-20 cm, 20-40 cm) in three repetitions in each plot, thus a composite sample of each depth in the plot (ca 100 g) was created. Thus, soil samples were analysed, and the bulk density (BD) was calculated using a site specific pedotransfer functions obtained from the samples collected (Cfr. Chapter 2). Eventually, the amount of OC stock (Mg ha^{-1}) was calculated using a specific equation which included bulk density (BD), rock fragments volume and the organic carbon content (%). Samples of organic layers were collected from three layers: OL (litter), OF (fragmented), OH (humus), and from these, the carbon stock was calculated (Mg ha^{-1}). Data on AGB were referred to each tree with a diameter above 10 cm included in our plot, of which we described the species, height and Diameter at Breast Height (DBH), at the standard height of 130 cm. Using the appropriate allometric equation for each tree (Table S1), we estimated the biomass (M) of each plot, and then using the conversion coefficient from the IPCC (2003) we obtained the OC stock (Mg ha^{-1}).

2.2.2. National Inventory of Forest and Carbon (INFC)

The National Inventory of Forest and Carbon pools (INFC2005) (Gasparini & Tabacchi, 2011) is the national inventory which collects the information regarding the state of the natural capital, and assesses and monitors GHG emissions, according to the Kyoto Protocol. It includes quantities of OC stock in three diverse pools (mineral soil, litter and tree above-ground biomass), collected at a regional scale. Data in the INFC were collected in forested habitats only, thus no data on grasslands were available from this methodology. The INFC employed a three-phase sampling design, with the initial two phases focused on estimating forest area and classifying it, while the third phase centred on collecting dendrometric data and soil data. Sample points, totalling approximately 301,000, were chosen across the Italian territory using orthophotos. In the second phase, a subsample was randomly selected for both forest and other wooded land, proportionate to the extension of the Italian regions. This involved an evaluation to identify the forest type and subtype. Finally, the third phase involved quantitative data collection on vegetation, deadwood, litter, and soil, engaging more than 100 crews comprised of two or three operators (Tabacchi et. al 2007). Further details on the methods used for the INFC are available at https://www.inventarioforestale.org/it/documentazione/. The methods used for the quantification of organic carbon stored in the INFC were comparable to the methods we used during our field activities, with the exception of the standard sampling depth of the third layer of mineral soil samples, which reached a maximum of 30 cm in the INFC. The OC stock data in the fieldwork were adjusted to a depth of 30 cm, finding the linear or non-linear model for the SOC content and reported our data to a depth of 30 cm, to allow comparisons with the INFC.

2.2.3. TESSA Toolkit

The TESSA (Toolkit for Ecosystem Service Assessment) toolkit was designed as a user-friendly guide for a quick ecosystem services assessment (Barredo *et al.*, 2015), and for monitoring purposes (Maes *et al.*, 2013). The toolkit is crafted as a step-by-step framework, guiding users through a series of questions. Its strengths lie in its user-friendly design, making it accessible to non-experts for evaluating ecosystem services (ES). The toolkit's simplicity enables users to assess ES effectively by suggesting specific methodologies. Methods include collecting new data or using existing datasets. Tessa toolkit is designed to support nature conservation strategies and enhance the management of diverse areas. It serves as a practical guide for monitoring and assessing ecosystem services at a site scale. Considering the “global climate regulation” toolkit, included in TESSA, the key step is the identification of habitats or land uses, which are considered the main factor affecting the OC stock. Hence, the steps of the climate regulation methods are guided by some decision trees, and key questions to help the user in the decision process (Peh et al. 2013).

The toolkit multiplies the values of OC stock for the specific LULC (Land Use and Land Cover) by the area. First, we converted our LUCL classification into TESSA habitat types, according to the IPCC 2006 and FAO ecological biomes (Table 3.1). The study areas considered were included in the ecological zone of Cold temperate moist according to the IPCC ecological zones and Temperate mountain system, according to FAO ecological zones. We then applied TESSA Version 2.0, in order to estimate the values of the carbon stocked in the three carbon pools: (a) AGB using Method 2, (c) Dead wood and litter with Method 6, (d) Mineral soil using Method 7. We proceeded as indicated below.

Method 2 – Above ground biomass

Method 2 leads to the estimation of above-ground live biomass carbon stock using IPCC tier 1 estimates. Aboveground live biomass in tree-dominated habitats in our study area was referred to Table 4.8 (aboveground biomass in forest plantations) in Chapter 4 of the IPCC (2006), and the estimation was mainly based on the location, the age and coniferous vs broadleaves. The selection of plantations instead of natural forest relies on the history of PAs forests, which have been mostly managed for human activities, however we acknowledge that this could be an approximation, but that led to the discrimination of forest types and a better result than considering these forest fully natural. For instance, the AD was highly managed and disturbed during world war II and plantations occurred during Fascism. The age of the forest was considered as >20 years, except for green alder shrubland, since this is a fast growing species and it is feasible to be a younger forest. For grassland, there were no values in the reference IPCC table for the AGB, meanwhile green alder shrubland was considered as a broadleaf forest < 20 years. To calculate the total above-ground live biomass carbon stock (Mg ha^{-1}) of the habitat, we multiplied the total above-ground live biomass with the conversion factor of 0.5 for tree-dominated forest plantations.

Method 6 – Litter and deadwood

We estimated the dead organic matter (litter and dead wood) carbon stock using IPCC tier 1 values from Table 2.2 in Chapter 2 of IPCC (2006) for litter in tree dominated habitats, whereas for grasslands there were no existing data from the IPCC. Referring to the ecological zone of Cold temperate moist we obtained an OC stock of 16 Mg ha^{-1} for broadleaves and 26 Mg ha^{-1} for needleleaf/evergreen forests.

Method 7 – Mineral soil

Estimating Soil Organic Carbon Stock in mineral soils, we used the IPCC tier 1 soil carbon inventory method. Since the climate and the soil types of our study areas were available, we used as reference the Table 2.3 in Chapter 2 of IPCC (2006). The soil types we collected were identified as High Activity Clay (HAC; Leptosols, Phaeozems, Cambisols, Umbrisols, Regosols) and Podzols. In our study areas, Podzols were mostly represented by Larch Forests at the AD, and spruce forest at the GP (both AV and PDM), whereas the HAC were all the remaining habitats.

2.3. Data analysis

We conducted a two-tailed T-test for each approach to detect the statistically significant differences between the mean values of OC stock in each habitat and method. Furthermore, we compared the total of OC stock, obtained by the sum of each pool in the habitat, across different approaches, aiming to identify proportions how the outputs could be related each other (e.g., proportions). To determine the minimum number of plots required for fieldwork, we randomly selected OC stock values from each habitat using the software R, version 4.3.1. (Allaire, 2012), and the function “sample” (Becker, 1988). We randomly extracted sequences of 3 plots, 5 plots, 10 plots, and 15 plots – where feasible - for each habitat, repeating the process 10 times. We calculated the absolute error compared to the average total value per habitat and quantified the mean absolute percentage error (MAPE) to evaluate the extent of change with increasing sampling effort. We considered a threshold of 5% as an acceptable error, indicating which number of plots was enough for the description of the habitat.

2.4. Mapping

Maps are an essential tool used to represent spatial information and to aid decision makers and managers in identifying areas with high carbon storage potential and in developing specific strategies to protect and enhance the ES supply. Hence, three maps were created using the software ArcGis (Booth & Mitchell, 2001), one for each approach, assigning to each LULC class the corresponding average OC stock value. This approach is comparable to using InVEst 3.10.1 (Zhao *et al.*, 2019) a spatially explicit software by the Stanford-based Natural Capital Project for assessing ecosystem services, which is one of the most commonly used types of software for OC stock maps creation and for ES and their trade off estimation. We preferred using ArcGis rather than InVest due to its versatility and possibilities for the elaboration of maps. The areas belonging to the GP, PDM and AV, were merged for the map’s visualization, as they belong to the same PA. We obtained an output map for the spatial distribution of OC stock in each methodology, and we attached a habitat map for each PA as reference map for data interpretation.

3. Results

As the main result, we detected differences in outcomes between fieldwork, the INFC, and TESSA (Table S2). Specifically, fieldwork and the INFC approaches showed greater similarity, while TESSA consistently led to an overestimation of the OC results. However, depending on the study area, more similarities can be found between the approaches.

At the AV (Fig. 3.2), regarding the AGB, we found more similarities between TESSA and fieldwork, rather than with the INFC approach. This could be attributed to the fact that for the AV the INFC had given lower values and incomplete data, particularly for mixed coniferous forests. In AV the two tailed T-test (Supplementary Materials, Table S.3.3.1) resulted in significant differences ($p<0.05$) between the AGB calculated with TESSA and INFC, whereas no significant differences were detected with the other method. Concerning soil and litter, no significant differences were found between fieldwork and INFC, whereas TESSA gave significant differences with both fieldwork data ($p<0.005$) and INFC data ($p<0.05$). An overall overestimation of values was encountered using TESSA, particularly at the AV. TESSA yielded more than double the total OC stock in almost every habitat, compared to fieldwork.

At the PDM (Fig. 3.3), we observed that the AGB values showed more similarities between TESSA and fieldwork, whereas no statistically significant differences resulted among approaches. Concerning soil, we found significant differences between TESSA data and the other two approaches, with lower values in the fieldwork data. Regarding litter OC stock, significant differences ($p<0.05$) were observed between TESSA and INFC values. Conversely, greater similarities were found between INFC and fieldwork data. The PDM results were particularly interesting for soil OC, as we encountered significant differences between the fieldwork data and the other approaches, resulting in lower values for the soil samples collected directly from the area. Despite the INFC giving lower values than TESSA, more similarities were found between these two approaches rather than the fieldwork. This aspect could be attributed to the diverse resolution of the approaches, with the INFC being a regional study, and fieldwork a very local resolution study.

At the AD (Fig. 3.4) we detected significant differences ($p<0.05$) in the mean values of soil OC stock between TESSA and INFC, in litter values between fieldwork and TESSA ($p<0.005$), and in AGB between TESSA and INFC data ($p<0.05$), whereas for the other categories, no significant differences were found. In this case, for instance for AGB, the data collected in the field had average values between those of TESSA and INFC, in fact our field data collection resulted in higher values than the INFC but lower values than TESSA, however no significant differences were found for this pool. Nevertheless, in soil we found lower values in our fieldwork data rather than from the other two approaches, particularly for the chestnut forest, from which field results on average gave 51.6 Mg ha^{-1} of OC stock, whereas in the other two approaches, this reached a value close to 96 Mg ha^{-1}.

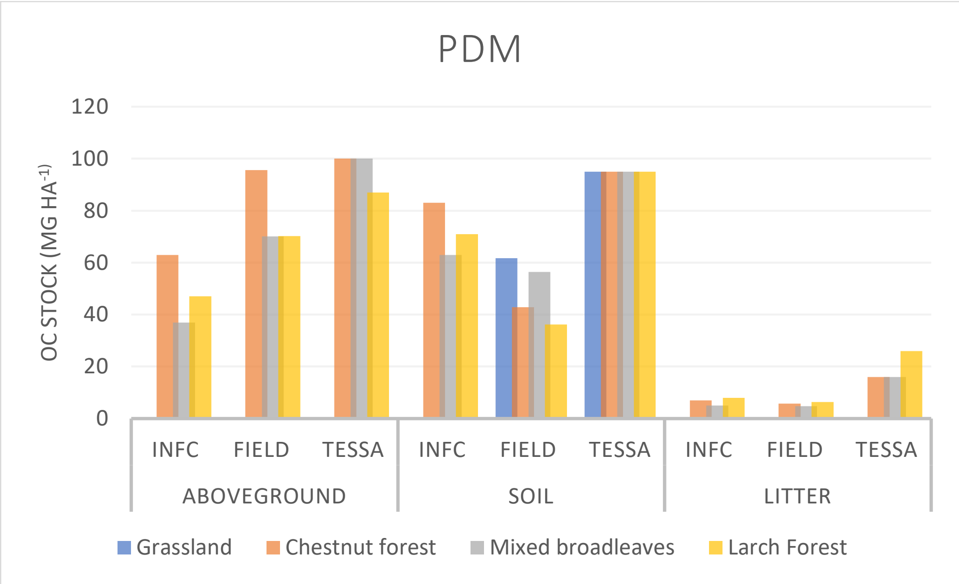

Figure 3.2. Output from each methodology of the average OC stock (Mg ha^{-1}) per each pool in Piedmont

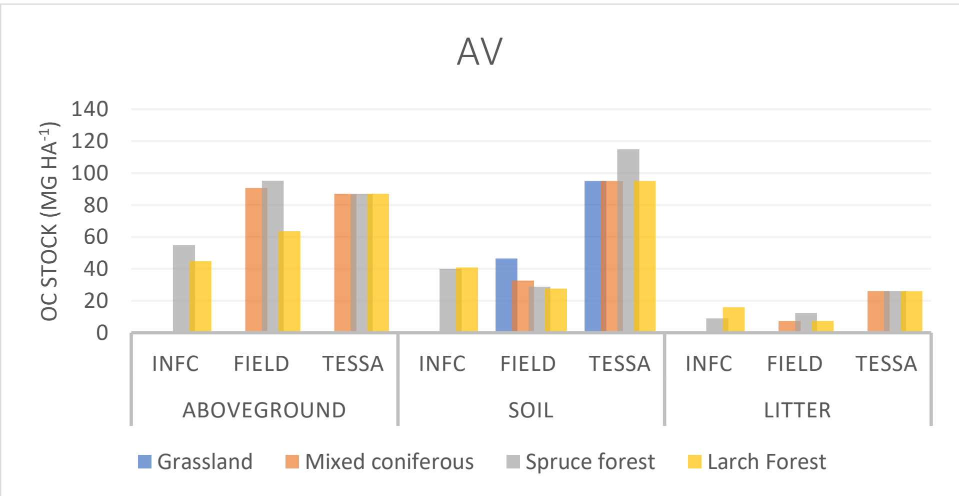

Figure 3.3. Output from each methodology of the average OC stock (Mg ha^{-1}) per each pool in the Aosta Valley

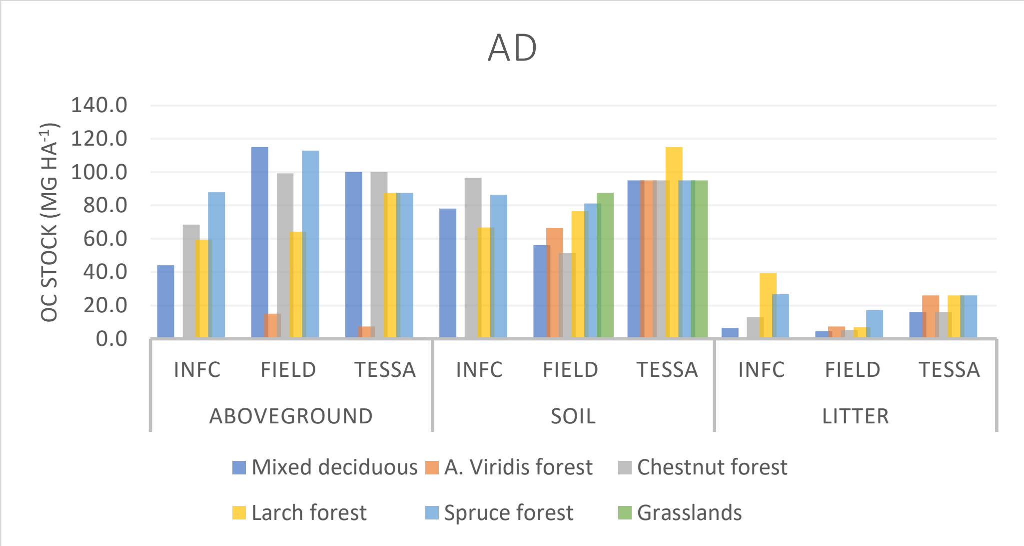

Figure 3.4. Output from each methodology of the average OC stock (Mg ha^{-1}) per each pool at the Adamello

Eventually, we produced three maps of the total OC stock for every PA, each corresponding to a different approach (Fig. 3.5, Fig. 3.6). By analysing the results with a consistent colour scale, we observed a noticeable visual distinction among the maps, primarily because of the tendency of the TESSA Toolkit to overestimate OC stock compared to the other two approaches. The first map utilized the INFC 2005 data and focused only on forested habitats, the second map was generated using fieldwork data, and the third map was generated using TESSA Toolkit data. Upon comparing INFC with the fieldwork data, we observed similarities in the magnitude of OC stock, however, a substantial portion of our study area, particularly grasslands, was not accounted for due to the absence of values. The PDM and the AV were combined into one map (Fig.3.4), as they belong to the same PA. Generally, we obtained the lowest values with fieldwork data compared to the other approaches. For the AV, the INFC did not comprise mixed coniferous forest as well, limiting the visual description. Nonetheless, across all maps, larch forests and spruce forests were consistently identified as the habitats most rich in OC, although the estimated values varied. At the AD (Fig. 3.5), the map clearly indicated a discrepancy in the sorting of the most stocking habitats, attributable to the larch forest and grasslands, in fact, the larch forest resulted less rich in OC stock than with the other two approaches. Nevertheless, we found that the maps showed similarities in the OC stock distribution across the habitats.

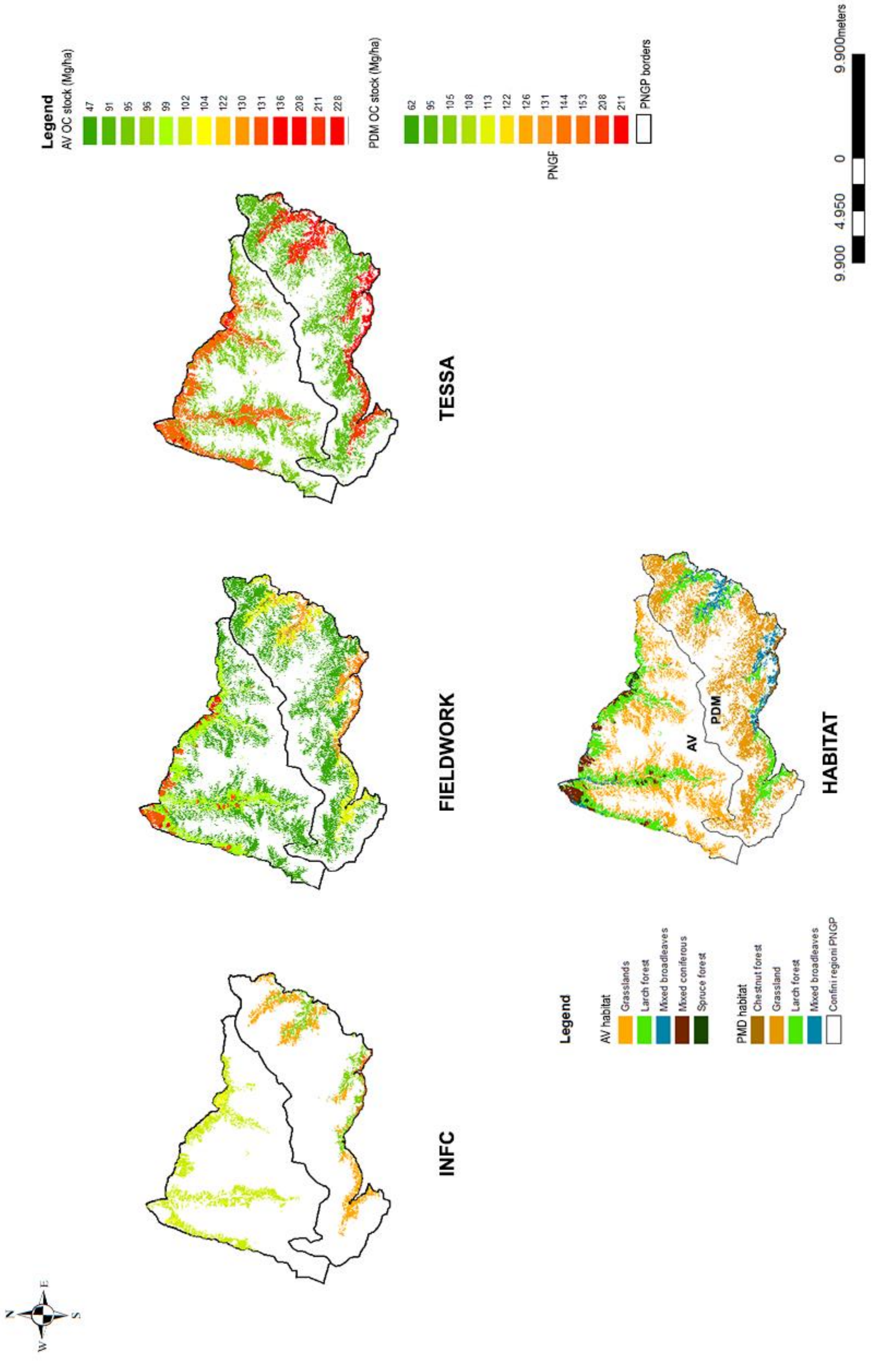

Figure 3.5. Total OC stock at the GP using the three approaches.

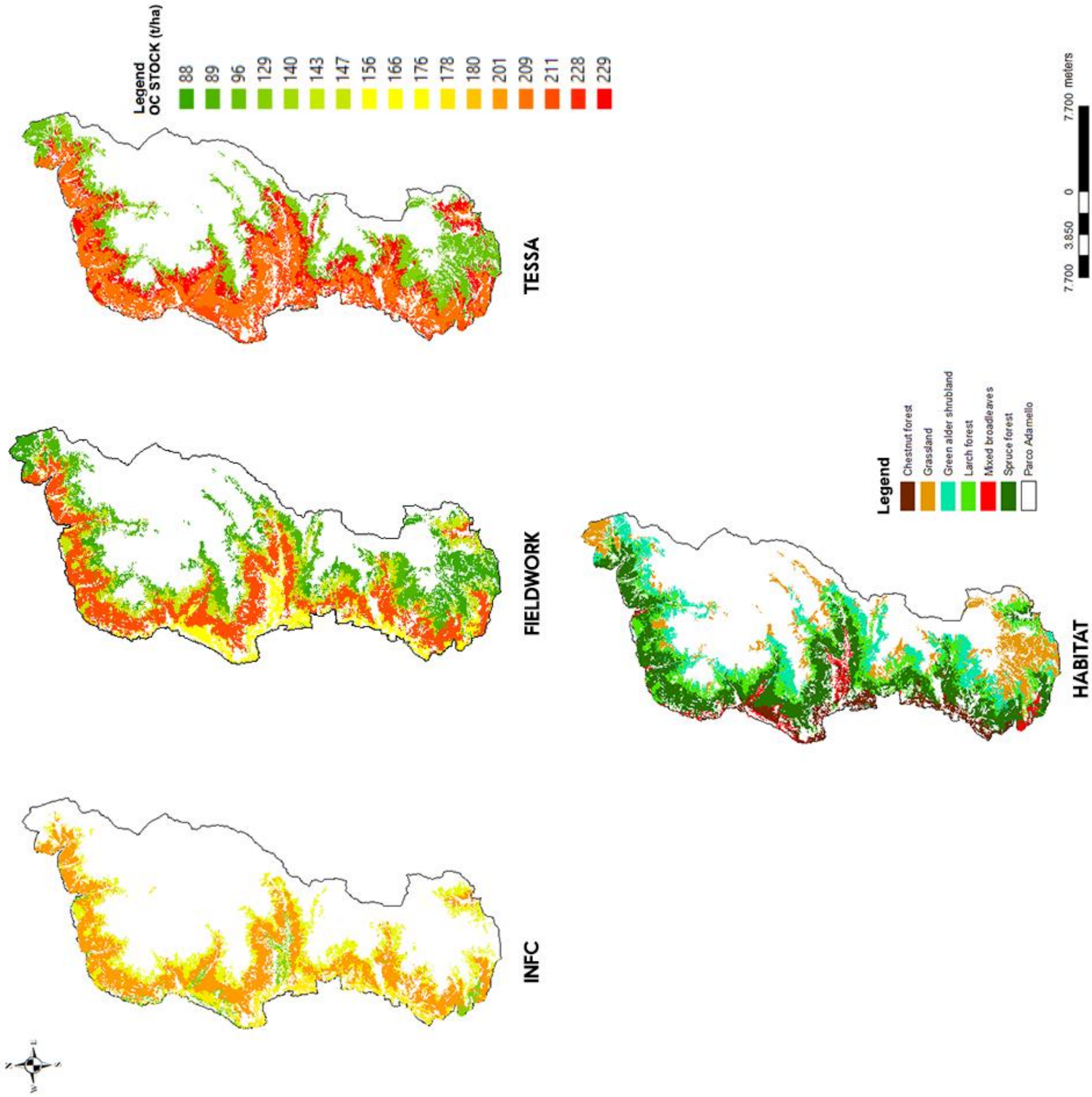

Figure 3.6. Total OC stock at AD using the three approaches.

Furthermore, we were interested in calculating the total OC stock in tonnes, for each PA. Then we obtained the result by multiplying the area of each habitat in the PA by the corresponding OC stock value per hectares (Table S.3.3). The results showed that TESSA at the AD overestimated the total OC stock to with a lesser extent compared to the GP (PDM and AV). At the AV (Fig.3.8) we found that the Larch forest stored the highest amount of OC, primarily due to its extensive coverage on the total area, being the second most extensive habitat. However, diverse values were obtained using the three approaches: the fieldwork data resulted in a total of 419,163 tonnes, the INFC provided a slightly higher value with 432,859 tonnes and TESSA yielded almost double with 882,694 tonnes. In PDM (Fig. 3.7) the most extensive habitat, which stocked the greatest amount of OC were the grasslands: in fact, they were definitely the most extensive habitat of the area, reaching more than 9000 ha. In this case we could not refer to the INFC data since grasslands were not included in that inventory. Nevertheless, TESSA overestimated the values compared to the fieldwork data, with respective totals 892,242 tonnes and 579,315 tonnes. The differences were slightly less pronounced than in the AV. At the AD (Fig.3.9), the spruce forest habitat stored the largest amount of OC, as confirmed by all three methodologies. In terms of total OC stock, we did not identify pronounced differences between the methods in the AD. The INFC yielded a total of 1,838,142 tonnes, the fieldwork data resulted in 1,688,893 tonnes, and TESSA estimated a total of 1,905,748 tonnes.

To better understand the differences between the methods we calculated the ratio of values using fieldwork data as the baseline reference (Table S.3.3), since we assumed that data collected in the field were the closest to the actual values of the area. This enabled us to determine the variations in the estimated OC stock per habitat in tonnes using the diverse approaches. Notably, the biggest differences were encountered in the AV. In this case, TESSA yielded values that were twice as high as the collected data. For instance, the larch forest ratio was 2.1:1 in relation to fieldwork data. Conversely, the INFC data resulted in a ratio close to 1:1. Similar results were obtained at the PDM, with TESSA doubling the outcome value, resulting in values between 1.5 and 1.8 times higher. At the AD we encountered the smallest disparities, although TESSA still yielded values approximately 1.5 times higher than the fieldwork measurements.

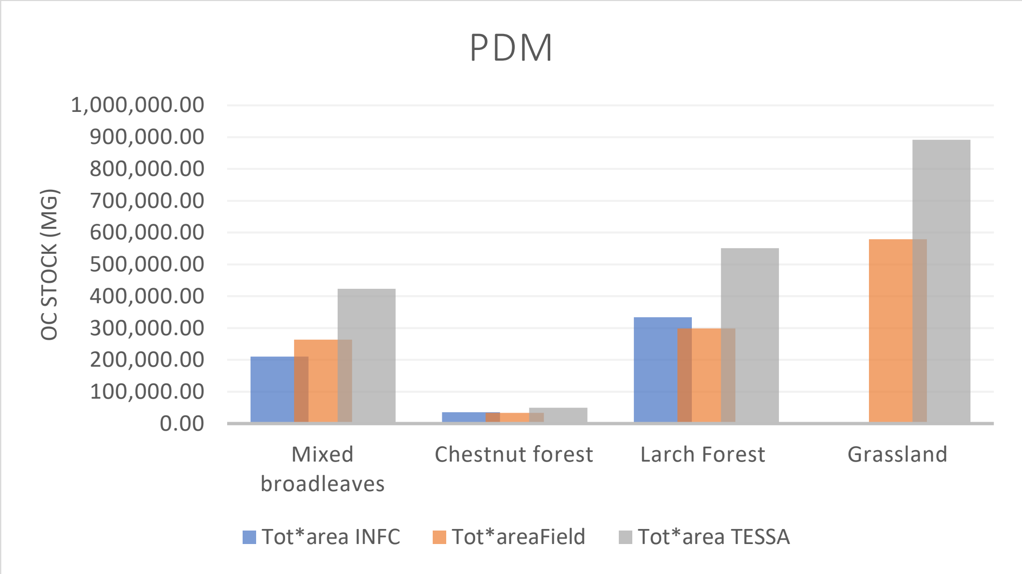

Figure 3.7. Total C stock (tonnes) per habitat at the PDM using the three methodologies.

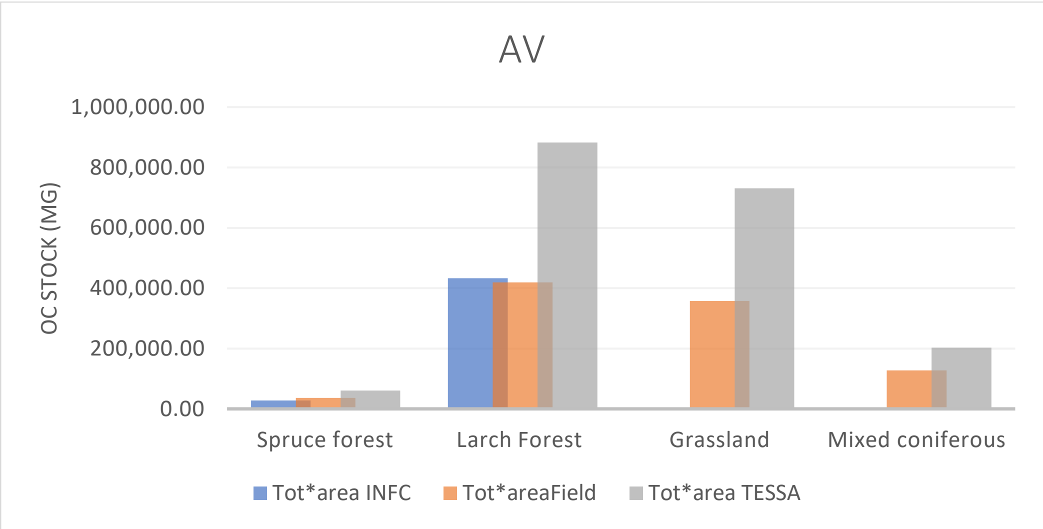

Figure 3.8. Total OC stock (tonnes) per habitat at the AV using the three methodologies.

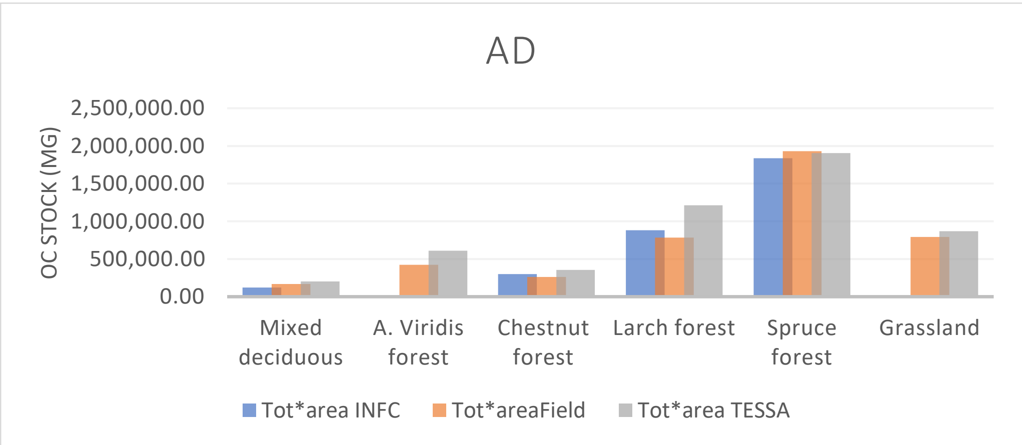

Figure 3.9. Total OC stock (tonnes) per habitat at the AD using the three methodologies.

Eventually, as our aim was also to provide suggestions for an efficient ES evaluation, we calculated the minimum number of plots needing to be assessed for each habitat in order to reach a sufficient description of the study area while minimizing the efforts, as fieldwork data resulted in the highest accuracy but was also the costliest approach. This result was obtained by carrying out a random extraction of the total OC stock value (three pools summed) several times and calculating the absolute error. Hence, we obtained the Mean Absolute Percentage Error (MAPE), which could be considered an indicator of the variations of the results by increasing the sampling efforts. We then calculated the MAPE for each habitat, and evaluated the trend obtained through a regression analysis (Fig. 3.10, Table S.3.4). We took as acceptable error a threshold of 5%. It emerged that for grasslands we needed at least 15 plots per each PA, since the classification was quite broad and included diverse grassland types (acidic grasslands, calcicolous etc.). Larch forest gave different values between AD and AV. Spruce forest and mixed coniferous forests, where present, both resulted in a minimum sampling effort of 10 plots each.

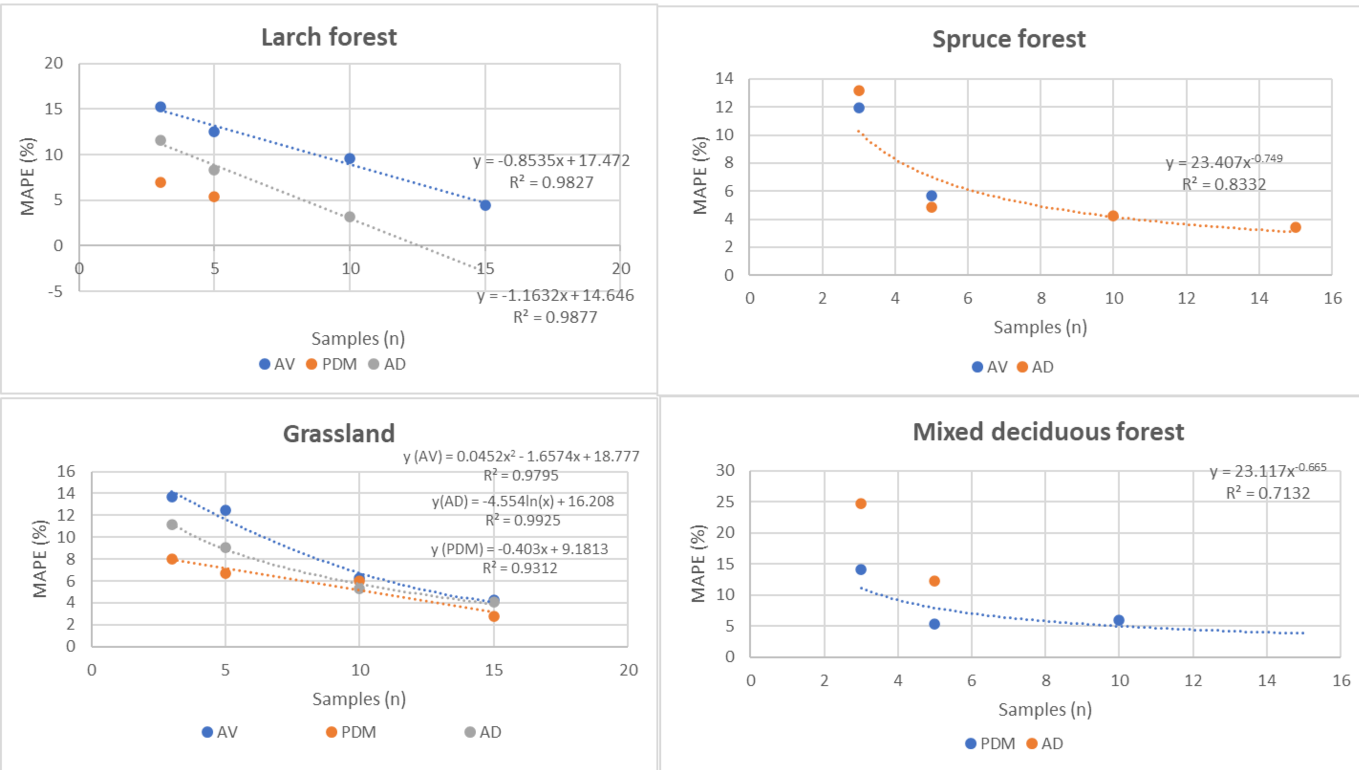

Figure 3.10. Regression analysis for the evaluation of the minimum number of samples for reducing the MAPE (%)

4. Discussion

This study aimed to compare three different approaches and to establish differences in the methods and outcomes in the evaluation of the OC stock. As the mountainous regions, and particularly the alpine environments, are crucial for the supply of ecosystem services and are highly vulnerable to the effects of climate change (Schröter *et al.*, 2005), there is an urgent need to evaluate the ES provided (Grêt-Regamey *et al.*, 2012b). Moreover, there is a lack of robust information on OC stock in alpine environments, due to the difficult accessibility of these areas (Prietzel & Christophel, 2014), the lack of site and species specific allometric equations for the AGB evaluation, and the resources and time required for intensive fieldwork campaigns. Hence, in this study we investigated whether, through less resource-intensive approaches, a proper description of the OC stock in these areas was possible. Notably, the three approaches (fieldwork, INFC and TESSA) had as their main differences the accuracy of the outputs and the effort to obtain the data. First, concerning the effort needed for data acquisition, fieldwork activities were the highest resource and time intensive approach, resulting in five years of fieldwork campaigns and laboratory analyses, involving a team of more than ten collaborators. Conversely, the TESSA toolkit was the most time and resources effective, resulting in a quick and effortless approach, requiring only a few days for the data collection and elaboration. The INFC was considered as a mid-intensive approach, due to the fact that data were collected by the INFC with fieldwork campaigns, but with an intermediate sampling effort due to the number of points collected on the total area (Gasparini & Tabacchi, 2011). We found that the three approaches yielded diverse outcomes, due to both data limitations and differences in the input resolution. For instance, regarding the soil OC stock, we found that TESSA merged the WRB soil categories into HAC, Podzols and LAC, leading to a flattening of the results. Interestingly, the comparison between INFC and fieldwork data revealed similarities in OC stock values across almost all pools. The fieldwork data served as the basic reference point in this study, as they were directly collected within the study area, reflecting values that closely approximate reality. It is important, however, to acknowledge that local variations in OC stock attributable to environmental factors (Ahirwal *et al.*, 2021), such as temperature, elevation and precipitation regimes, must be taken into account (Prietzel & Christophel, 2014) and biases related to our fieldwork activities might be present. However, we encountered few discrepancies between INFC and fieldwork data, and these can be primarily attributed to the regional scale of the former, encompassing forests across diverse elevations and environmental characteristics, while our fieldwork data were specific for the studied PAs. Nevertheless, in our PAs, and in general in the alpine environments, grasslands constituted one of the most extensive habitats in the total area, and they are now a habitat of interest, since their carbon storage potential was for long undervalued (Hall *et al.*, 1995; Nagler *et al.*, 2015), hence they were included in our sampling design for fieldwork activities. No grassland data were compiled in the INFC, which was developed with the specific aim of evaluating the carbon stock in forested habitats, but we suggest carefully considering the habitats existing in the PA and their extent before choosing the approach for the evaluation. In fact, grasslands represent 37% at AV, 49% at PDM and 18% at AD of the total OC stock, and we would have omitted a huge quantity of OC stocked by not sampling them. However, we consider that an integration of the existing inventories concerning the alpine grasslands could be a useful step for the description of such important habitats, due to their evident OC stock potential. TESSA resulted in outcomes with high discrepancies with the other two approaches, generally indicating that higher values had been assumed for each habitat and study area. We suppose that this could be due to the simplification carried out in the input data, but further analysis must be undertaken to understand the reason of the overestimation in the studied habitats, probably also due to limitations of our study, in which there was no possibility of distinguishing plantations and natural forest for each habitat since a mixture of these exist, and the selection was based on plantations, being the most recurrent.

In terms of qualitative descriptions, the habitats that stocked the majority of OC on the total value were respectively larch forest in AV, grasslands in PDM and spruce forest in AD. These findings were consistent across all the three approaches, but with diverse magnitudes between the methods. The larch forest at the AD represented an exception for the qualitative description, achieving a mismatch with both INFC and TESSA, and possibly related to the fact the larch forests in this PA were particularly sparse and the value we obtained may be related to a peculiarity of the area. According to the TESSA guidelines, fieldwork is generally preferable, as it quantifies the actual value of OC stock in the area. Nonetheless, several studies were conducted using TESSA for the evaluation of ES (Birch *et al.*, 2014; Peh *et al.*, 2014; Blaen *et al.*, 2015; Liu *et al.*, 2017; Manolaki & Vogiatzakis, 2017; Perosa *et al.*, 2021), being quick, cost-effective, not requiring many existing data and overcoming the difficulties of sampling in poorly accessible areas. Generally, these studies encompassed many ES, giving a broader description of the complex supply of benefits of a specific area and helping to identify pools of complex ES supply. Additionally, in a rapid screening of a study area, maps created with TESSA could be a rapid and effective tool for helping managers to identify priority areas for the climate regulation supply. For instance, maps could be used along with other ES for a description of the possible ES supply areas and might aid researchers in creating an experimental design on which validation points could be collected, to obtain quantitative data on OC stock. It should be noted, however, that we do not recommend employing only the TESSA Toolkit for local studies where the quantification of OC is the primary objective, as the results did not align with the collected data, and no reliable ratio could be established to explain the trends. In the light of this, using the outcomes of TESSA toolkit as a reference for economic evaluations for the OC stock could lead to biased values which are method dependent (Yang, 2006) and might lead to possible biases in the decision-making process.

4.1. Implications for management and biodiversity conservation

High mountain areas play a fundamental role in OC stock (Kohler & Maselli, 2009) and positive relationships between carbon stock and biodiversity were detected in literature (Lecina-Diaz *et al.*, 2018), particularly at a regional scale (Midgley *et al.*, 2010). In this case, the maps we elaborated could result as an important tool for checking the presence of positive overlaps in carbon sequestration and biodiversity conservation areas. Hence, the improved estimations obtained from fieldwork data or INFC could be the best option to geolocate the OC stock. We consider that for the management of PAs, qualitative descriptions might not be enough, and data campaigns must be carried out where specific inventories are not present. To define the wealth of the PAs and investigate the effects of management strategies it is crucial to have a precise quantification of the carbon stocked in aboveground biomass and soil, to develop a better management of forests (Nystrom & Stahl, 2001; Duvemo & Lämås, 2006) and grasslands. Moreover, setting a time zero baseline from accurate data could help in the monitoring the gains and losses in carbon, aiding in the creation of historical trends of carbon changes by keeping a fixed methodology. Maps are a fundamental tool that can help managers in understanding the distribution of carbon within the boundaries of the PAs, and geolocate the carbon stock and its changes. For instance, having an accurate quantification of OC stock and biomass can lead to a forest planning that integrates the timber harvesting with the conservation of the carbon sequestration service (Dong *et al.*, 2015). The lack of data on the OC stock in alpine habitats, above all related to soil (Canedoli *et al.*, 2020), can be overcome with fieldwork campaigns, in which metadata of each plot can also be collected, with the advantage of being useful even for further studies, that overcome the OC stock quantification only, but that provide much information on the determining factors of the its distribution and the interactions with the environmental features. PAs within the Italian boundaries are not mandatorily required to provide any ES evaluation, however most PAs are voluntarily estimating the ES values, aiming to the improvement of the environmental performance of the PAs, allowing systematic assessment, monitoring and management. Among these PAs, also the Gran Paradiso National Park carried out the ES assessment according to the EMAS certification (Parco Nazionale del Gran Paradiso, 2019, 2022), in which the carbon storage though fieldwork activities was quantified. Hence, due to this widespread evaluation of ES within PAs, we highly recommend undertaking fieldwork activities to evaluate the carbon stock in PAs, in order to have an accurate description of the areas and the possibility of making reliable comparisons between PAs.

Also, giving a broader view that goes beyond PAs only, an adequate assessment of the actual carbon stock values may be useful as baseline in the voluntary carbon credit market, which is now a common option in EU for giving rewards to virtuous environmental management that lead to gains in carbons stock (Blanc *et al.*, 2019). In each carbon forest project it is required to build a baseline (Diaz & Delaney, 2011; Seifert-Granzin, 2011), from which scenarios will be developed and monitoring of the practices will be carried out to detect gains or losses in carbon. Among these activities the methodologies are often diverse and there is a need for common and transparent approaches (Petrokofsky *et al.*, 2011; Yanai *et al.*, 2020; Zhou *et al.*, 2023). Even though AGB studies for the carbon credits are generally field based activities, with the measurements of height and DBH, we encourage that the baseline of each carbon pool is set through fieldwork activities, above all for soil data.

Using an accurate approach for these kind of evaluations is fundamental since many management consequences and economic issues can emerge. For instance, using the TESSA toolkit valuation as the main source of data for the baseline of a forest project would have led to values higher than the actual ones, management strategies and monitoring would have been biased by the overestimation. Moreover, we want to underly that the quantification of the OC stock has already many uncertainties (Vanguelova *et al.*, 2016), due to the distribution of the OC among soil or the selection of allometric equations, so having data that fits the reality as much as possible would be the only way to correctly plan the management and conservation of these areas. There are also many management strategies that affect the OC stock, such as afforestation for the increase of OC stock due to the gain in the AGB pool, but in some cases it can reduce the OC stock for instance replacing a highly stocking grassland or peatland with a new afforestation (Mayer *et al.*, 2020): having reliable data can help managers in identifying promptly the activities that negatively affect the OC stock, and improve the conservation of the area. However, it is important to note that the carbon stock cannot be the only indicator for the environmental protection and area management, and more ES must be valuated during these monitoring activities. For instance, this study suggested that coniferous forests have the highest stocking capacity in each of the three pools, but for a correct management of the area also other aspects have to be considered, such as habitat provision and biodiversity.

Furthermore, it is essential to incorporate a sampling protocol that accounts for both management strategies and the historical context of the area. This consideration is crucial for accurately assessing the organic carbon (OC) stock, especially given the observed higher values in plantations compared to natural areas. This aspect was notably highlighted in the TESSA toolkit selection framework. Integrating such information into fieldwork activities enhances the precision and thoroughness of area descriptions. Eventually, we propose as a possible framework, that after a screening of the possible priority areas for the OC stock and other ES with TESSA, data in the field must also be collected, and used to check the accuracy of the inventories or TESSA data. However, being that fieldwork campaigns can be time and resources intensive, we understand that these might not be an option in some cases. Hence, we proposed a minimum number of plots per habitat, aiming to reduce the sampling effort, but keeping a low error in the average description of the OC stock and provide a reliable quantitative description. Our findings, specifically referring to our PAs, indicated that a minimum of 10 plots were suitable for the homogeneous habitats, predominantly composed by one species, such as spruce forests, and 15 plots for grasslands and mixed forests, which had an average value of OC stock that can be affected by the heterogeneity of the vegetation composition. Chestnut forests at the AD, for instance, were an interesting habitat, since their results diverged from the INFC and had a high MAPE. We can attribute this difference to two main factors: a) a potential bias in our fieldwork activities, as the chestnut forest should have been sampled more to reduce the error; b) the fact that chestnut forests have already been subjected to intense management practices, first for food provision and then for timber supply (Conedera & Krebs, 2007), which could impact the tree component of the vegetation structure and consequently the OC stock. However, based on the estimated numbers for achieving low error, in our study area a sampling composed of 170 plots would have been sufficient, reducing our sampling effort by 88 plots: this would have led to a reduction of costs and time for field activities, but still provided an acceptable OC stock estimation. We propose to develop further studies that quantify the minimum number of plots for reaching a reliable quantitative description of the OC stock with a reduced error, in order to obtain more information on how to reduce the cost and efforts needed for fieldwork activities.

Eventually, even though a rapid assessment, such as TESSA, can give promptly a huge quantity of information, including other pools such as below ground biomass OC stock, which would be highly resources intensive to evaluate in the field, and can include more habitats due to the rapidity of the study, quantitative and unbiased information is needed for an effective management and monitoring of these vulnerable areas. In the Italian context, the INFC has proven to be an effective tool for quantifying OC stock in forested habitats. Additionally, inventories need to be regularly updated to improve the quality of the evaluations and better describe the current status of the area, as was done for the INFC which was recently updated (Gasparini *et al.*, 2022), since relying on outdated information may lead to erroneous decision-making. Nevertheless, conducting fieldwork studies is very costly in terms of time and resources, and is difficult to undertake in remote areas such as alpine PAs. Hence, it is essential to find a compromise between resolution and costs, and the integration of methodologies, rather than the substitution of one for another, may be the most effective strategy in this regard.

5. Conclusion

Due to the vulnerability of alpine areas to climate change, we have an urgent need to develop efficient and informed management strategies, based on accurate evaluations of ecosystem services. Finding a compromise between the research effort and the quality of the outcomes has always been an open issue for researchers. In this study we evaluated OC stock in two alpine protected areas using three different approaches. Consistent differences were observed between the areas and the habitats, and discrepancies in the magnitude of the outcomes were found, with TESSA having the most diverse results if compared to the other two approaches. While it is crucial to consider both resolution and accuracy in research, the limitations of time and resources often call for efficient methodologies like TESSA, which can provide a quick evaluation. However, although TESSA was found to be efficient in the qualitive description of the OC stock, it was of limited value for its quantification. The INFC was a valuable tool for the OC stock description, but with the limitation of a lower resolution due to the regional scale, rather than local, which could omit the peculiarities of the area, and the complete lack of information on some habitats. Based on our findings, we would suggest using TESSA for a preliminary screening to identify the priority areas in need of attention. Subsequently, a fieldwork campaign must be undertaken to obtain information leading to finding the minimum number of plots to describe the OC stock or, where appropriate, to use an inventory and validate the values with a few plots. We believe that a balance between efficient resource utilization and reliable ES information can be found, and this will be a key point in order to provide recommendations to managers and decision makers.

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Supplementary materials

Table S.3.1. Allometric equations used for the estimation of the biomasses in this study, where DW4 is the total above ground phytomass (kg), d is the Diameter at Breast Height (cm), and h is the height of the tree (m), and b' are the specific coefficients.

Species	Allometric equation (general formula)	Coefficient matrix	Source
Abies alba	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-2.1386 ; $1.8125*10^{-2}$;1.1089]	Tabacchi et al., 2011
Acer campestre	$Dw4 = b_1+b_2d^2h$	***b***' = [6.4595 ; 2.6368*10]	Tabacchi et al., 2011
Acer pseudoplatanus	$Dw4 = b_1+b_2d^2h$	***b***' = [6.4595; 2.6368·10]	Tabacchi et al., 2011
Alnus viridis	$M=Dw4=ad^b$	[a= 44.06 b=2.395]	He et al., 2018
Betula pendula	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10; $1.1993*10^{-2}$; 3.1553]	Tabacchi et al., 2011
Carpinus betulus	$Dw4 = b_1+b_2d^2h$	***b***' = [3.2485; 3.0167·10]	Tabacchi et al., 2011
Castanea sativa	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-2.1739; $2.1442*10^{-2}$; $9.7075*10^{-1}$]	Tabacchi et al., 2011
Fagus sylvatica	$Dw4 = b_1+b_2d^2h$	***b***' = [1.6409; $3.0775*10^{-2}$]	Tabacchi et al., 2011
Fraxinus excelsior	$Dw4 = b_1+b_2d^2h$	***b***' = [2.1893; 3.2949*10]	Tabacchi et al., 2011

Fraxinus ornus	$Dw4 = b_1+b_2d^2h$	***b***' = [2.1893; 3.2949*10]	Tabacchi et al., 2011
Laburnum anagyroides	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10; 1.1993*10^{-2}; 3.1553]	Tabacchi et al., 2011
Larix decidua	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.4060*10 1.4664*10^{-2} ; 3.2309]	Tabacchi et al., 2011
Picea abies	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [1.4146*10^{-2}, 1.7620*10^{-2}; 5.6209*10^{-1}]	Tabacchi et al., 2011
Pinus nigra	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-3.3972*10; 1.7363*10^{-2}; 4.1912]	Tabacchi et al., 2011
Pinus sylvestris	$Dw4 = b_1+b_2d^2h$	***b***' = [2.8848; 2.2080*10^{-2}]	Tabacchi et al., 2011
Prunus avium	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10; 1.1993·10^{-2}; 3.1553]	Tabacchi et al., 2011
Quercus rubra	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-7.1745; 3.3299·10^{-2}; 1.2623]	Tabacchi et al., 2011
Quercus spp	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-7.1745; 3.3299*10^{-2}; 1.2623]	Tabacchi et al., 2011
Salix appendiculata	$Dw4 = b_1+b_2d^2h$	***b***' = [9.0561; 2.1087*10^{-2}]	Tabacchi et al., 2011
Salix caprea	$Dw4 = b_1+b_2d^2h$	***b***' = [9.0561;	Tabacchi

		$2.1087*10^{-2}$]	et al., 2011
Salix glabra	$Dw4 = b_1+b_2d^2h$	***b***' = [9.0561; $2.1087*10^{-2}$]	Tabacchi et al., 2011
Alnus glutinosa	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.6747*10 $1.7930*10^{-2}$; 2.6664]	Tabacchi et al., 2011
Juglans regia	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10 $1.1993*10^{-2}$; 3.1553]	Tabacchi et al., 2011
Popolus tremula	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10 $1.1993*10^{-2}$; 3.1553]	Tabacchi et al., 2011
Sorbus aria	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10 $1.1993*10^{-2}$; 3.1553]	Tabacchi et al., 2011
Sorbus aucuparia	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10 $1.1993*10^{-2}$; 3.1553]	Tabacchi et al., 2011
Tilia spp	$Dw4 = b_1+b_2d^2h+b_3d$	***b***' = [-1.2825*10 $1.1993*10^{-2}$; 3.1553]	Tabacchi et al., 2011
Pinus cembra	$Dw4 = b_1+b_2d^2h$	***b***' = [3.3073; $1.8848*10^{-2}$]	Tabacchi et al., 2011

Table S.3.2. Carbon stock measurements (Mg ha^{-1}) the FIELD, INFC and TESSA in AV, PDM and AD

	AV (Mg ha^{-1})	ABOVEGROUND			SOIL			LITTER		
lucode	LULC_name	INFC	FIELD	TESSA	INFC	FIELD	TESSA	INFC	FIELD	TESSA
1	Grasslands	-	-	-	-	46.5	95	-	-	-
2	Mixed coniferous	-	90.7	87	-	32.7	95	-	7.48	26
3	Spruce forest	55	95.2	87	40	28.8	115	9	12.4	26
4	Larch Forest	45	63.7	87	41	27.7	95	16	7.4	26

	PDM(Mg ha^{-1})	ABOVEGROUND			SOIL			LITTER		
lucode	LULC_name	INFC	FIELD	TESSA	INFC	FIELD	TESSA	INFC	FIELD	TESSA
1	Mixed broadleaves	37	70.15	100	63	56.4	95	5	4.77	16
2	Grasslands	-	-	-	-	61.7	95	-	-	-
3	Chestnut forest	63	95.7	100	83	42.9	95	7	5.76	16
4	Larch Forest	47	70.3	87	71	36.3	95	8	6.4	26

	PA(Mg ha^{-1})	ABOVEGROUND			SOIL			LITTER		
lucode	LULC_name	INFC	FIELD	TESSA	INFC	FIELD	TESSA	INFC	FIELD	TESSA

1	Mixed deciduous	44.1	115	100.0	78.2	56.2	95.0	6.4	4.5	16.0
2	A. Viridis forest	-	15.2	7.5	-	66.5	95.0	-	7.4	26.0
3	Chestnut forest	68.6	99.42	100.0	96.7	51.6	95.0	12.9	5.0	16.0
4	Larch forest	59.5	66.8	87.5	66.8	76.5	115.0	39.5	7.0	26.0
5	Spruce forest	88.0	86.4	87.5	86.4	81.2	95.0	26.8	17.2	26.0
6	Grasslands	-	-	1.2	-	87.7	95.0	-	-	-

Table S.3.3. Total OC stock per habitat and total OC stock per habitat on the total area

								RATIO		
Aosta Valley (AV)	**Total INFC (t/ha)**	**Total Field (t/ha)**	**Total TESSA (t/ha)**	**Area (ha)**	**Tot*area INFC**	**Tot*areaField**	**Tot*area TESSA**	**INFC/FIELD**	**TESSA/FIELD**	**TESSA/INFC**
Spruce forest	104	136	228	264.89	27,548.14	36,141.05	60,394.01	0.8:1	1.7:1	2.2:1
Larch Forest	102	99	208	4,243.72	432,859.34	419,152.13	882,693.55	1:1	2.1:1	2:1
Grassland	-	46	95	7,691.74	-	357,363.87	730,715.68	-	2:1	-
Mixed coniferous	-	131	208	973.00	-	127,267.88	202,383.17	-	1.6:1	-
Piedmont (PDM)	**Total INFC (t/ha)**	**Total Field (t/ha)**	**Total TESSA (t/ha)**	**Area (ha)**	**Tot*area INFC**	**Tot*areaField**	**Tot*area TESSA**	**INFC/FIELD**	**TESSA/FIELD**	**TESSA/INFC**
Mixed broadleaves	105	131	211	2,006.07	210,637.04	263,496.90	423,280.14	0.8:1	1.6:1	2:1
Chestnut forest	153	144	211	235.80	36,076.64	34,032.29	49,752.75	1.1:1	1.5:1	1.4:1
Larch Forest	126	113	208	2,648.40	333,698.27	299,057.22	550,866.99	1.1:1	1.8:1	-
Grassland	-	62	95	9,392.02	-	579,315.00	892,242.00	-	1.5:1	-
Adamello (AD)	**Total INFC (t/ha)**	**Total Field (t/ha)**	**Total TESSA (t/ha)**	**Area (ha)**	**Tot*area INFC**	**Tot*areaField**	**Tot*area TESSA**	**INFC/FIELD**	**TESSA/FIELD**	**TESSA/INFC**

Mixed deciduous	129	176	211	961.26	123,665.49	168,892.56	202,935.41	0.7:1	1.2:1	1.6:1
A. Viridis forest	-	89	129	4,748.94	-	422,961.00	611,331.43	-	1.4:1	-
Chestnut forest	178	156	211	1,674.26	298,269.72	261,184.83	353,470.13	1.1:1	1.4:1	1.2:1
Larch forest	166	148	229	5,308.91	879,951.50	785,187.49	1,213,855.27	1.1:1	1.5:1	1.4:1
Spruce forest	201	211	209	9,135.90	1,838,142.42	1,931,328.56	1,905,748.05	1:1	1:1	
Grassland	-	88	96	9,022.00	-	790,858.60	867,465.50	-	1.1:1	-

Table S.3.3.1. T-test results, with statistically significant p-values (p<0.05) highlighted in red. The number of observations was organized based on the available data for each methodology.

VDA

ABOVEGROUND BIOMASS	Average field	Average INFC	Average TESSA	p-value	df
Field vs INFC	64.6	41.7		0.30	4
Field vs TESSA	71.0		90.0	0.27	3
INFC vs TESSA		41.7	91.0	0.01	4
SOIL					
Field vs INFC	38	31		0.53	10
Field vs TESSA	38		98	0.00	10
INFC vs TESSA		31	98	0.00	10
LITTER					
Field vs INFC	7.4	11		0.40	4
Field vs TESSA	7.4		23.5	0.00	6
INFC vs TESSA		11	23.5	0.02	5

PMT

ABOVEGROUND BIOMASS	Average field	Average INFC	Average TESSA	p-value	df
Field vs INFC	78.7	49.0		0.1	4
Field vs TESSA	78.7		95.7	0.1	4
INFC vs TESSA		49.0	76.8	0.2	10
SOIL					
Field vs INFC	38.3	59.2		0.21	10
Field vs TESSA	38.3		98.3	0.00	10
INFC vs TESSA		59.2	98.3	0.01	10
LITTER					
Field vs INFC	8.5	5.5		0.39	7
Field vs TESSA	8.5		18.3	0.08	6
INFC vs TESSA		5.5	18.3	0.03	10

AD

ABOVEGROUND BIOMASS	Average field	Average INFC	Average TESSA	p-value	df
Field vs INFC	98.0	65.0		0.07	6
Field vs TESSA	67.8		63.9	0.89	10
INFC vs TESSA		65.0	93.8	0.03	6
SOIL					
Field vs INFC	66.4	82.0		0.16	6
Field vs TESSA	69.9		63.9	0.77	10
INFC vs TESSA		82.0	100.0	0.07	6
LITTER					
Field vs INFC	8.4	21.4		0.18	4
Field vs TESSA	8.2		22.0	0.00	8
INFC vs TESSA	21.4	21.0		0.96	6

Table S.3.4. Values not included in the regression charts for the evaluation of the minimum number of plots

AV	Mixed coniferous	PDM	Chestnut forest	AD	Green alder	Chestnut forest
3	15.60	3	6.92	3	22.10	13.63
5	10.76	5		5	13.59	
10	4.51	10		10	5.91	
15	5.60	15		15		

CHAPTER 4

DETECTION OF FOREST-NON-FOREST CHANGES AT THE ADAMELLO REGIONAL PARK USING LANDSAT SCENES

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In preparation

Abstract

Remote sensing imagery is an effective method to assess the impact of climate change and human activities on vulnerable areas, such as Alpine protected areas (PAs). The tracking of land cover transformations in these areas is critical to support managers and decision makers in the protection of these and to assess whether current management strategies against deforestation are efficient. The objective of the study was to identify land cover changes between forested and non-forested areas (FNF) in the Adamello Regional Park, an Alpine protected area located in the Italian Alps. The collection of LANDSAT scenes was carried out on a decade-by-decade basis from 1988 to 2022. To classify the forest and non-forest areas for each scene, a supervised classification using Random Forest algorithm was performed using Google Earth Engine. Extensive validation checks were performed to ensure the accuracy of the classification. The FNF changes were then mapped using the IDRISI TerrSet software for both the entire period and each decade. The results showed a 2914-hectare net increase in forested areas at the Adamello from 1988 to 2022. The forested land remained consistent at 21833 hectares, whereas non-forested land covered 21753 hectares, comprised urban areas, grasslands, agricultural lands, waterbodies and glaciers. The decade from 2000 to 2010 witnessed the most significant net increase in forested areas. Between 2010 and 2022, a significant loss of forests occurred in the North of Italy, probably caused by the Vaia storm and biotic disturbances. Our investigation using ArcGIS led to the determination of the forested areas' loss and gain in each municipality. We found that some municipalities increased their forested areas by 10% of the total land area between 1988 and 2022. We gathered data on distance from roads, vegetation attitudes, forest usage classification, elevation and slope, and compared this information with the FNF changes. It emerged that significant relationships are present with the FNF change and the vegetation attitudes, and the slope. This study was a first step in determining how the forest changes among the decades, in which areas and what possible reasons are, giving the magnitude of change for each municipality. Maps can help managers identify areas that need urgent conservation action. Further studies using resolution satellites data and validation points in situ should be carried out to verify which are the tree species that are extending their coverage.

1. Introduction

The Alpine forests are key for the supply of many ecosystem services (raw materials, water regulation, CO2 sequestration, natural hazard reduction and recreational values) (Grêt-Regamey et al., 2008; Häyhä et al., 2015), and represent 35% of the area of the alpine countries (Dellagiacoma et al., 2015). Climate change pose a significant threat to these areas, particularly due to the accelerated warming compared to lowlands (IPCC, 2022), and human activities worsen this ongoing phenomenon adding further pressures to this fragile environments (Vigl et al., 2021). Due to their relevance as Ecosystem Services (ES) supply and biodiversity conservation, it is fundamental to investigate how forests spatial extent is changing over the time, and to provide a description of the potential drives of change. A loss in forested areas can be due to several reasons and affects the provision of fundamental ES. Hence, determining the main drivers can help in an efficient management. Considering the potential drivers of a forest loss human pressures (e.g., timber over-harvesting) and natural disturbances are the most observed. Timber harvesting has been of great importance to humans, providing essential resources for shelter, fuel, and various industries throughout history, having a significant cultural and economic significance. However, it is fundamental that timber harvesting must be carried out in order to ensure an ecological integrity of the area (Dorren et al., 2004). Biotic and abiotic disturbances such as wind, insect outbreaks, pathogens and wildfires are the most common disturbances to forested areas and are a major cause of forest cover loss. These are predicted to increase in terms of magnitude and frequency due to the climate change (Bentz et al., 2019; Jakoby et al., 2019; Seidl et al., 2017). One example could be the threat caused by the spruce bark beetle (e.g. *Ips typographus*), that causes the death of Norway spruce (*Picea abies)*, or reduces its resistance to natural hazards (Nardi et al., 2022). However, many studies demonstrated that there is an existing trend in mountain areas toward an increase in forest coverage (Sitzia et al., 2010). Nonetheless, it is important to note that an increase of forested areas in mountain alpine areas may not be completely a positive result. For instance, we could observe an increase of forested habitats related to the land abandonment of alpine croplands (Natale et al., 2007; Tattoni et al., 2017), or to the shift upwards of vegetation belts casing a change in LUCL classes. This will negatively affect the supply of important ecosystem services provided by grasslands (Schirpke et al., 2017), as well as the huge biodiversity that inhabits these habitats (Wilson et al., 2012). Moreover, biodiversity is significantly influenced by changes in forest cover dynamics, serving as a fundamental factor essential for the delivery of numerous ecosystem services. Recognizing that the initial condition of an area is paramount when assessing alterations in ecosystem services provision, we considered that a decline in forested coverage within the study region would result in a corresponding loss of ecosystem services, as highlighted by Schwaiger *et al*. (2019). For example, the promotion of carbon sequestration, crucial for climate change mitigation, can be facilitated through afforestation and proper forest management practices, and highly reduced through deforestation. Furthermore, the reduction of forested areas would impact cultural values, including health and recreational aspects, as well as water related ES, as indicated by Ellison *et al*. (2012). Mountains provide a diverse array of ecosystem services (ES) to both mountain and lowland communities (Pătru-Stupariu *et al.,* 2020). These services range from essential resources like wood and food, crucial for sustaining mountain livelihoods, to services such as water regulation (Gratzer & Keeton, 2017) and climate regulation, facilitated by carbon storage in mountain forests. Any alteration in land use, particularly deforestation, poses a threat to the ecosystems' ability to provide these essential services, rendering mountain communities highly susceptible to the impacts of deforestation. This vulnerability is related to potential disruptions in key services like food, timber, and water provision. The relationship between changes in land use and the supply of ecosystem services is intricate, as modifications to any component of the ecosystem can significantly impact the overall provision of ES (Mori *et al.,* 2013). Hence, a lot of caution must be given to the study of forest cover dynamics, to understand the current land use changes (Winkler et al., 2021), detect how these habitats are changing, and the consequent provision of ES.

Remote sensing imagery is a powerful tool for comprehending the impact of climate change and human interventions on vulnerable regions (Gao et al., 2020; Seidl et al., 2017), allowing repeated measurement over a large area and time span, providing a synoptic view including much information on the study area, and with a high degree of homogeneity, as images are acquired under fixed conditions (Lechner et al., 2020). Remote sensing was widely used for monitoring forest coverage at different scales, from global (Kennedy et al., 2016; Townshend et al., 2012) to national and local assessment (Huang et al., 2007; Zhang et al., 2005). The use of LANDSAT data is effective for national and local scale due to its resolution (30m) (Houghton & Hackler, 2000;

Lechner et al., 2020), and allows to detect forest information, from forest-non forest cover dynamics to the forested surface loss due to forest burning (Boyd & Danson, 2005). There is no perfect remote-sensing system, but the choice of the system will depend on the aim of the study, and resources available. For the study, we aimed to conduct an analysis of forest changes over decades, and LANDSAT was the system that ensured a large time series (Ye et al., 2021; Zhu, 2017), and provided free access to moderate-resolution imagery.

Monitoring changes in these areas is crucial for assisting policymakers and decision-makers in conserving alpine regions. This study was carried out in an alpine protected area located in the Italian Alps, the Adamello Regional Park. The study in the variation of the forest coverage and structure would be of a great importance to understand the dynamics occurring within the area, and forecast both vegetation cover, from which a prediction of the changes in ES supply in the future can be carried out. The outcome of this study would also aid managers in identifying the areas that are subjected to land cover change, the possible drives of these changes, to acquire information on the wealth of the protected area and the action to be taken to improve the biodiversity conservation. This study aims to describe land cover change between forest (F) and non-forest (NF) and associated potential drivers. The drivers of change are described using secondary literature that includes Parks documentation and regional datasets. The study was carried out to investigate changes in forest cover over the last 34 years (1988-2022) using multi-temporal Earth Observation datasets. A decade-wise analysis was undertaken to give a better description of the possible drivers that led to the forest changes, detecting the specific time-periods where substantial changes occurred.

2. Materials and methods

2.1. Study area and data collection

Our study area the Adamello Regional Park (AD), a protected area instituted in 1983 by the regional law, n. 79 dated 16th September 1983. It is located in the Rhaetian Alps, in the Northwestern part of Italy, and has an area of 51,000 ha. Its elevation spans from lower altitudes, 390 m.a.s.l, to the peak of the Adamello at 3,539 m.a.s.l. According to the Parks' forestry plan (PIF) (Comunità montana dell Valle Camonica, 2018), the forested habitats cover the 23,257 ha. These are divided into five classes of usage – naturalistic, protective, productive, landscape conservation and touristic-recreational. The surface of the productive area is 37% of the total forest coverage, whereas the protective and naturalistic are 6% and 39% respectively.

To track the changes in forest cover dynamics, we used multi-spectral data collected by the LANDSAT-5 TM and Landsat 8-9 OLI sensors (Table 4.1). All images were acquired during the summer season (June-July), to ensure the greening of broadleaves forests, and centred on the ROI (Path: 193, Row: 028). The least clouded images were acquired during the season, the spatial resolution was 30m. We chose LANDSAT scenes due to its historical dataset, which is the longest remotely senses data available at fine-moderate resolution. We used the Landsat Collection 2 Level-1 calibrated top-of-atmosphere (TOA) reflectance. We aimed to keep a decadal time span between each image. One multi-spectral Landsat data was chosen from the USGS platform (https://earthexplorer.usgs.gov/) for each decade preferably at an interval of 10 years, except for 1988 and 2022, due to cloud cover issues. Data for evaluating the environmental variables (slope, elevation) were collected from the Regione Lombardia Geoportal (Table 4.2), and shapefiles concerning the vegetation attitudes and usage of the forest were provided by the Adamello Regional Park and referred to the forestry plan of the Park, (PIF) (Comunità montana dell Valle Camonica, 2018).

Table 4.1. LANDSAT DATA chosen for the study

Date acquired	Sensor	Details of data
1988/07/20	LANDSAT 5 TM	• Bands selected: B1 (blue), B2 (green), B3 (red), B4 (near infrared), B5 (shortwave infrared 1), B7 (shortwave infrared 2)
2000/06/19	LANDSAT 5 TM	• Bands selected: B1 (blue), B2 (green), B3 (red), B4 (near infrared), B5 (shortwave infrared 1), B7 (shortwave infrared 2)
2010/07/17	LANDSAT 5 TM	• Bands selected: B1 (blue), B2 (green), B3 (red), B4 (near infrared), B5 (shortwave infrared 1), B7 (shortwave infrared 2)
2022/07/02	LANDSAT 8-9 OLI	• Bands selected: B2 (blue), B3 (green), B4 (red), B5 (near infrared), B6 (shortwave infrared 1), B7 (shortwave infrared 2)

Table 4.2. data on the study area obtained from the region Lombardia geoportal

Data	Details	Source
Digital Terrain Model	• Raster • WGS84/UTM32	(Geoportale della Regione Lombardia, 2015)
Road Map	• Vector • WGS84/UTM32	(Geoportale della Regione Lombardia, 2023)

2.2. Classification and mapping of changes

The Landsat multi-spectral images for each time step were imported in Google Earth Engine (GEE), which allows simplified computation of a multitude of remote sensed data (Lechner et al., 2020). GEE is a free cloud computing platform provided by Google, which supply remote sensed data from a vast archive of datasets and has computing tools that simplify the analyses of these geospatial data. GEE is widely used for the analyses of forest coverage and dynamics, as it offers computations speed and simplicity, for processing a multitude of data (Jahromi et al., 2021; Moore & Hansen, 2011).

These images were visualised in both true and standard false colour composites for visual interpretation and for ease of screening of the vegetated areas and select the training data. We extracted a table containing all training points for each image, and a few random samples for each class were selected. The spectral values and signature of the random points was checked by the operator to ensure that these training sites are spectrally separable to be used for classification. At the first level, land cover classification was carried out considering 11 classes as the spectral signature of various nonforest class are different. The training sites were revisited and revised in order to improve the accuracy. In the second level, the land cover raster was reclassified into forest and non-forest by grouping all the non-forest classes into one class. To gather the training set for first level classification, we collected at least 50 samples for each class. These samples were chosen within a buffer area of 5 km from the Adamello Regional Park, in order to better detect classes which could have been misclassified due to their small extent within the PA. Training points were acquired in representative areas for each class (e.g., industrial areas, extensive crops, forests), to ensure a labelled dataset that included all the 11 classes chosen. The dataset contained 11 classes as follows: (1) Urban, (2) Cropland, (3) Dense forest, (4) Sparse forest, (5) Water, (6) Snow, (7) Grassland, (8) Rock, (9) Cloud, (10) Barren, (11) Shadow. The 80% of the randomly sampled training data was used for training the model, whereas 20% of the data was used for testing. The training set was used to develop the model for classification, while the testing set was fundamental for assessing the model's accuracy.

A widely used machine learning approach for supervised classification called Random Forest was carried out in GEE for each year. The Random Forest algorithm is a machine learning algorithm, used for classification and regression analyses. Through a set number of decision trees, it builds a forest of decision trees, in which variables are combined in order to obtain robust and precise predictions. The random forest classifier is widely used for land use classification (Gislason et al., 2006; Hayes et al., 2014; Rodriguez-Galiano et al., 2012), due to its computation capacities, in term of promptness and robustness, and possibility to the handle efficiently large databases (Hastie et al., 2009; Rodriguez-Galiano et al., 2012). We considered as variables for our training set bands from blue to the shortwave infrared 2 in LANDSAT 8-9 OLI (B2, B3, B4, B5, B6, B7) and for LANDSAT 5 TM (B1, B2, B3, B4, B5, B7). The Random Forest was set to 100 trees, the other hyperparameters for Random Forest were set as the default options provided in GEE.

The next step after classification is accuracy assessment of the classified output. We used statistics such as overall accuracy, Producers and Consumer Accuracy for accuracy assessment. The first step in accuracy assessment is the creation of the confusion matrix. The confusion matrix is created by a table that evaluates the performance of an algorithm by comparing the predicted and actual values. The confusion matrix was a 11 by 11 matrix, according to the number of classes, whereas the numbers inside the matrix are the frequency of pixels in that class. Rows contained mapped pixels in a particular class, whereas column in reference (actual class). From the proportion of correct predictions over the total prediction, it is possible to estimate the overall accuracy, expressed in percentage, being fundamental for an overall indication on the correctness of the classification. Producer's and consumer's accuracy are commonly used for valuing the accuracy of a classification, producers' indicates the probability of correctly identifying a category withing the dataset, whereas the consumers' is a measure that assess the likelihood on an incorrect assignment to a class during the classification (Ginevan, 1979).After the accuracy assessment at the class level, a reclassification was performed. We merged the non-forested classes, classified as NF (Class 1), forested classes classified as F (Class 2), and Clouds/Shadows (Class 3). The attribution of the new classes was as follows: Urban (1), Cropland (1), Dense forest (2), Sparse forest (2), Water (1), Snow (1), Grassland (1), Rocks (1), Clouds (3), Barren (1), Shadow (3).

The rasters with the forest nonforest (FNF) classification were exported in TIFF format and processed in ArcGIS. To assess the accuracy of the reclassification, 60 random points were generated within the ROI. The land cover type for all the 60 sample points for each year were verified using high resolution historical images in Google Earth Pro. Therefore, the ROI was clipped from the LANDSAT scene, and the final land cover maps were generated. A total of four maps were generated, one per each decade (tiff), thus these were imported in Terrset Idrisi, a software commonly used for land change detection and prediction (Eastman, 2016). These were processed using the land change modelling tool, obtaining four maps describing FNF changes as follows: a) 1988 to 2000, b) 2000 to 2010, c) 2010 to 2022, d) 1988 to 2022. IDRISI Terrset was used to quantify the changes in forest and non-forest categories. Maps visualisation was set in order to show only direct changes between forest and nonforest categories, excluding from the visualisation the cloud exchanges, however these were included in the calculations of changes.

To provide an initial overview of changes, we gathered information on the environmental features and management of the study area. A total of 5000 random points were generated throughout the ROI, mostly fell within the persistence class, however 310 fell under the NF- F category, 87 under the F-NF category and the remaining under the "no change" category. Data on elevation, slope, and roads were obtained by using raster and vectors available on the Regione Lombardia Geoportal (https://www.geoportale.regione.lombardia.it/). The parks' boundaries were used to clip the roadmap in ArcGIS, and multiple buffers were created from the road network with increasing distances of 10m, 50m, 100m, 500m, 1000m, and more than 2000m to identify possible correlations between forest cover dynamics and the road network. To collect data on the vegetation cover and classification of forest, we extracted data on management from the forestry plan of the Park. Statistical analysis was conducted using StatSoft Statistica and IBM SPSS Statistics software. Analyses of variance (ANOVA) was conducted to establish significant differences between categories, while a Chi-Square test was performed for categorical variables including buffer distance from roads and classification.

3. Results

3.1. Land cover classification

The classification carried out using the Random Forest algorithm produced four maps with 11 classes. The 1988 map had an overall accuracy of 95% for the 11 classes of the first classification; the 2000 map had an overall accuracy of 95%, the 2010 map had an overall accuracy of 93%; finally, the 2022 map had an overall accuracy of 96%. As the classification accuracy exceeded our threshold of 90%, and we accepted the efficiency of the classification. Therefore, we conducted a further reclassification merging the classes to obtain forest, non-forest and cloud, since the focus was to investigate deforestation and afforestation. The result indicates a substantial increase in forest cover over time (Fig.4.1). The producer’s accuracy (Table S4.1) values are presented as percentages, which indicate the proportion of correctly identified samples in the dataset, whereas consumers’ accuracy indicated the percentage correctly attributed during classification. It emerged that dense Forest (Class 3) and sparse forest (Class 4) had a producers’ accuracy slightly lower than other categories, particularly for the year 2000, as 86% of dense forest and 81% of sparse forest were correctly classified in the reference dataset, indicate by the producers’ accuracy. However, for the 2000 the consumer accuracy showed that the 86% for dense forest and 91% for sparse forest in the classification were actually belonging to the correct classification. Dense and Sparse forest had probably due to the similarity of the forested categories, and exchanges occurred between the two.

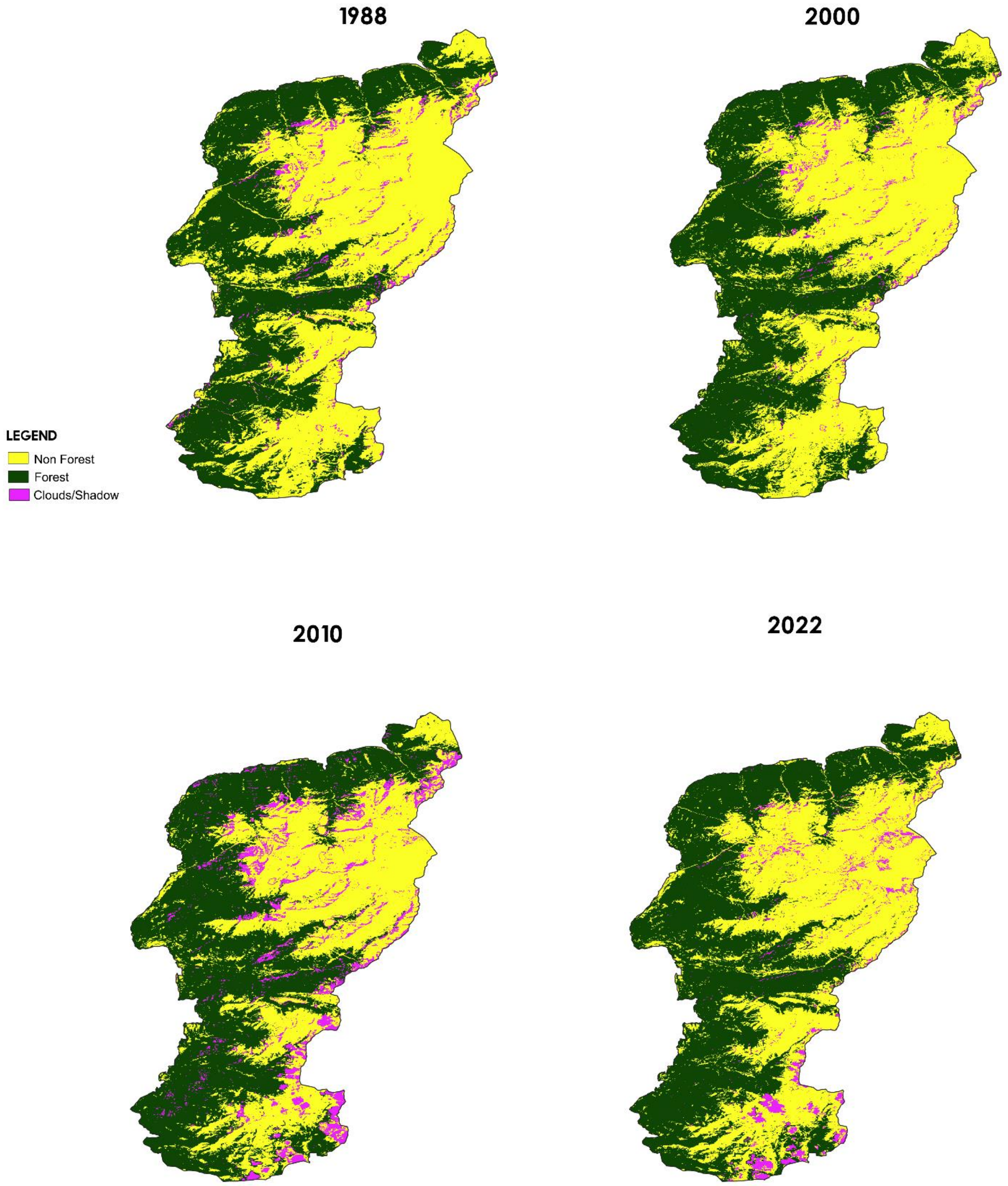

Figure. 4.1. Forest and non forest maps for the four decades

3.2.Change detection: 1988-2022

The persistence of forest and non-forested area was mapped from 1988 to 2022 (Fig. 4.2), indicating the areas that have not changed over the years. The detection of overall change was essential to investigate the total variation within the AD boundaries, while the decadal changes helped to understand in which decade the main events occurred and to provide a possible explanation for the results obtained. We detected 21,753 ha of nonforest and 21,833 ha of forest have not changed over the last 34 years. But there are areas which have experienced changes (Fig.4.2, Fig.S.4.1), revealing fluctuations within categories F and NF, but ultimately an overall increase of forested area over the above period was found. Within the park's boundaries, there was a net increase of the forested area of 2,914 hectares (Fig. S.4.2). Conversely, the non-forested areas decreased of 3,316 hectares. The difference between these values, 401 hectares, was due to cloud and shadow cover at the time of image capture, thus preventing accurate classification below the cloud cover. We carried out analyses to identify possible relationships with the environmental features. The ANOVA showed that there was no statistically significant difference between F-NF and NF-F with respect to elevation (Fig. 4.3), whereas statistically significant differences were found concerning slope ($p<0.05$), showing that F-NF had generally higher slopes than NF-F.

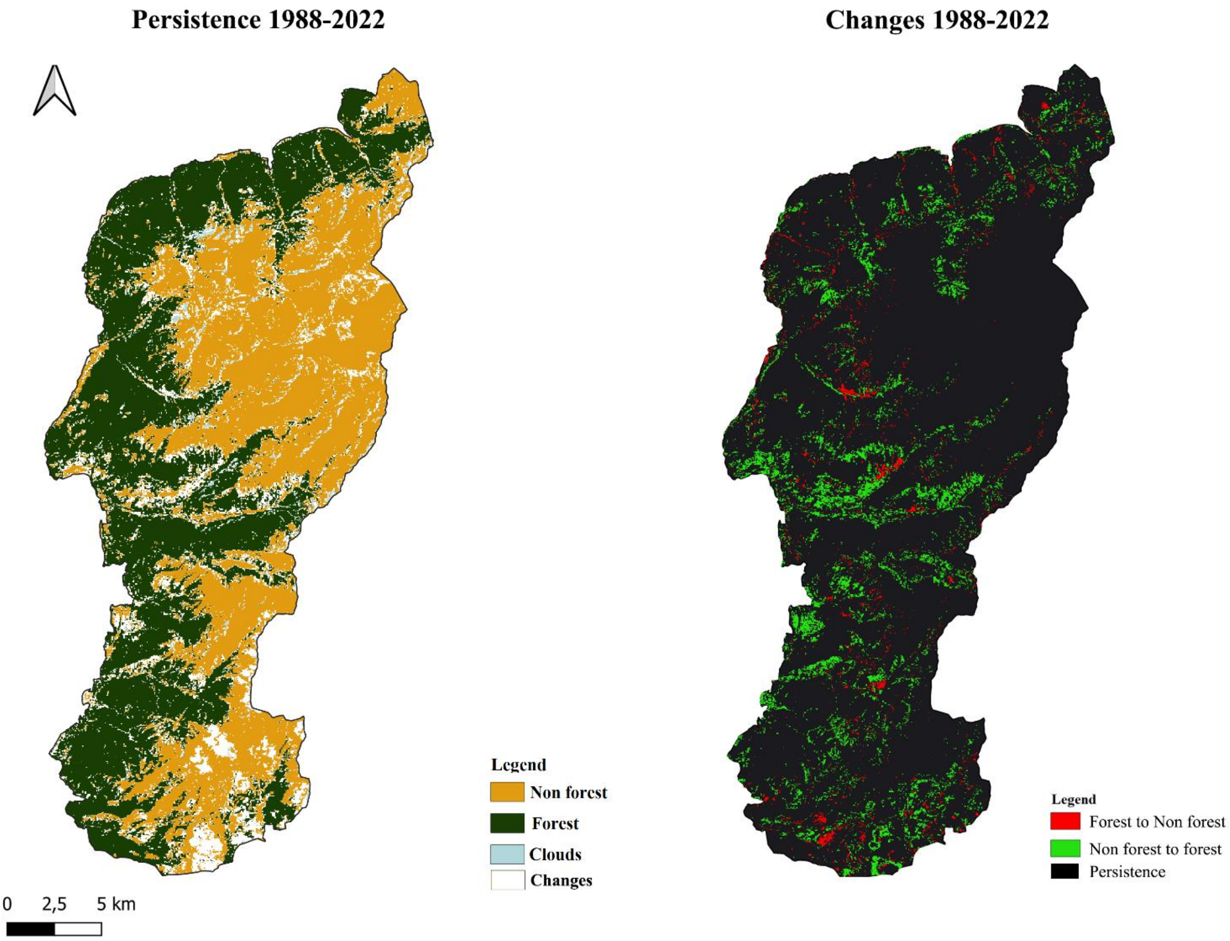

Figure 4.2. persistence and changes between forest and non forest areas from 1988 to 2022

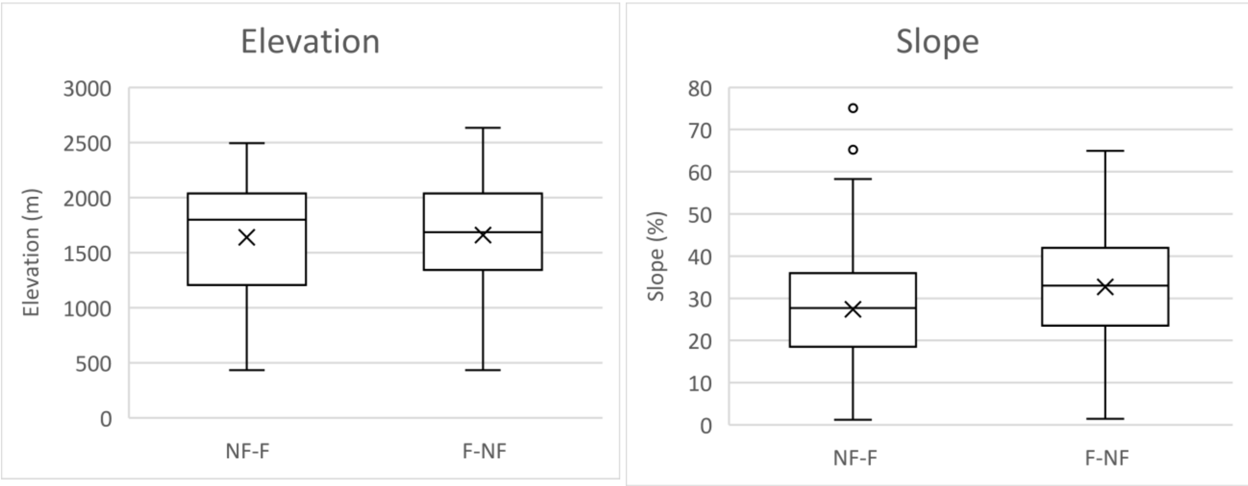

Figure 4.3. Changes classes across (a) elevation (b) slope in areas that were converted into forests (nf- f) and non forest (f-nf)

The vegetation attitudes were extracted from the Parks' map of the forestry plan (Comunità montana dell Valle Camonica, 2018), created in 2017. Our random samples were joined with the attributes of the habitat map, to identify the vegetation attitudes cover belonging to the FNF changes. Part of the random points belonging to FNF changes did not match the map of vegetation attitudes. We address this issue to the fact that the maps only referred to forested maps until 2018, however during fieldwork activities for a previous project at the AD we detected some mismatches from vegetation attributes map and the current vegetation cover. Further investigation must be carried out to determine the exact reasons, one possibility could be that the regrowth was not detected in 2018, probably related to fast-growing species, such as *Alnus viridis.* Thus, 43% of samples related to forested areas (NF-F) and 39% of deforested areas (F-NF) have not been classified, both for habitat type and classification of forest usage class, which specifically referred to the forestry plan. However, in the remaining sample points we analysed the vegetation attitudes coverage (Table 4.3), and we noted that the green alder shrubland is the forested habitat the included most of the points related to new forests (17.4%), followed by larch (12%) and spruce forest (11%). The highest reduction in forested habitat towards non forested was found in spruce forest (25.3%) and larch forest (13.8%). We performed a Chi-Square test (Table S.4.2) and it resulted in a statistically significant association ($p<0.005$) between FNF category and vegetation type. Concerning the classification of the forest provided by the Park, we encountered that most of the NF-F points were related to naturalistic attitudes (27%) and landscape conservation (12%), whereas in F-NF we encountered naturalistic attitudes (24%) and productive (14%), nonetheless no significant association was found with the Chi-square test. Also, for the five classes of distance from roads, no statistically significant association was found.

Table 4.3. vegetation attitudes and percentage of points of areas converted into forest (nf-f) and non forest (f-nf) and the related vegetation cover

HABITAT	NF-F%	F-NF%
NO CLASS	43.9%	39.1%
BEECHWOOD	0.3%	0.0%
FRAXINUS AND ACER FOREST	3.5%	1.1%
GREEN ALDER SHRUBLAND	17.4%	10.3%
BIRCH FOREST	0.6%	0.0%
CHESTNUT FOREST	3.5%	4.6%
CORYLUS AVELLANA FOREST	1.9%	0.0%
LARCH FOREST	12.9%	13.8%
PINUS MUGO SHRUBS	1.6%	3.4%
NEOFORMATIONS	0.3%	0.0%
HORNBEAM FOREST	1.9%	0.0%
SPRUCE FOREST	11.3%	25.3%
PINE FOREST	0.3%	0.0%
OAK FOREST	0.0%	1.1%
SALIX FOREST	0.3%	1.1%

3.3. Decadal change: 1988 - 2000

During the first decade after the establishment of the Park, a relatively balanced scenario emerged where both gains and losses for forest and non-forest habitats were detected (Fig. 4.4, Fig.S.4.3). However, the trend was mainly towards afforestation, resulting in a net increase of 1,391 hectares of new forests (Fig.S.4.4), whereas the loss of non-forested habitats was approximately 866 hectares. The increase in forested areas resulted to be mostly spread in the central part of the Park, whereas local losses were localised in the northern part, approximately close to the municipalities of Ponte di Legno, Temù, Vione and Vezza d'Oglio, and southern part, in the area of Bienno, Breno and Niardo.

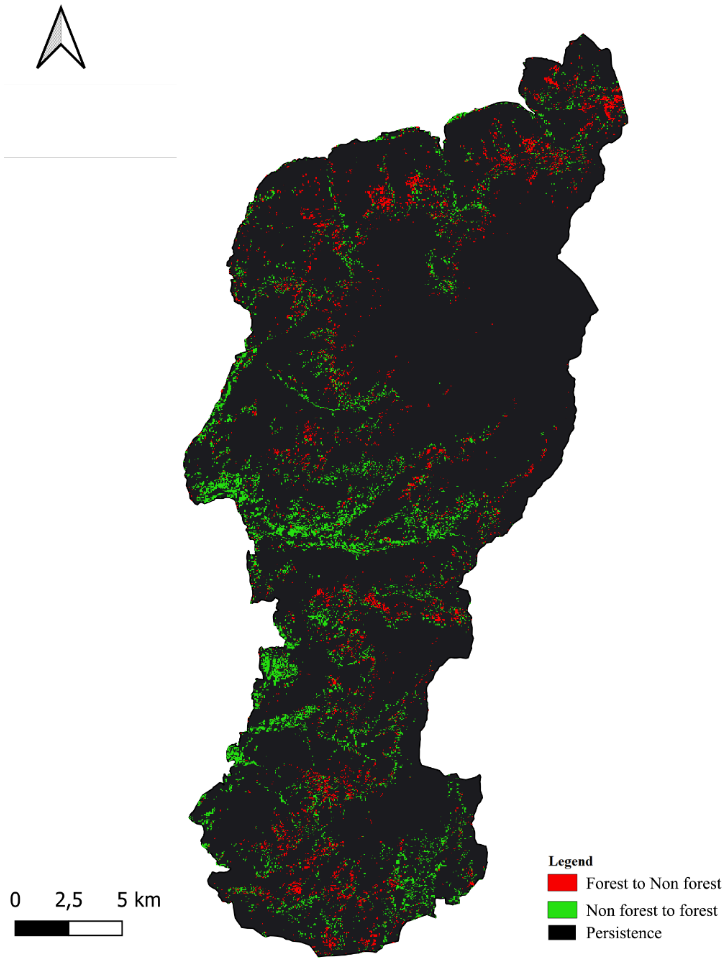

Figure 4.4. Map of the gain (green) and losses (red) of forested areas from 1988 to 2000

3.4. Decadal change: 2000 - 2010

Despite 2010 being the least cloudy year of the decade, clouds covered an area of 3,191 hectares and it was not possible to classify these points for the 2010. As found in the first decade, we detected a net increase of 1,553 hectares in forest coverage during 2000-2010, and a decrease of 4,744 hectares in non-forested areas (Fig. S.4.5, Fig. S.4.6). It was observed that the increase in forested areas was widespread across the park (Fig. 4.5). The afforestation was found to be quite evenly distributed across the park's area.

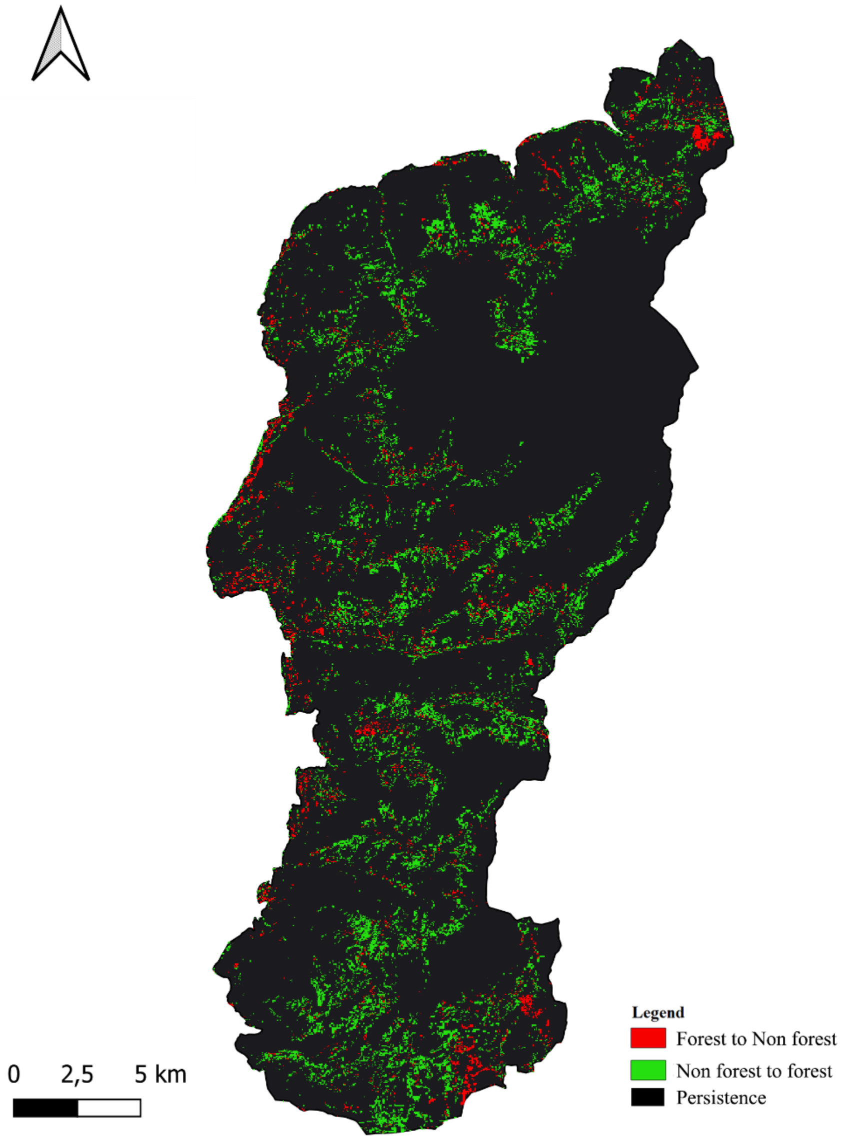

Figure 4.5. Map of the gain (green) and losses (red) of forested areas from 2000 to 2010

3.5.Decadal change: 2010 - 2022

During the third decade of our study, a net loss of forested habitat occurred. Although the net loss was only of -30 hectares of forested areas, the gain of non-forested of 2,293 hectares (Fig.S.4.7, Fig. S.4.8), partly related to the cloud coverage of the previous scene. However, it was interesting to note that despite the afforestation was still ongoing, there was a major loss of forested habitats. We assume that this could be due to the extreme event happened during 2018, the Vaia Storm (Tecnici, 2019; Udali et al., 2021; Vacchiano & Forestale, 2018). We geolocated the changes (Fig.4.6) and we could highlight the changes were quite evenly distributed among the area, having some hotspots of deforestation.

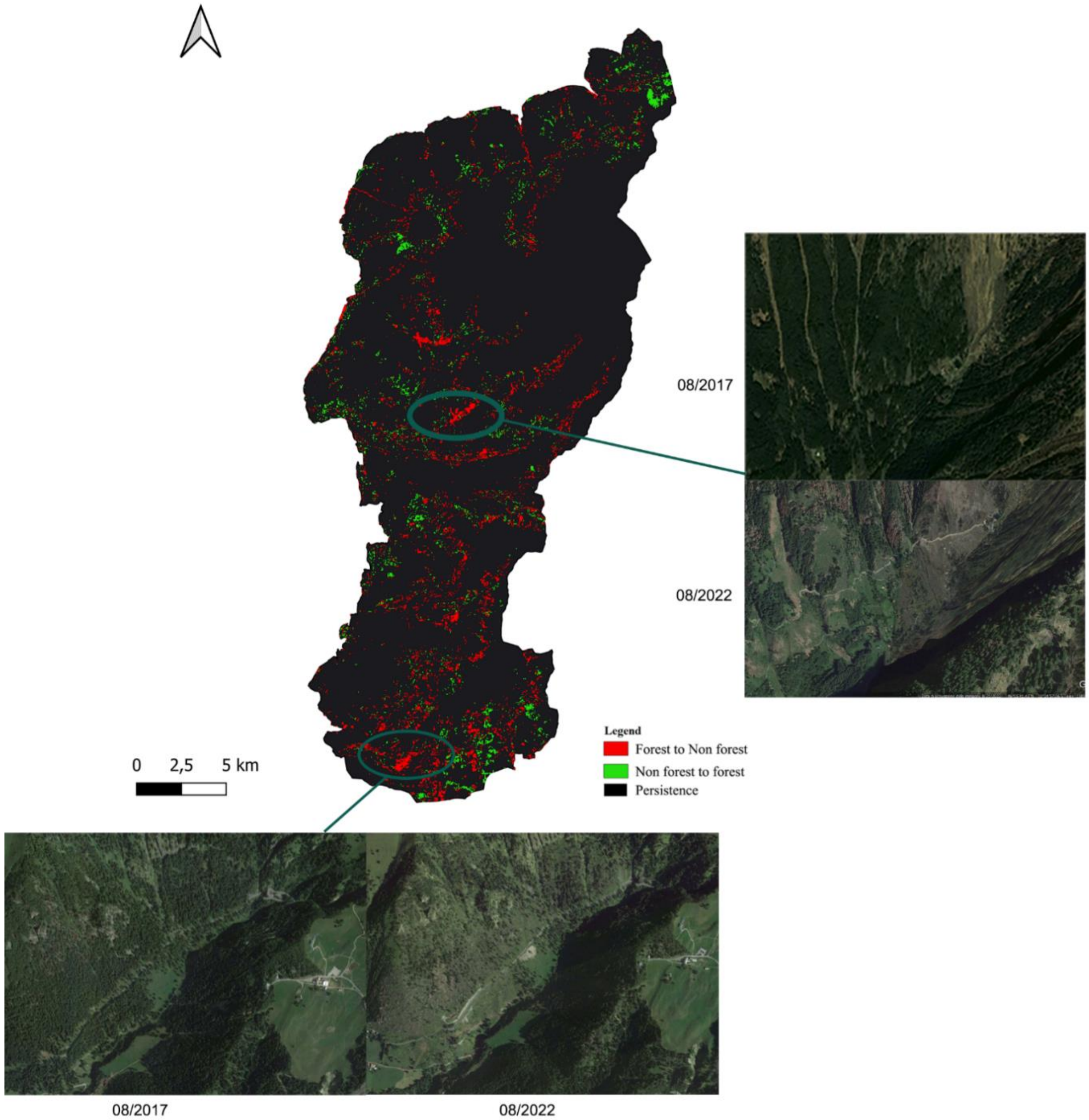

Figure 4.6. Map of the gain (green) and losses (red) of forested areas from 2010 to 2022

3.6. Extent of the change among municipalities

Our goal was to detect how the change in land use affected two classes: forest and non-forest. The analyses revealed a net increase of 3,523 ha of forest due to changes from non-forest habitats to forested areas and a loss of 910 ha of forest that were converted into non-forest

(Table S.4.3). To aid managers to understand the magnitude of changes and give precise information, we described the changes within the decades for each municipality belonging to the park, indicating the changes in term of overall extent (ha) and percentage of change on the total area of the municipality (Table S4, Table S5). However, we did encounter a limitation due to the raster-based analyses, as certain polygons (30x30m) extended beyond the designated boundaries due to size of the cell. We therefore classified these pixels as boundaries. We had 7 ha of forest to non-forest and 20 ha of non-forest to forest associated with this classification. The net change towards forest was detected in all the municipalities belonging to the Adamello Regional Park (Table 4.4). A net increase of the forested area by the 5% of the total extent of the municipality was detected in 13 municipalities over 19, and Sonico resulted in the lowest relative forest increase. The cumulative increase (in ha) in forest areas showed that Saviore dell'Adamello, Cevo, Breno and Edolo were the municipalities that were accounted for almost the 50% of the overall increase in forest areas. However, considering the cumulative changes toward nonforest we found that Breno, Saviore dell'Adamello e Sonico were the municipalities that had the highest reduction in forested areas, resulting in a loss of more than 100 ha, that mostly occurred in the decade 2010-2022, and likely to be related with the Vaia storm and to the huge extension of the municipalities. For instance, it is acknowledged that Vaia particularly hit the Val Malga, located in Sonico (Piretti, 2023), and in Saviore the loss might be also related to spruce bark beetle outbreaks (Prandelli, 2023).

Table 4.4. Overall change towards new forested areas per municipality (in ha) and relative change on the total extent of each municipality (%)

Municipality	Net change NF-F (ha)	%
Berzo Demo	165.2	12
Bienno	55.2	4
Braone	76.4	6
Breno	256.9	5
Cedegolo	62.1	6
Ceto	189.9	6
Cevo	300.7	8

Cimbergo	191.5	8
Edolo	239.6	4
Incudine	14.4	2
Malonno	10.4	6
Niardo	115.5	6
Paspardo	86.1	9
Ponte di Legno	135.1	3
Saviore dell'Adamello	447.6	5
Sonico	73.4	1
Temù	110.8	5
Vezza d'Oglio	20.4	2
Vione	49.3	5

4. Discussion

This study shows that, in the Adamello Regional Park, there has been a net increase in forest expansion since the establishment of the park. This result confirms the trends found in the literature (Bebi et al., 2017), where alpine areas are experiencing an increase in forest cover. The decadal time span allowed a more precise description of the forest cover dynamics, that showed a net increase of more than 1000 ha per decade until the 2010. Hence, we could assess that the trend was towards an afforestation over the years, that if no disturbance occurred would have continued in a stable manner. We then identified a net loss of 30 ha of forested area over the decade 2010-2022, demonstrating that, despite ongoing afforestation, major deforestation events have occurred, overturning the continuous trend that was the background to all these analyses. We address this latest result mostly to the Vaia storm (Chirici et al., 2019; Tecnici, 2019), that hit the Adamello Regional Park and other regions on October 29th 2018, causing the loss of 8 million cubic meters of standing trees (Motta et al., 2018), with a consequent loss of many fundamental ecosystem services (Pilli et al., 2021). It is demonstrated that in the Vaia storm impacted mostly the Norway spruce, Silver Fir and European beech (Pilli et al., 2021), however, at AD, silver fir and European beech are not very abundant, while Norway spruce forest is the most extensive in the study area. Moreover, during this decade wildfires occurred (Giuseppe Arrighetti, 2022), according to the European Forest Fire Information Systems (EFFIS) (https://effis.jrc.ec.europa.eu/). However, the alpine area has a history of fire-related disturbances (Bebi et al., 2017; Valese et al., 2014), and the magnitude of the change cannot be attributed to wildfires only. In addition, there is evidence of the widespread presence of the spruce bark beetle (*Ips typographus*) in the Alps (Massimo Faccoli, 2009; Faccoli & Stergulc, 2004; Wermelinger, 2004), which is particularly relevant for Norway spruce, the most abundant species within the Park's boundaries. Climate change affects bark beetle outbreaks (Massimo Faccoli, 2009), and on the forest health (Bošel'a et al., 2014), positively reinforcing forest degradation and reducing the ability of tree individuals to defend themselves against pests. These factors are likely to be exacerbated by ongoing climate change, which is particularly affecting the Alpine region (IPCC, 2022) in terms of changes in precipitation regimes, accelerated warming and extreme events. The decade 2010-2022 was a clear indicator of the magnitude of the changes that can occur due to extreme events, and as these are predicted to increase in frequency and intensity, we suggest that park management and monitoring cannot avoid taking these events into account for planning in the near future.

In terms of overall changes, we found that slope and vegetation attitudes were the variables most correlated with the dynamics between forest and non-forest. Further research should be carried out to understand whether there is a causal relationship with slope, which resulted in more deforestation rates were the slope was higher. One possibility could be related to the instability of high slope areas, in which landslides and avalanches may impact the vegetation cover. We sought a correlation with the road, considering it a possible indicator of the relationship between NF and human intervention, being unlikely that timber harvesting occurs in extremely remote areas. Nonetheless, the Chi-square test resulted in non-significant statistical differences, indicating that the values obtained are mostly occurring by chance, and no association was detected. This result remarked the possibility of biotic and abiotic disturbances as the main factors driving the FNF changes at the AD. Concerning the classification of forest usage, we found that the majority of the areas that were converted to forest belonged to the naturalistic and landscape conservation classes, and this suggest a possible efficient fight against deforestation, however no statistical significance was detected, hence further investigations must be undertaken. The major loss in forest occurred in productive classes, and this was expected due to the management and the destination of the area, while the second category was naturalistic. The habitat map used for the correlation between vegetation and FNF was published in 2018, hence it represents the forest attitudes before the Vaia storm, being a reference for understanding the changes that occurred in the latest decade. Since it is quite recent, we assumed that the habitats that corresponded with a FNF were reliable. However, during fieldwork activities for a previous project on ES, some discrepancies between the map and the actual vegetation cover of some habitats were, found based on in situ observations. In particular, the larch forest resulted mostly mixed with *Picea abies* or very sparse, while we found that the green alder shrubland was more extensive on ground than in the map. From the study, it emerged that most of the afforestation was related to areas attributable to green alder shrublands and Norway spruce forests. The result was quite interesting, since it was giving two important information about the trends in forest cover. *Alnus viridis* is an early successional shrub native from the Alps (David, 2010), that colonises the disturbed areas, such as after an avalanche, or slopes at very fast rates. Its habitat range is quite expanded, from medium altitudes to more than 2000 m.a.s.l (Richard, 1990). It was reported previously in the Alps the rapid expansion of this species (Bühlmann et al., 2014; David, 2010), and on the light of the result we can hypothesise that this occurring also at the Adamello, belonging to the 43% of points that fell in no classification according to the PIF. However, this result must be further investigated and monitored, since the green alder expands at a very high speed, but can lead to nitrogen enrichment and suppresses, or decelerates, the succession towards forests (Bühlmann et al., 2014). On the other hand, the increase in the area related to Norway spruce could be a in indicator of the thickening of the already existing forests, and it might be related to the classes attributed to the areas by the PIF (Comunità montana dell Valle Camonica, 2018). The increase of the areas suitable for larch forest should investigated with fieldwork validation and high-resolution classification, since from fieldwork activities for another project on ES at the AD, we detected that most of the forests mapped as larch forests at the AD were mixed coniferous forest, composed both by *Larix decidua* and *Picea abies*. Thus, a validation of all the vegetation cover must be carried out to determine precisely the species that are expanding, and to give insights on the future scenarios at the AD. Due to the unprecedented changes our world is experiencing, it is essential to develop monitoring approaches to detect trends in land cover change to help managers develop informed management strategies. Extreme events are predicted to increase in intensity and frequency (Stott, 2016; Ummenhofer & Meehl, 2017; Zwiers et al., 2013) and, as our study shows, can quickly reverse a trend that has been ongoing for decades. Understanding how these episodic events affect ecosystems and their components is for sure challenging, but crucial for the development of predictive models, beyond the current basis of forest trends and global warming (Ummenhofer & Meehl, 2017).

5. Conclusion and future perspectives

Through analysis of satellite images, we were able to assess the changes in forest and non-forest areas in the Adamello Regional Park over the past four decades. Our findings indicate that there has been an overall increase in forested areas since the park's establishment, and a consequent non-forest areas decrease. Though the decade-wise analysis, we found that forest regrowth was more significant during the second decade (2000-2010) than the first decade, and the major losses occurred in the decade 2010-2022, in which extreme events (Vaia Storm), severe droughts, wildfires and biotic disturbances occurred. Despite these challenges, we found an overall positive trend toward reforestation from 1988 to 2022 within the boundaries of the Adamello Regional Park, however it is fundamental to determine which are the species that extended their coverage, and this could be done using high resolution satellite data and validation through in situ activities. This study was crucial for giving a first description of the changes that occurred from the Parks' institution, identifying a trend that was reasonably similar to the ongoing trend of the Alps, however a forest expansion can also lead to negative effects, such as the reduction of fundamental ecosystem services, caused by the transition of land cover categories.

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Supplementary materials

Table S.4.1. Producers and consumers' accuracy values for each class and per year

Producers' accuracy					
Class	**Class name**	**1988**	**2000**	**2010**	**2022**
1	Urban	0.83	0.92	0.85	0.88
2	Cropland	1.00	1.00	1.00	0.90
3	Dense forest	1.00	0.86	1.00	1.00
4	Sparse forest	1.00	0.81	0.77	1.00
5	Water	0.94	1.00	1.00	1.00
6	Snow	1.00	1.00	1.00	1.00
7	Grasslands	1.00	1.00	0.88	0.82
8	Rocks	1.00	1.00	0.92	0.89
9	Clouds	1.00	1.00	1.00	1.00
10	Barren	1.00	0.95	1.00	1.00
11	Shadow	0.80	0.90	0.92	1.00
Consumers' accuracy					
Class	**Class name**	**1988**	**2000**	**2010**	**2022**
1	Urban	1.00	1.00	0.85	0.88
2	Cropland	1.00	1.00	0.90	1.00
3	Dense forest	0.88	0.86	0.83	1.00
4	Sparse forest	0.71	0.94	0.91	0.86
5	Water	1.00	0.93	1.00	1.00
6	Snow	1.00	1.00	1.00	1.00

7	Grasslands	1.00	0.79	0.94	1.00
8	Rocks	1.00	0.92	1.00	0.89
9	Clouds	1.00	1.00	1.00	1.00
10	Barren	0.91	1.00	0.94	0.92
11	Shadow	0.92	1.00	0.92	1.00

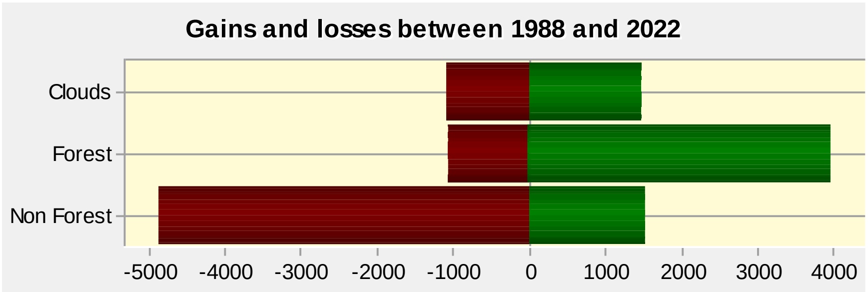

Figure S.4.1. Gain and losses in hectares of forest-non forest and clouds from 1988 to 2022

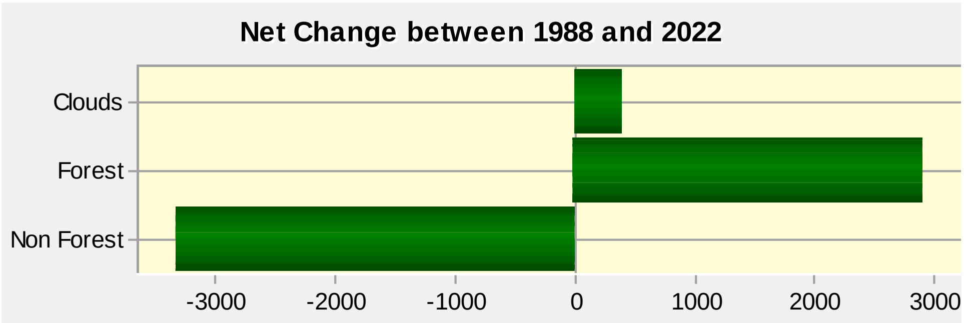

Figure S.4.2. Net gain and losses in hectares of forest-non forest and clouds from 1988 to 2022

Table S.4.2. Values of the Chi square test using fnf classification and vegetation type as variables

Chi-Square test

	Value	df	Asymptotic (bilateral) significance
Pearson Chi squale	27,087[a]	11	0.004

Likelihood ration	27.693	11	0.004
Cases	219		

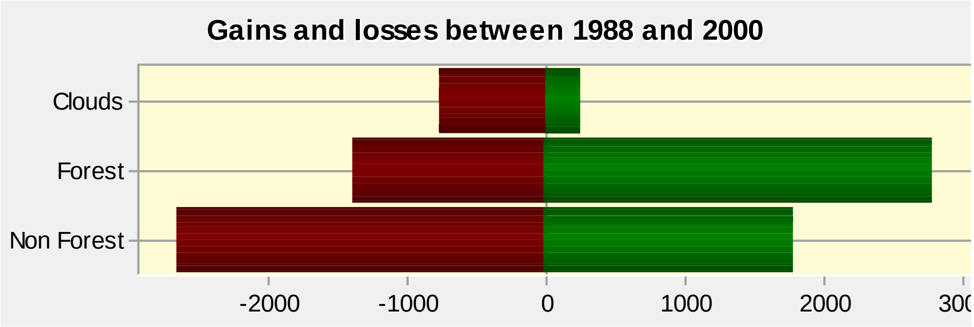

Figure S.4.3. Gain and losses in hectares of forest-non forest and clouds from 1988 to 2000

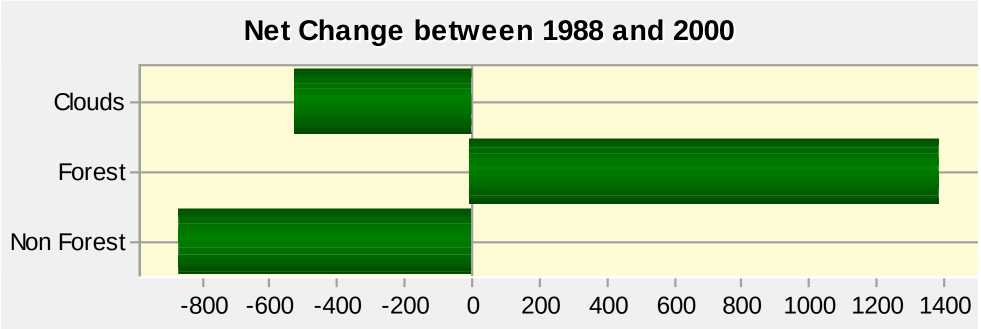

Figure S.4.4.Net gain and losses in hectares of forest-non forest and clouds from 1988 to 2022

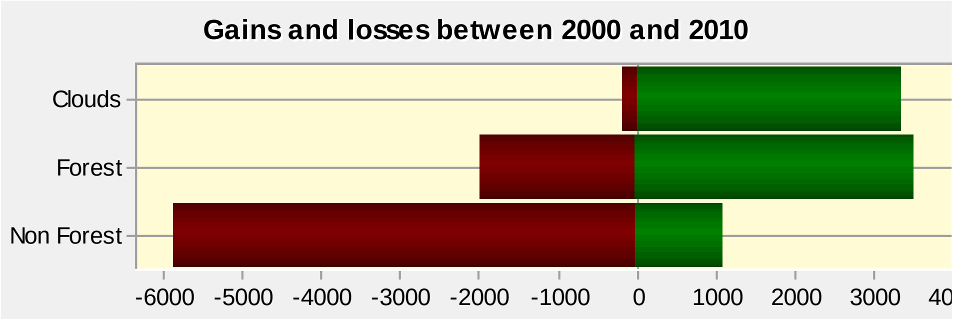

Figure S.4.5. Gain and losses in hectares of forest-non forest and clouds from 2000 to 2010

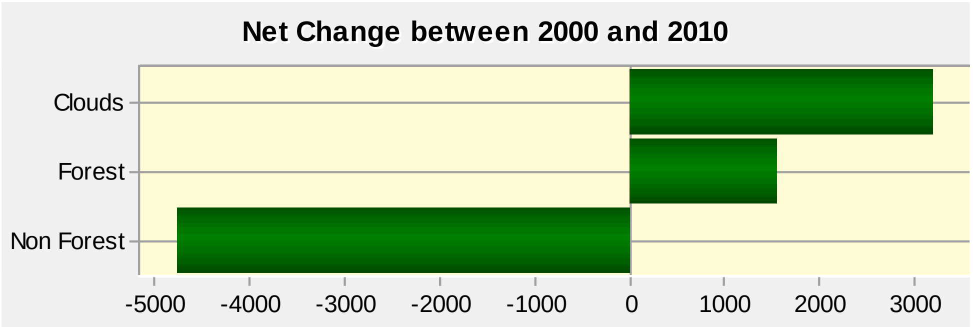

Figure S.4.6. Net Gain and losses in hectares of forest-non forest and clouds from 2000 to 2010

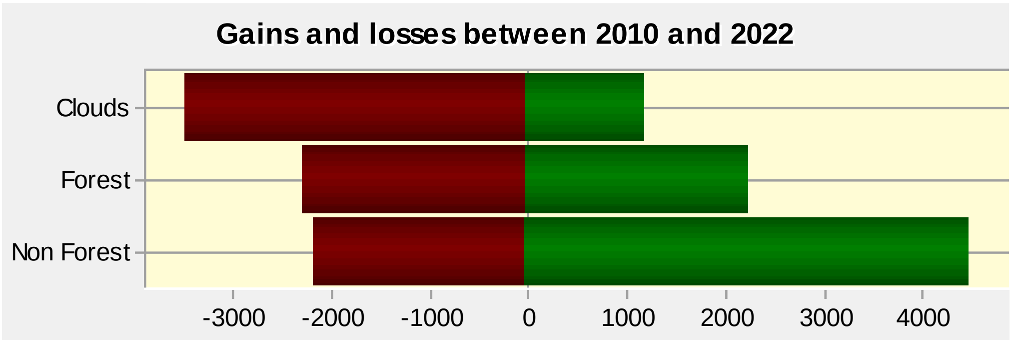

Figure S.4.7. Gain and losses in hectares of forest-non forest and clouds from 2010 to 2022

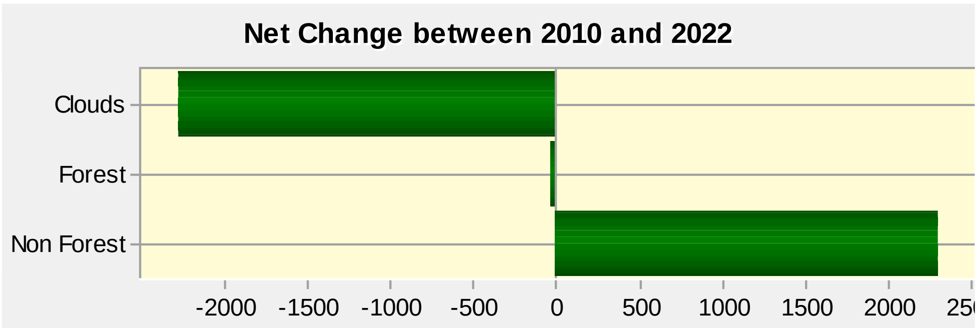

Figure S.4.8. Net gain and losses in hectares of forest-non forest and clouds from 2010 to 2022

Table S.4.3. Overall change from 1988 to 2022

Category	Decrease to	Area	Increase due to	Area	Net change
Forest	Non forest	910	Non forest	3523	2914
	Clouds	155	Clouds	456	
Non forest	Forest	3523	Forest	910	-3315
	Clouds	1329	Clouds	627	

Clouds	Forest	456	Forest	155	401
	Non forest	627	Non forest	1329	

Table S.4.4. Decade-wise change towards NON-FORESTED areas in hectares in each municipality and relative change in percentage on the total extent of the municipality

	Change in Area from Forest to Non Forest								
	Total area municipality (ha)	1988-2000		2000-2010		2010-2022		1988-2022	
Municipality		Change (ha)	%	Change (ha)	%	Change (ha)	%	Change (ha)	%
Berzo Demo	1366	14	1	53	4	26	2	12	1
Bienno	1287	74	6	27	2	130	10	73	6
Braone	1208	51	4	16	1	61	5	14	1
Breno	5155	108	2	160	3	345	7	124	2
Cedegolo	1063	22	2	25	2	28	3	13	1
Ceto	2934	53	2	40	1	195	7	58	2
Cevo	3546	101	3	66	2	166	5	57	2
Cimbergo	2415	81	3	57	2	119	5	42	2
Edolo	5485	109	2	49	1	130	2	63	1
Incudine	923	28	3	8	1	25	3	20	2
Malonno	184	3	2	24	13	13	7	8	4
Niardo	2012	75	4	27	1	93	5	18	1
Paspardo	925	27	3	25	3	27	3	13	1
Ponte di Legno	4363	217	5	114	3	122	3	85	2
Saviore dell'Adamello	8391	108	1	100	1	330	4	105	1
Sonico	5542	104	2	93	2	206	4	127	2
Temù	2054	78	4	44	2	67	3	39	2
Vezza d'Oglio	1083	41	4	6	1	23	2	14	1
Vione	986	66	7	19	2	25	3	15	2

Table S5. Decade-wise change towards forested areas in hectares in each municipality and relative change in percentage on the total extent of the municipality

Change in Area from Non Forest to Forest										
	Total area municipality (ha)	1988-2000		2000-2010		2010-2022		1988-2022		
Municipality		Change (ha)	%	Change (ha)	%	Change (ha)	%	Change (ha)	%	
Berzo Demo	1366.1	164	12	53	4	49	4	177	13	
Bienno	1286.6	59	5	27	2	46	4	128	10	
Braone	1207.6	52	4	16	1	25	2	91	8	
Breno	5154.8	289	6	160	3	180	3	381	7	
Cedegolo	1062.9	68	6	25	2	17	2	75	7	
Ceto	2933.9	196	7	40	1	39	1	248	8	
Cevo	3545.8	250	7	66	2	89	3	358	10	
Cimbergo	2415.2	192	8	57	2	58	2	233	10	
Edolo	5485.5	128	2	49	1	99	2	303	6	
Incudine	922.9	23	2	8	1	11	1	34	4	
Malonno	183.8	32	17	24	13	8	4	18	10	
Niardo	2012.3	98	5	27	1	25	1	133	7	
Paspardo	924.5	66	7	25	3	41	4	99	11	
Ponte di Legno	4363.0	104	2	114	3	168	4	220	5	
Saviore dell'Adamello	8391.1	382	5	100	1	94	1	552	7	
Sonico	5541.8	188	3	93	2	66	1	201	4	
Temù	2054.2	86	4	44	2	46	2	150	7	
Vezza d'Oglio	1083.0	23	2	6	1	9	1	34	3	
Vione	985.7	26	3	19	2	29	3	65	7	

CHAPTER 5

ASSESSMENT OF CULTURAL ECOSYSTEM SERVICES

SUBCHAPTER 5.1

How Do People Experience the Alps? Attitudes and Perceptions in Two Protected Areas in Italy

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Abstract

Protected areas play an important role due to their twofold capacity for biodiversity conservation and the provision of many benefits to human well-being. Tourism can be a tool for protecting nature, enhancing people's sensitivity, and a threat to biodiversity management. This study investigates users' attitudes and perceptions and managers' concerns related to the frequentation of two protected areas in the Italian Alps: the Gran Paradiso National Park and the Adamello Regional Park. We carried out 32 semi-structured interviews with park managers and municipalities to identify their perception of tourism and possible threats related to the use of the parks. Thus, we administered questionnaires to 3399 users of the PAs to investigate their attitudes and perceptions. We made considerations on whether there were similarities in the attitudes identified by the park managers and results of the questionnaires. Questionnaires confirmed the managers' perception of mass tourism regarding one-day stays and the purpose of the visits, but we could not exhaustively confirm the increase of new visitors. We performed a binary logistic regression to understand the relationship between short-term stays and attitudes of visitors (origin, frequency of visits, stakeholders' category, and biographical data). Eventually, interviews stated an exacerbation of the growth of visitors due to the COVID-19 pandemic; thus, we investigated if the pandemic changed the assiduity of visits, and half of the users claimed a change in their assiduity of visits, but mostly declared a decreased frequentation of the area.

1. Introduction

Mountain environments and Protected Areas (PAs) are highly appreciated as tourist destinations for enjoying nature and carrying out outdoor activities (Scolozzi *et al.*, 2015; Tenerelli *et al.*, 2016). The Alps are the most frequented mountain regions in Europe and represent one of the earliest forms of tourism (Romeo R., Russo L., Parisi F., Notarianni M., 2021), with around 120 million tourists per year. Protected areas have a twofold capacity: they are a tool for biodiversity protection and contribute to human well-being. These areas, in fact, provide many benefits to human well-being including physical health (Lemieux *et al.*, 2012; Keniger *et al.*, 2013), mental health (LaPage, 2005), and social and cultural benefits (Lemieux *et al.*, 2012; Keniger *et al.*, 2013). In this context, tourism plays a key role as an intermediary between protected areas and human well-being. Tourism is a resource for mountain economies (Rewitzer *et al.*, 2017), providing an income to residents; however, it can also represent a threat to mountain ecosystems and their biodiversity (Buckley, 2004). Moreover, tourism is also a resource that can lead to the achievement of many of the 17 Sustainable Development Goals (SDGs), contributing to natural resource conservation, job opportunities, and sustainable production (Romeo R., Russo L., Parisi F., Notarianni M., 2021). Hence, tourism can contribute to conservancy objectives, helping in building resilience to climate change (Buckley, 2011) and spreading environmental awareness through stakeholders. On the other hand, regarding the type of activities related to mountain tourism, as highlighted by the 9th World Congress on Snow and Mountain Tourism (UNWTO, 2016), there is a current tendency of people visiting mountain areas for the purpose of seeking sport and adventure tourism or health tourism. These practices do not threaten the environment intrinsically, but some activities in particular seasons can affect biodiversity conservation (Spenceley, 2008), changing the composition of communities (LUKAČ & HRŠAK, 2005; Kangas *et al.*, 2010) and threatening terrestrial wildlife (Buckley, 2004); such activities include hiking or climbing. Hence, sustainable tourism in mountain areas is a key concept for conservation strategies, aiming to maximize the benefits while reducing the negative impacts on the environment (Cozma *et al.*, 2021). Another topic of high interest in this study is mass tourism, but since there are still some uncertainties in its definition, (Vainikka, 2013) here we define the term *mass tourism* as referring to a huge number of tourists that visits a particular area, generally in short-term stays, and not integrating with local communities (this, in some cases, could also be defined as *speed tourism*, but for clarity reasons we will address this phenomenon using *mass* *tourism* only). During 2020, the outbreak of the COVID-19 pandemic caused a variation of touristic fluxes due to the travel restrictions and lockdowns, whereas during the summer of 2020 and 2021, the period where our studies were carried out, the safety restrictions were eased, except for local lockdowns. The COVID-19 pandemic offered a widespread possibility of reconsidering the importance of nature and outdoor activities. Despite the general reduction of travels worldwide due to the COVID pandemic (World Travel and Tourism Council (WTTC), 2021), that caused a loss of 4.5 trillion $ of GDP, there is a local effect related to the study areas considered that shows a countertendency with the global one.

The main aim of this research was to detect and monitor users' attitudes at the parks and understand if there were similarities in the managers' perception of the fruition of PAs and the declared use of the parks by different categories of users. Regarding attitudes, we mainly focused on the following topics:

(1) Tourists' origin, purpose of the visits, and activities carried out;

(2) Mass tourism, in terms of duration and frequency of the visits, percentage of new visitors, and related activities;

(3) The effects of COVID-19 on the fruition of the areas.

We aimed to integrate these two sources of information to understand if there was a common ground regarding the PAs between two different categories of PAs, such as managers and visitors, and to monitor the attitudes towards touristic activities to comprehend the trends and the dynamics of tourism in the PAs and to support ideas for the monitoring of tourism in the Alpine environment, which matches with biodiversity conservation objectives. We then tried to suggest some ideas in the discussion for an integrative type of planning and decision making, which considers users as a key point in the process.

2. Materials and methods

2.1. Study Areas

The selected two study areas (Figure 5.1.1), the Adamello Regional Park and the Gran Paradiso National Park, both situated in the Italian Alps, belong to a broader study on the evaluation of ecosystem services in alpine-protected areas that we are carrying out. The areas share common features, such as altitude, vegetation cover, and soil types, and are areas with a high naturalistic and conservation value. However, they had a different story and are regulated by two different laws; thus, we can assume that there may be some differences in the management strategies and fruition of the areas.

Figure 5.1..1. *Map of the study areas: on the left is the Gran Paradiso National Park and, on the right, the Adamello Regional Park.*

The Adamello Regional Park was founded in 1983 by the regional law n.79/1983 and is situated in the North of Italy, in the region of Lombardy. The elevation ranges from 390 to 3539 m.a.s.l., representing the peak of its highest mountain, the Adamello. Due to this range and its 51,000 ha of coverage, different types of vegetation cover exist, achieving a great number of patches of vegetation covers and habitats. The park provides a huge number of services from sports activities, such as hiking or climbing, to natural and cultural activities, such as the Museum of petroglyphs. According to the ISTAT data on the touristic density (The composed index includes information on the touristic offer (e.g., number of sleeping accommodations for 1000 inhabitants), on the demand (e.g., number of tourists), and on the economic activities related to tourism (e.g., number of employees in the tourism sector). It is ranked between 0 (no tourism) and 5 (fifth quintile of touristic density). See https://www.istat.it/it/archivio/247191 (accessed on 10/02/2023) for further details), sixteen out of the nineteen municipalities that are included in the protected area have a touristic vocation. Among these municipalities, the majority is defined as mountain municipalities with cultural, historical, artistic, and landscape vocation. Eight municipalities have a high (Breno, Edolo, Vione) or very high (i.e., Ponte di Legno, Temù, Cevo, Saviore dell'Adamello, Vezza d'Oglio) touristic density.

The Gran Paradiso National Park was founded in 1922 and is the oldest National Park in Italy. It is regulated under the Framework Law 394/91 and covers an area of approximately 70,000 ha, encompassing two regions (Piedmont and Aosta Valley). The elevation ranges from 800 m to 4061 m, represented by the peak of the Gran Paradiso Mountain, which is one of the most famous European summits. Many activities are provided and supported by the park, covering many possibilities from sports tourism to natural and cultural tourism. The ISTAT indicator on touristic density shows that the municipalities in the Gran Paradiso National Park are very attractive places for tourists. Ten out of thirteen municipalities are ranked as very high touristic places. They are classified as mountain municipalities with cultural, historical, artistic, and landscape vocation. In comparison, the touristic density in the Gran Paradiso National Park municipalities is higher than the Adamello Regional Park municipalities (mean of 3.8 versus 2.2 in an index that goes from 0, no tourism to 5, fifth quintile of touristic density).

2.2. Interviews and Questionnaires

Our campaign was structured in two different steps to investigate the diverse opinions of different stakeholder categories. First, we carried out semi-structured interviews (Table S.5.1.1) with park workers and the municipalities' representatives. The interviews were 30 min long and encompassed mainly questions about activities offered by the park and municipalities, criticism in the relationship with touristic attitudes, and the effects of COVID-19 on touristic activities. These interviews allowed us to figure out the criticisms related to tourism and protected areas. Additionally, we categorized park users through the compilation of a list of main stakeholder categories after a consultation with each park.

Second, we administrated a questionnaire (Table S.5.1.2) over two months (July to August 2020) to different stakeholder categories (Table S.5.1.3), trying to cover all the park's users. We used a random sampling criterion, and we administered questionnaires in the place of interests of the PAs. In addition, the questionnaire was published online (Canedoli & Rota; Claudia & Noemi) to collect data from park users remotely. The final sample size contains a total of 3399 respondents (1059 for Adamello Park and 2340 for Gran Paradiso Park), representing diverse socio-demographic groups and different park users' categories. We selected the stakeholder categories considering all the possibilities related to protected areas, ranging from tourism to park workers. The structured questionnaire encompassed a list of closed-answer questions that aimed to describe users' attitudes towards the PAs, considering four main topics: (1) type of stakeholder's category, (2) frequency and duration of visits at the PA and activities carried out, (3) perception of natural areas and changes in the frequency of visits after COVID-19, and (4) biographical data.

2.3. Data Elaboration

The semi-structured interviews were registered and saved in written format, to allow data elaboration. Regarding questionnaires, we first elaborated the provenience of stakeholders using the software Tableau (Chabot *et al.*, 2003). We clustered the activities carried out in the park into 16 mixed categories, created from the association of the main activities (relaxing, cultural, nature, sport, gastronomic tourism). Then, we standardized data in Zscore (Abdi, 2007) to allow better comparison between the PAs.

Concerning frequency and duration of visits, we only analyzed data from users which declared to be tourists to avoid bias, since this type of information was required for correlating results with managers' perception on tourists' behaviors at the PAs. The total of tourist respondents for the Adamello Regional Park (AD) was 896, while for the Gran Paradiso National Park (PNGP), it was 2096. Regarding the topic of short-term stays in tourism, we tried to detect if there were relevant differences in the duration based on the type of activity. We first evaluated the duration of the stay, then we clustered the type of stays into two, considering short-term stays (one or two nights) and long-term stays (one week or more) according to the Eurostat description of tourism trip length (Eurostat).

We compared the duration of the stay with the activity carried out to detect which categories were related to short-term stays. To understand if there was a new flux of visitors, we investigated the answers regarding the frequency of visits, with a particular focus on visitors that declared to be on the first visit. Again, we sought to find relationships with the activity categories. We then evaluated if there were changes in the frequency of visits after the COVID-19 pandemic, in order to detect if there were any variations as stated in the semi-structured interviews, and we investigated correlations with the stakeholders' categories.

Thus, we performed Pearson χ^2 Test (Plackett, 1983) using the software StatSoft Statistica (StatSoft, 2001), to investigate the relationship between categorical variables. In this case, we clustered the replies from both PAs in one database and carried out analysis using data from both PAs merged since we aimed for a broader investigation of touristic activities. From the semi-structured interviews, a concern emerged regarding mass tourism, represented mostly by short-term stays. We wanted to explore the impact attitudes of users on the duration of the stays, focusing on short-term stays. We performed a binary logistic regression with the software IBM SPSS Statistics 29 (Verma, 2012) to determine the relationship between the binary categorical outcome of short-term stays (0: long term, 1: short term) and the other categorical variables collected in the questionnaires (frequency, activities, stakeholder's category, and biographical data). The forward stepwise method (Bewick *et al.*, 2005) was used to choose the fitting variables for the model; standardized coefficients (B) and odds rations Exp(B) were calculated. We assessed the fit of the model using the Nagelkerke pseudo R^2 and the percentage of correctness.

3. Results

3.1. Semi-Structured Interviews

Concerning activities carried out, in both the PAs, the respondents highlighted a predominance of nature tourism, outdoor activities both for winter season (skiing and snowshoeing) and summer activities (biking, climbing), and cultural tourism related to petroglyphs at the AD, whereas at the PNGP, cultural tourism was defined more marginal and related to religious events due to the presence of sanctuaries allocated at high elevations. Food tourism was the least considered and mainly related to specific events for both PAs.

Thus, interviewees expressed a concern regarding sport outdoor activities; in fact, even if sport outdoor activities are generally considered sustainable, these can affect fauna during the more fragile seasons (i.e., the breeding season). Due to the perceived huge number of tourists that are approaching mountain environments for the first time, park managers raise the issue of safety during outdoor activities, related to poor knowledge of the environment and inadequate equipment. In both the study areas, we detected that stakeholders perceived an ongoing trend towards an increase of visitors. Here, we found that, generally, municipality representatives consider the growth of tourism more as a relevant source of income. Park managers also pointed out tourism as a possible source of income, but they expressed some concerns regarding the possible effects on biodiversity conservation. At the PNGP, some municipality representatives declared the problem of local infrastructures, deemed inadequate for the growing touristic flux, stating that the larger number of cars circulating across the protected area caused some traffic congestions and led to restrictions and fines. This concern was also expressed by park workers; at the AD for instance, managers stated the need to govern and limit car mobility, promoting the use of bikes and other non-motorized vehicles. However, in both the PAs, managers also expressed a concern regarding the risks of an increase of visitors regarding biodiversity conservation and tourists' behavior. For instance, at the AD, dogs, outdoor activities, and the use of drones were indicated as a possible threat to the fauna of the park (Moscardo *et al.*, 2002; Orams, 2007; Tadesse & Kotler, 2012). At the PNGP, managers also feared the impact of human activities with threats related to naturalistic photography, climbing, and activities with motorized vehicles. In both the PAs, there was a perception that the number of tourists was inversely proportional to the quality of tourism; there was a claim for a higher quality of tourism, in terms of a higher interest in the territory, community, traditions, and the environment, in which the tourist could perceive himself as an inhabitant of the territory. Moreover, some interviewees proposed limiting access to places of biodiversity conservation concerns. At the AD, a park manager highlighted the necessity of park rangers to control tourism activities and, where appropriate, penalize the actions that damage biodiversity. An important difference between the two areas of study is that the PNGP is equipped with a Park Guard, the park rangers, which among its tasks include monitoring and surveillance of the activities carried out within the protected area, while the AD is not equipped with this type of monitoring. Most of the respondents highlighted mass tourism as the biggest issue concerning the PAs, defined generally by the respondents as one-day stays tourism or very short stays, and huge numbers of tourists. Mass tourism was depicted as a high number of cars across the boundaries of the PAs, the consequent disturbance on fauna, and a crowding along the hiking trails. At the PNGP, some interviewees indicated the quality of tourism as declining, mostly because of the one-day stay trips, which, in some cases, led to a more stressful working condition for some touristic and restoration workers due to pretentious and nervous behaviors of visitors. Furthermore, an issue emerged related to the expectancies that tourists can have concerning park services, and the contrast between the more relaxed rhythms of mountain areas and the faster rhythms of cities. The lack of knowledge of the correct behavior to be adopted in the mountains was a trait highlighted by all the interviewees.

However, there was a consensus in the fact that there was a new sensitivity towards natural areas above all, after the COVID-19 pandemic, leading to many people having their first visit to mountain areas; the concern here was to appropriately inform the new visitors of basic background information to properly tackle the mountain, act carefully, and behave appropriately for safety purposes. At the AD, park workers highlighted the responsibility of PAs in helping new visitors in developing the appropriate behavior in mountain environments. Eventually, all the interviewees agreed with the fact that after the COVID-19 pandemic, the number of visitors increased exponentially. At the AD, municipality representatives distinguished winter from summer tourism; in fact, during winter, there were a lot of travel restrictions, thus tourism was completely blocked with huge economic consequences, whereas during the summer season, the travel restrictions were related to foreign countries, allowing only short-distance trips, thus many tourists spent the holidays at the AD. At the PNGP, the municipality representatives stated that the COVID-19 pandemic boosted the already existing positive trend in tourism. For both PAs, the perception of this increase of tourism led to the concern of its duration; in fact, interviewees wondered if the trend was permanent or only a temporary effect of the international travel restrictions, which led tourists to visit PAs as a recovery plan related to COVID.

3.2. Questionnaires

3.2.1. Origin, Purpose of Visits and Activities Carried Out

A total of 3399 questionnaire interviews were collected, 1059 at the Adamello Regional Park and 2340 at the Gran Paradiso National Park. Concerning the Adamello Regional Park (Figure 5.1.2), 78% of the respondents were residents in Lombardy, the region in which the park is situated, whereas the PNGP had significantly lower values ($p < 0.0001$), with tourists coming from outside the regional boundaries of the PAs, mainly from Lombardy (32%) and Piedmont (32%). The international tourists were just an irrelevant part of the sample: 4 at the AD, from France, Portugal, and Germany, and 8 at the PNGP, from Germany, Austria, Vietnam, Belgium, France, and the Netherlands. At the time of the survey, international travel restrictions were implemented in many places, affecting the presence of foreign tourists in Italy.

Concerning socio-demographic information (Table S.5.1.4), in the Adamello Regional Park, the highest number of responses came from the age classes <20, from 21 to 30 and from 41 to 50, with little higher values in the female gender (55% of the responses). In the Gran Paradiso National Park, the highest response values came from the age classes of 41 to 50 and 51 to 60; the female gender (54% of the responses) was slightly higher than males.

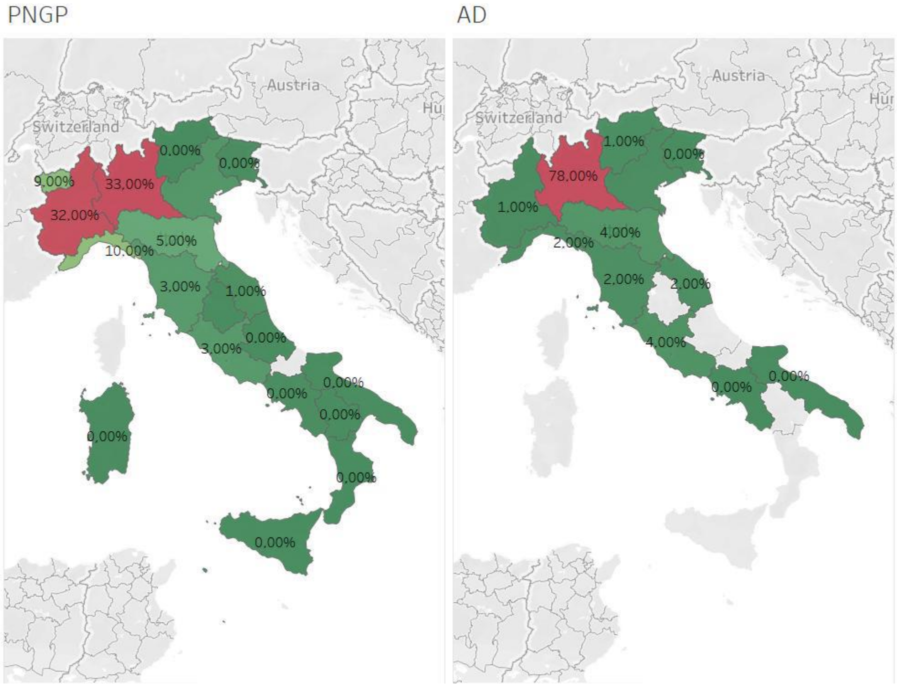

Figure 5.1.2. *Provenience and percentage of the totality of users at the Gran Paradiso National Park (**left**) and Adamello Regional Park (**right**).*

Concerning the Adamello Regional Park (Table 5.1.1), most users (48%) declared carrying out activities encompassed in the “all categories” group. Thus, the remaining 62% is mostly represented by tourists which look for natural and sport tourism (10%), sport tourism (8%), and cultural, naturalistic, and sport tourism (8%). The gastronomic tourism reached 7% of the total, only if aggregated with nature and sport tourism. Considering the single categories, sport tourism was the most considered, confirming the perception of the semi-structured interviews, while gastronomic was the least considered. Concerning the PNGP, as for the AD, most users declared to do all type of activities, but reaching only 25% of the total. Nature and sport tourism accounted for 21% of respondents, whereas the third most considered type was cultural, naturalistic, and sport tourism (16%). Sport tourism itself reached 11%, while nature tourism 5%. The least considered was cultural tourism itself, together with the relaxing tourism, reaching less the 1% of replies.

Table 5.1.1. *Activities carried out by tourists at the PAs.*

What Are Your Recreational Activities in the Park?	**AD (n° of Replies)**	**AD % of the Total**	**PNGP (n°of Replies)**	**PNGP % of the Total**
All categories	428	48%	519	25%
Cultural and gastronomic tourism	3	0%	3	0%
Cultural and nature tourism	30	3%	7	0%
Cultural and sports tourism	21	2%	56	3%
Cultural tourism	7	1%	4	0%
Cultural/gastronomic/naturalistic tourism	31	3%	3	0%
Cultural/gastronomic/sports tourism	16	2%	37	2%
Cultural/naturalistic/sports tourism	75	8%	331	16%
Gastronomic (food and wine tourism)	3	0%	26	1%
Gastronomic and naturalistic tourism	13	1%	2	0%
Gastronomic tourism and sports	21	2%	50	2%
Gastronomic/nature/sports tourism	59	7%	277	13%
Nature and sports tourism	87	10%	443	21%
Nature tourism	19	2%	95	5%
Relaxing	7	1%	4	0%
Sports tourism	76	8%	237	11%

To disentangle the activities and to carry out a comparison between the PAs, we evaluated the number of replies containing each of the activities mentioned; thus, we standardized in Z scores to better compare the PAs (Figure 5.1.3). On the one hand, the AD had more homogeneous values for the categories, with sport and nature tourism as the predominant purpose of visits, and relaxing purposes as the category that was least considered. On the other hand, in the PNGP, sport tourism was predominant, followed by nature tourism, while gastronomic and cultural tourism were less considered compared with the AD. This can be explained by the fact that Adamello Park is a smaller and relatively little-known park, while Gran Paradiso Park is a notorious protected area known to the general public and especially to climbers and mountaineers, who find there very renowned climbing walls and peaks. For instance, the Gran Paradiso Peak is considered a notorious destination for alpinism, since it is the only 4000 m peak entirely within Italian boarders (Giani & Cardellina). Furthermore, these differences emerged during the semi-structured interviews, where at the AD, stakeholders stated the presence of many sources of tourism, encompassing natural, outdoor and sport activities, and cultural, above all related to the presence of petroglyphs. At the PNGP, we observed a higher preference for sport tourism; thus, we can assume that given its high reputation as a destination for outdoor mountain lovers and relevance as the first Italian park, the type of tourism was more targeted towards sport tourism carried out in nature.

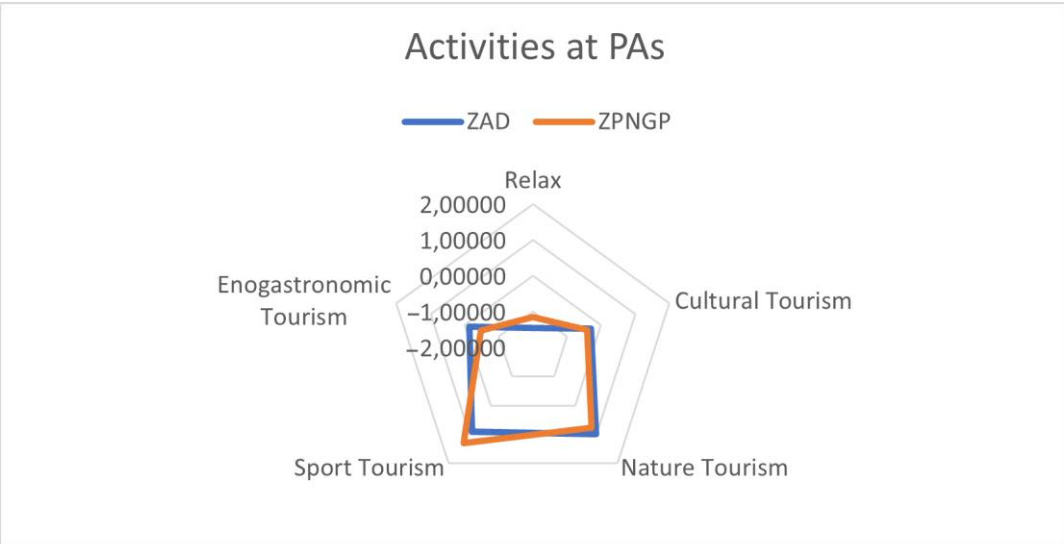

Figure 5.1.3. *Type of activities carried out at the AD (ZAD) and PNGP (ZPNGP) standardized in Z scores.*

3.2.2. Mass Tourism: Duration of the Stay, Frequency Related to the Purpose of Visits

Most interviewees affirmed that the duration of their stays was one day long, with a common trend in both the PAs. This data (Figure 5.1.4) matched with the results of the semi-structured interviews, where municipalities and park managers stated the issue of short-term stays in the

PAs. The Adamello Park had higher values of one-day stays (37%) compared with the Gran Paradiso (34%), but this category had the highest values in both PAs. The Gran Paradiso National Park resulted in higher values for longer stays than the Adamello Regional Park, with 19% of users stating that they stay more than two weeks, compared with 10% at the AD. The least considered type of permanence was the two-week stay, with a value of 10% for both PAs. Here, the results matched with the interviews; in fact, the category of overnight stays was much higher than all the others, reaching values almost twice that of longer stays (e.g., two weeks stays or more).

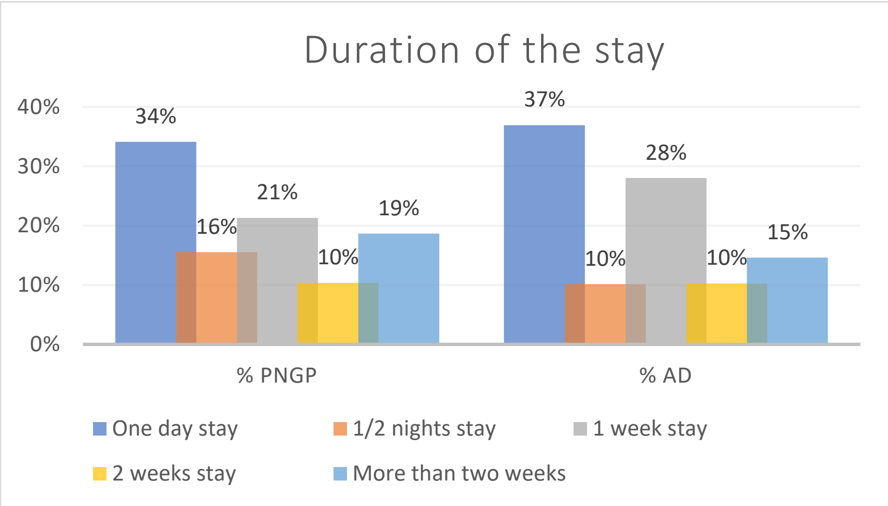

Figure 5.1.4. *Duration of the stays in percentage at the PAs.*

The AD showed a total of 55% respondents on short-term stays, whereas the PNGP had 50%. We can assume that this could be related the different origin of visitors, which were mostly related to a local tourism at the AD, whereas at the PNGP, we detected a tourism with a longer range of distance, suggesting that people spend more time in accommodations at the PAs due to the longer trip (for clarity purposes, we did not consider the mixed category encompassing all the activities, which could be misleading for the detailed description of categories and duration). Among the categories that showed a preference for longer term stays (Table 5.5.2) were those related to cultural/naturalistic/sports tourism (57% AD, 60% PNGP) and relaxation tourism (50% at PNGP, 56% at AD). At the PNGP, the categories of tourists that reached the highest percentages declaring to do short-term stays were gastronomic/nature tourism (67%), gastronomic tourism cultural/naturalistic tourism and cultural/sport tourism, both reaching 60% of respondents, cultural tourism (56%), and nature tourism (55%). At the AD, the categories that showed higher response rates for short-term stays were cultural/gastronomic tourism, cultural tourism, and gastronomic tourism, reaching 100% of responses each; this was followed by gastronomic/sport (77%), gastronomic/nature tourism (71%), and cultural/sport tourism and cultural/nature tourism, reaching 67% of respondents. Even though the percentages were slightly different, we encountered similarities between the PAs in the categories which declared shorter term stays. The sport tourism category only reached similar values in both the study areas, with 56% of respondents at the AD and 55% at the PNGP, suggesting that the perception that emerged from the semi-structured interviews, in which stakeholders declared a relationship between sport activities and short-term stays, could be confirmed mainly if we consider it along with the percentages of mixed categories encompassing sport tourism (e.g., cultural/sport tourism for both PAs). Since we were considering natural protected areas, we also focused on activities related to nature; for both the PAs, we obtained similar values, with a higher percentage of short-term stays with visits for nature purposes only, showing higher values of short-term stays at the PNGP (63%) than the AD (59%). From the Pearson's chi-square test, we detected a significant relationship (p = 0.0000) of long-term stays with the category of cultural/nature tourism. Nature tourism resulted in the category with the highest percentages of short duration of visits for PAs merged, showing a tendency of overnight stays only, whereas the category cultural/nature/sport tourism showed the opposite tendency.

Table 5.1.2. *Duration of the stay related to the type of activity carried out at the PAs.*

	Short term stay				**Long term stay**			
	Gran Paradiso		**Adamello**		**Gran Paradiso**		**Adamello**	
	number of replies	**% of the category**	**number of replies**	**% of the category**	**number of replies**	**% of the category**	**number of replies**	**% of the category**
Cultural and gastronomic tourism	2	50	3	100	2	50	0	0
Cultural and naturalistic tourism	6	60	20	67	4	40	10	33
Cultural and sports tourism	38	60	20	67	25	40	10	33

Cultural tourism	5	56	7	100	4	44	0	0
Cultural tourism/gastronomic/nature	2	67	19	54	1	33	16	46
Cultural/gastronomic/sports tourism	20	44	13	62	25	56	8	38
Cultural/naturalistic/sports tourism	141	40	39	43	214	60	52	57
Gastronomic and nature tourism	2	67	10	71	1	33	4	29
Gastronomic tourism	16	55	3	100	13	45	0	0
Gastronomic and sports	31	52	17	77	29	48	5	23
Gastronomic/nature/sport tourism	147	49	33	46	153	51	39	54
Nature and sports tourism	246	50	57	53	248	50	51	47
Nature tourism	64	63	13	59	37	37	9	41
Relaxation	2	50	4	44	2	50	5	56
Sports tourism	157	55	48	56	130	45	38	44
Total	879	50	306	55	888	50	247	45

Regarding the frequency of visits (Figure 5.1.5), the majority of the respondents were recurrent visitors in both the PAs. Similar values between the areas also emerged in the first-time visitors (19% of replies rate in both the PAs). The PAs showed some slight differences in respondents that have visited the PAs less than 3 times, with values higher for the Adamello (27%) than the Gran Paradiso (17%). However, the PNGP had higher values compared with the AD regarding recurrent visitors, both for the category “more than three times”, having 4% more respondents than the AD, and “recurrent destination”, with 7% more than the AD.

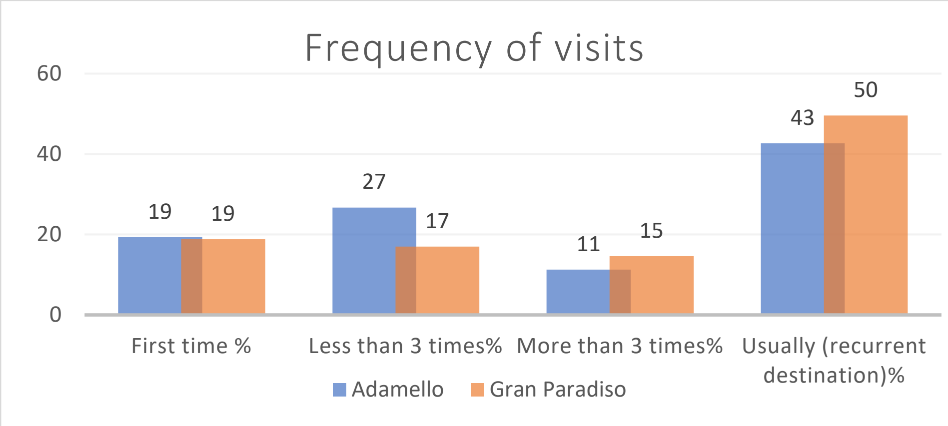

***Figure 5.1.**. Frequency of visits at the PAs in percentage referring to the total answers of visitors.*

We highlighted for both PAs (Table S.5.1.5) that the category of visitors related to cultural tourism was the one with the highest percentage of new visitors (57% AD, 60% PNGP), while relaxation activities had the highest percentages in the assiduity in the visits at the PAs (78% AD, 100% PNGP). Sport and nature tourism were mainly related to recurrent visits, with values close to 50% for both PAs, and were evenly distributed in the frequency in the remaining categories. This general trend could be counterintuitive if compared with the previous semi-structured interviews, where interviewees declared an increase of new visitors that visited the areas, but we must state that there was an overall 20% of respondents of both PAs that declared that it was their first time visiting the PA, partly confirming the perception of new visitors, but with a different purpose as stated from the managers. We performed a Pearson χ^2 test for the relationship between the variables of the frequency of visits and activities; we observed significant evidence (p = 0.00001) to conclude that there is an existing relationship between the recurrent assiduity of visits and the categories of enogastronomic/nature/sport tourism, nature tourism, nature/sport tourism, enogastronomic tourism, cultural/nature/sport tourism, sport tourism, enogastronomic/sport tourism, “all categories” and cultural/enogastronomic/nature tourism.

Since the short-term stays were pointed out as one of the main concerns of the semi-structured interviews, we carried out a binary logistic regression analysis (Tables 5.1.3 and 5.1.4) to test the relationship with the other attitudes detected. The significant variables identified with the forward stepwise method for both the PAs include recurrent visits, origin, natural activities, stakeholder category, and senior visitors. In the case of the PNGP, cultural activities and first-time visitors were also considered, while at the AD, sport activities and young visitors were chosen. The pseudo-R^2 at the AD was 0.31 and 0.30 at the PNGP, indicating that 30% of the variance in the outcome variable can be explained by the predictor variables. Even though we recognize that this is not perfectly fitting, we assume that our variables fit our model moderately well, due to the huge complexity of a variable as the duration of stays, which could be related to many other variables that were not encompassed in the questionnaire. The percentage of correctness, indicating how much the model correctly predicted the outcome, was 72% at the AD and 71% at PNGP. The results of the binary logistic regression showed that both areas resulted in a significant positive relationship ($p < 0.001$) with the stakeholder category of residents outside the PA, whereas a negative relationship ($p < 0.05$*; $p < 0.001$**) was detected for recurrent visitors*, interregional visitors*, senior visitors**, and sport activities*, suggesting that these categories were less likely to result in a short-term stay. It was interesting that at the PNGP, the activity categories negatively related to short-term stays were cultural activities and sport activities, whereas at the AD, they were nature and sport activities. Food and relaxation categories were excluded from the forward stepwise due to their low significance. Moreover, at the PNGP, we also encountered a positive relationship ($p < 0.001$) between new visitors and short-term stays.

Table 5.1.3. *Results of binary logistic regression analysis using the binary dependent variable of short-term stays (0: long term; 1: short term) as dependent variable at PNGP.*

Independent Variables		*B*	*S.E.*	*Wald*	*gl*	*Sign.*	*Exp(B)*
	Recurrent	−1.153	0.122	89.997	1	<0.001	0.316
	First visit	0.589	0.139	17.851	1	<0.001	1.801
	Interregional origin	−1.428	0.117	149.692	1	<0.001	0.240
	Cultural activities	−0.378	0.103	13.341	1	<0.001	0.685
	Senior visitor	−0.331	0.121	7.450	1	0.006	0.718

Resident outside PNGP	0.813	0.223	13.267	1	<0.001	2.255
Owner second house	−0.962	0.161	35.841	1	<0.001	0.382
Sport activities	−0.431	0.206	4.389	1	0.036	0.650

Table 5.1.4. *Results of binary logistic regression analysis using the binary dependent variable of short-term stays (0: long term; 1: short term) as dependent variable at AD.*

Independent Variables	***B***	***S.E.***	***Wald***	***gl***	***Sign.***	***Exp(B)***
Interregional origin	−0.526	0.178	8.714	1	0.003	0.591
Nature activities	−0.823	0.209	15.545	1	<0.001	0.439
Sport activities	−0.986	0.249	15.724	1	<0.001	0.373
Recurrent visitor	−1.489	0.185	64.857	1	<0.001	0.226
Young visitor	0.806	0.166	23.511	1	<0.001	2.238
Senior visitor	−0.535	0.239	5.028	1	0.025	0.586
Resident outside AD	1.880	0.535	12.374	1	<0.001	6.555
Owner second house AD	−0.502	0.235	4.553	1	0.033	0.605

3.2.3. The Effects of COVID-19 on Attitudes

About 40% of respondents claimed a change in the frequency of visits after COVID-19; despite this not representing the majority of respondents, it shows a tendency of change of almost half of the respondents. Users who indicated a change in the frequency of visits to the parks were asked if the variation was in a positive (more visits) or a negative way (less visits). About 65% of users at the PNGP and 70% of those at the AD stated that there were changes in their frequency in terms of less frequent visits.

The categories (Table S.5.1.5) that mostly experienced a negative change in frequency (Figure 5.1.6) at the AD were "naturalistic associations", along with workers and tourism workers. At the PNGP, the major changes were in the categories of owner of a second house and tourists. The AD had higher percentages of variation (50%) for the category of craftsman and producers than the PNGP (15%), and for tourism workers and employees of the park, with a 20% difference compared with the PNGP. On the other hand, residents and researchers changed more the frequency of visits at the PNGP than the AD. Investigating if the changes were towards more or less frequent visits (Table S.5.1.6), we observed an overall reduction of visits in both PAs. Similar percentages of changes were found for most of the categories, with the exception of: (1) employees of the parks, which showed a complete opposite trend, with a total reduction of visits at the PNGP; (2) researchers, which declared unanimously to have more frequent visits at the AD, rather than the PNGP with only 57% of the total; and (3) tourism workers, with a total 100% of less frequent visits at the AD and 88% at the PNGP.

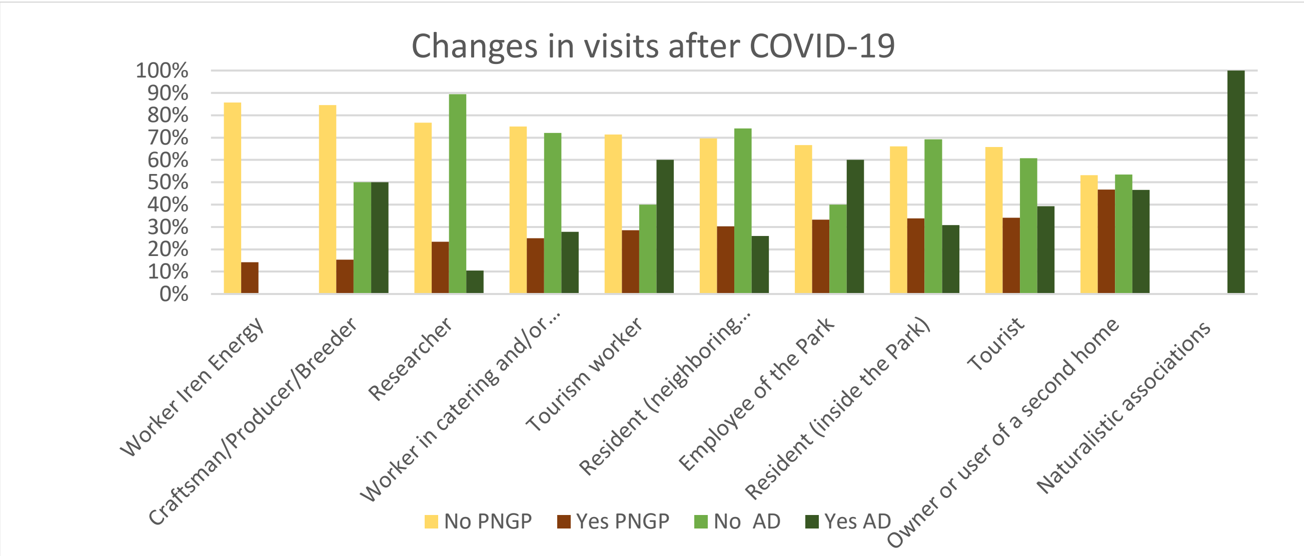

Figure 5.1.6. *Percentages of the changes in users' frequency of visits after the COVID 19 pandemic at the Adamello Regional Park; no changes in frequency of visits were indicated with "No", while any type of change was indicated with "Yes".*

4. DISCUSSION

4.1. Origin of Visitors and Activities Carried Out

Concerning the origin of the visitors, we detected a significant difference between our study areas, having a local tourism centered inside the regional boundaries at the AD, and an interregional tourism at the PNGP. This was an expected result, due to the diverse tourist vocation of the two areas and the fact that the PNGP is more publicly known, due to its relevance as the first Italian National Park. Concerning activities carried out, we found many confirmations of interview statements in the questionnaire results. From both the PAs emerged a common trend of a predominance of the selection of "all categories", in particular at the AD, where almost half of respondents selected this option. This difference could be due again to the diverse history of the PAs; in fact, the PNGP has a strong background as biodiversity conservation area and for mountaineering activities (von Hardenberg, 2013, 2021), and could lead to a more targeted type of tourism towards nature and sport, whereas the AD is a more recent and smaller PA, and could result in less focused touristic attitudes. The semi-structured interviews highlighted the importance of nature and sport tourism and cultural tourism as an additional category. Questionnaires confirmed this perception, having nature and sport tourism as the second most represented category.

It was interesting that the questionnaire results highlighted the tendency of using the PAs for sport activities only, more than natural purposes only, which we expected to be the main purpose for visits at natural protected areas due to the biodiversity conservation service, as highlighted in similar studies (Dràbkovà, 2012; Paul & Nagendra, 2017; Wang *et al.*, 2022). This could be due to an ongoing trend related to sport tourism, which is predicted to increase in the following years (World Travel and Tourism Council (WTTC), 2022), and likely linked to the growing desire to perform sport in "clean" environments instead of in cities both for air purity and landscape appreciation (Malchrowicz-Mośko *et al.*, 2019), and also for an interest in nature and wilderness (Butzmann & Job, 2017), which could be the motivation for visitors to practice sports at the PAs. Rural and developing areas of the PAs could take advantage of this trend, using it as a key strategy for local development, by promoting sustainable and attractive sport events such as biking paths in nature, hiking or canyoning (Soares & Nunes, 2020), as also stated in the semi-structured interviews. According to the semi-structured interviews, slow outdoor tourism should be developed to couple the need for a rest from the speed of cities and the respect for nature, also supporting physical activities in nature (Farkić & Taylor, 2019). Outdoor activities in the PAs have a century-long tradition (Eagles & McCool, 2002) which must also be taken into account in PA management strategies. Human activities of any type, in particular sport events in nature, must be respectful of biodiversity and phenology, planning accurately each activity to avoid disturbances to species and ecosystems, and respecting the vulnerable seasons. Due to this intrinsic value of PAs, related to the protection of nature, we expected results with a higher percentage of nature-related activities. Despite this, natural activity reached lower values compared with the other main categories. At the AD, tourism only for naturalistic purposes reaches 2% of responses, whereas at the PNGP, it reaches 5%. However, this result is still quite low, especially considering that sport tourism only reached percentages that are twice as high as those of nature. We assume that there was an overlap in considering outdoor experiences, encompassing both recreational and educational activities (e.g., watching nature) and adventure experiences (Buckley, 2009). This was confirmed by clustering the type of activities and standardizing using Z-scores; we then detected that nature and sport tourism were the main categories identified, but the results were spread in mixed categories. Even if both the PAs have cultural attractions, for instance petroglyphs and museums, the cultural value only was poorly detected. The same happened for the enogastronomic value only, which resulted in it being less represented at the AD, and reaching 1% of replies at the PNGP, confirming the semi-structured interviews. Eventually, as the results highlighted, gastronomic and cultural activities resulted in higher percentages if experienced together with other types of activities, such as sport and natural activities.

4.2. Mass Tourism, in Terms of Duration and Frequency of the Visits, Percentage of New Visitors and Activities Categories

From the first interviews the main problem that emerged was "mass tourism", explained as short-term stays which do not contribute to the development of the park and overexploit parks resources. The tourism quality was indicated as declining, referring mainly to this trend of exploitation, the presence of traffic in PA roads, and the huge number of tourists above all for one-day stays. Thus, we asked people attending the park about the duration of their stay; this could be an indicator of the phenomenon described. Both PAs confirmed the perception of the semi-structured interviews; in fact, more than 30% of the respondents declared doing a one-day stay, whereas longer stays did not reach 20%, apart from one-week stays, which was the second category that emerged at the AD overall, reaching almost 30%. Here, we have to consider as a possible factor the decline of the duration of stays that occurred all over Europe in 2021, in which the regions of Lombardy, Piedmont, and Aosta Valley recorded more than a 50% reduction of the number of nights spent in a touristic accommodation compared with 2019 (Commission &

Eurostat, 2022). Considering the clustered categories of the durations of stays, the categories showing longer stays were related to cultural/naturalistic/sport tourism, relaxation, and cultural/gastronomic/nature tourism. Nature tourism only reached higher percentages of short-term stays, even if the highest values were related to cultural and gastronomic tourism at the AD and cultural/gastronomic/nature and gastronomic/nature tourism at the PNGP. Thus, we must keep in mind that almost 40% of the respondents from both PAs stated doing one-day stays, which reflected the phenomena of mass tourism in our interviewees' perception. A lot of attention should be given to this point, creating opportunities for longer term stays and increasing the attractiveness of slow tourism in these particular PAs, above all in the AD, where the overall value of short-term stays was higher that the PNGP. The results of the binary logistic regression for each PA indicated some positive relationships with the attitudes we collected. The Pseudo-R^2 of 30% suggested that other factors beyond the variables included were likely to contribute to the model related to such a complex variable as the duration of the stays in a PA, for instance, income, type of accommodation, attractiveness of the area (Gokovali *et al.*, 2007), and personal preferences. Our aim was the presence of some relationship to give a first explanation of short-term stays, pointed out from the interviews as a main issue in PAs' touristic fluxes management, above all relating to the increasing number of visitors. The results of the regression indicated that there was a relationship between frequency and length of the stay, which could possibly be related to the familiarity of the visitors with the area (Gokovali *et al.*, 2007). First visits at the PNGP were correlated to shorter term stays, perhaps because of the desire to explore rapidly new areas (Nicolau *et al.*, 2018). For both the areas, people recurrently visiting the PA were less likely to stay for short-term stays; this could be due for instance to the familiarity of visitors to the area (Lau & McKercher, 2004; Alegre & Pou, 2006; De Menezes *et al.*, 2008), which leads to perform different type of activities and could develop a preference for visiting the area. For both areas, visitors coming from interregional origins were less likely to stay for short-term stays; it is therefore likely that this trend was related to the expenditure of trips (in terms of economic costs and time expenditure), which led to the preference of longer experiences related to long distance trips (Nicolau *et al.*, 2018). Moreover, we found that senior visitors were less likely to stay for only a few days; from our perspective, these results were reasonable, and the relationship with senior tourism and long-term tourism is widely discussed in the literature and is also correlated with seasonal migration in touristic areas (Ono, 2008; Lyu *et al.*, 2021). The owners of a second house were positively correlated with longer term stays; this could be reasonably correlated with the lack of extra monetary expenditure for an accommodation (Masiero & Nicolau, 2012). Eventually, users performing sport activities at both PAs, nature tourism at the AD, and cultural tourism at the PNGP were less likely to stay for short-term stays. It was interesting to explore these categories and see that both PAs share the same trend for sport tourism, which was related to longer stays; this could be also related to an economic expenditure of visitors. In fact, outdoor sport activities reduce the expenditure of a trip (Downward *et al.*, 2020), and this could lead visitors to undertake longer visits. Interestingly, we found a relationship with longer term stays at the PNGP and cultural tourism, the area in which the cultural tourism was indicated as marginal compared with nature and sport tourism, and mostly related to sanctuaries situated in the mountains. We presume that there could be a correlation with the fact that these sanctuaries are situated in natural environments and people can freely access them while hiking, but further studies should be carried out to better understand this variable.

We were interested in the changes and attitudes of the frequency of attendance of the PAs; thus, we studied the question related to the assiduity of visits. We considered this as a possible explaining factor of the increase of visitors, a factor that was stressed by the park managers during semi-structured interviews. Since there are no data available on the number of tourists that visit the specific PA we were interested in each year, we could not perform comparisons with the previous situation, but assume that this could be considered as a first step towards the description of the new visitors trend. Most respondents stated an assiduity in the visits. Moreover, the chi-square test showed a significant correlation between recurrent visitors and long-term stays, as explained below. The categories of activities with the highest values for recurrent visits were relaxation, nature, and sport tourism. Nevertheless, 19% of respondents for both PAs declared being at their first visit. We analyzed this reply considering the type of activity carried out and we could not point out a significant relationship with first-time visitors and activities. Even though visitors for nature and sport tourism were predominant, in our opinion, park administrators could encourage a shift towards a new perception of the PAs and new practices that go beyond naturalistic and sport purposes, comprising also cultural and less explored types of tourism (e.g., enogastronomic), which could also be related to longer duration. The regular visitors were strongly related to relaxation purposes and to mixed categories, encompassing nature and cultural/enogastronomic purposes. PAs have been an effective tool for raising environmental awareness and for showing the importance of natural heritage (EUROPARC, 2010). Perhaps cultural heritage value, linked to food traditions and cultural attractions, could also be valued in PAs.

During the decision making, stakeholders should also be aware of the current demographic trends, considering that it will be very likely to have an increase of visitors due to the global demographic growth (Parks and Benefits, 2012). This was already partially confirmed by our results: the semi-structured interviews highlighted this trend and our questionnaires resulted in 19% of respondents that declared to be on their first ever visit to the PA. We thereby assume, considering the responses of the semi-structured interviews, that decision makers were already aware of the issues that can emerge in the future, and strategies of sustainable transportations are already taken into account. The issue that emerged from the interviews related to the users' fluxes was related to traffic, pollution, and relatively small awareness of new tourists of the responsible behavior to have in mountains. It is reasonable to hypothesize that the growing fluxes of tourism may lead to the exacerbation of the issues that stakeholders stated, such as car traffic and pollution. The Alps are a destination for millions of people every year (WWF) and there could be the need for reducing the GHG emissions with the improvement of the mobility sector by, for instance, strengthening and improving the public transport, e-mobility or shared vehicles, and stimulating walking or cycling (Blindenbacher *et al.*, 2020). Moreover, due to the advances in travel availability and the reduction of costs, it is likely to have an increasing number of visitors that come from more distant areas (Parks and Benefits, 2012). This research showed that the tourism was still related to local, regional, and national trips, but this could be one of the possible changes of the future, and one of the future issues for a sustainable mobility, considering tourism related to PAs in a broader sense also includes the impacts of traveling towards the destination. Public transport or other sustainable options should be affordable, attractive, widely advertised, and efficient, including both travel from the starting point to the destination and internal mobility inside the PAs (Scott & Braun, 2010). Eventually, these considerations should be checked within different time periods with other questionnaires, to test if there is a relationship between the new visitors and the travel restrictions related to COVID-19 (Rogowski, 2022), which could have driven the tourism fluxes in different paths afterwards, and to monitor visitor trends.

4.3. COVID-19: Changes in Numbers of Visits

Since our data collection was carried out *during one of the first waves of* the COVID-19 pandemic, we assumed that users' attitudes and perceptions could be influenced due to the particular period, thus, in this study, we encompassed some questions regarding the frequency of visits after the pandemic, to test whether the semi-structured results could be a perception or an effective trend. The semi-structured interviews stated a growing trend of visits after the COVID-19 pandemic and from the questionnaires, it emerged that almost 40% of users changed the number of visits to the PAs due to the pandemic. It is therefore reasonable to assess that a change in the PAs' visits had occurred. Surprisingly, the majority of users declared having less visits, rebutting the interview statements. This could be due to many factors; one of these could be the fact that during 2021, the COVID-19 pandemic was still ongoing and there are no clear boundaries on when it has stopped, thus people could have misunderstood the question. Furthermore, considering the stakeholder categories separated, we obtained AD naturalistic associations and park workers were the only ones experiencing more visits. This could be linked with the travel restrictions that occurred during the pandemic; in fact, during the summer, the restrictions were eased but not removed, and summer was believed to be a relatively safe period. Despite this ease of restrictions, people could not feel safe in traveling, fearing the possibility of contamination (Farzanegan *et al.*, 2021; Rogowski, 2022), and thus rearranged their travels due to safety reasons (Moya Calderón *et al.*, 2022); moreover, local restrictions could have been applied, which in some cases completely blocked the mobility. For instance, the Aosta Valley, where part of the PNGP is situated, was considered a "red zone" during May 2021, thus all travels were forbidden, with restrictions even inside the regional boundaries. The stakeholder categories that experienced more changes were the AD users related to naturalistic associations, employees of the park, and tourism workers, whereas for the PNGP, they were owners of second houses and tourists. We presume that second-home tourism could have been considered as an opportunity of overcoming fears of contamination and travel restrictions, and to travel safely even with the pandemic ongoing (Seraphin & Dosquet, 2020), instead of doing trips in other touristic areas. At the AD, the most affected categories declared a change in terms of less frequent visits, whereas at the PNGP, we have for both categories 30%, which increased the number of visits. The majority of people belonging to the category of tourists declared that they did not change their frequency because of COVID-19, and only one-third of tourists who changed the frequency of their visits said that they visited the PAs more often.

5. CONCLUSIONS

This paper aimed to understand if the managers' and municipalities' perceptions of users' frequentation of the PAs matched with the users' replies, and to get some information regarding the use and frequentation and attitudes towards the PAs, also considering the tourists' point of view.

- In most cases, we confirmed the responses of the semi-structured interviews, with an emerging trend of short-term stays and an attractiveness of the areas related to sport outdoor activities, as the majority of respondents were encompassed in sport and nature categories. The visitors' origin differ between the two protected areas: at the AD, we detected a more local tourism, whereas the PNGP, possibly due to its broader fame, had more interregional visitors.
- The perception of tourism in the semi-structured interviews had some ambiguities. Even though there was a common agreement in the importance of tourism as a possibility for economic development and biodiversity awareness, managers and municipality representatives expressed a concern regarding the quality of tourism, which was perceived as declining. In particular, they were concerned about mass tourism, which was mainly related to the short-term stays. Mass tourism was deemed as a practice that overexploits the resources of the PAs instead of supporting the local development. With the questionnaires, we could confirm the perception of a predominance of short-term stays, in particular of overnight stays. We found a relationship between short-term stays and other attitudes (frequency of visits, activities, origin, biographical data), and we found that users performing activities such as sport tourism are less likely to stay for a few days. We also found a relationship between longer stays and particular categories such as age group of seniors (61 to <70) and recurrent visitors. Since fluxes of users in protected areas are still an estimated number, we could not carry out any comparison with the previous years to confirm the managers' perception of an increasing tourism, but we estimated a value of almost 20% of new visitors in both the PAs; further studies need to be carried out to better understand the magnitude of this trend.

- Eventually, managers and representatives identified an exacerbation due to the COVID-19 pandemic of the already existing trend of new visitors. From questionnaires, we identified 40% of users that declared a change in the frequency of visits after the pandemic, but mainly the variation was towards less frequent visits, thus we could not confirm the interviewees' perception. However, it would be interesting to monitor the variation of fluxes after the pandemic; in fact, one of the concerns of managers was whether the variation was a temporary effect of the lockdown or a permanent trend.

From the literature, there emerges a challenging issue related to tourism in the European Alps; some changes in the use of these areas were forecasted. For instance, variation related to a forecasted increase of summer touristic flows, due to the more frequent heath waves and the need of people to look for cooler places, with an increase of mountaineering activities and alpine lakes (Pröbstl-Haider *et al.*, 2015), and a drop in winter tourism trends (Pröbstl *et al.*, 2008), for instance, due to the reduction of snow cover. Hence, it is fundamental to start collecting data on the visits to the PAs to monitor, together with biodiversity data, data on user flows of the PAs to understand how fluxes of visitors change across seasons and years, the consequent human impact on biodiversity, and to develop specific management strategies according to users' fruition of the areas. A further step, along with touristic flux monitoring, would be to engage people in longer stays. This could be facilitated by raising awareness on the opportunities offered by the areas, which will go further than the sport activities only, including cultural traditions and historical habits and behaviors for nature conservation in the PA.

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Supplementary materials

Table S5.1.1. Questions of the semi-structured interviews.

1) What are the main natural and cultural attractions of the area?

2)	What kind of tourism does your area visit and what are the main activities of tourists?
3)	The park offers many cultural services, but for them to be used it is necessary for people to visit the Park; this inevitably causes an impact on the protected area. How do you see tourism interacting with habitat conservation and wildlife protection? Are there types of tourism that have a greater impact on the territory in your opinion (e.g. mountaineers, climbers, etc)?
4)	Tourism is certainly a resource for the Park but can in some ways cause problems in the management of fauna and in the conservation of habitats. What is your perception of this? In your experience have you had episodes of criticality between tourism and conservation or have they never come into conflict?
5)	Are there any tourism models that you consider more sustainable than others? Considering your experience at the Park, how did you try to develop more sustainable tourism?
6)	Have you seen a change over the years with respect to the type of tourism, and attitudes /attitudes of people attending the park?
7)	What is the type of forest management within the Park and how does it differ from the forests of the neighbouring territories but excluded from the Park?
8)	Has an assessment of ecosystem services already been carried out at the Park? If so, of which?
9)	[ONLY IF YOU ANSWER THE PREVIOUS QUESTION] Are ecosystem services a possible conservation tool? If so, how?
10)	In your opinion, are there any critical issues in the concept of ecosystem services?
11)	This summer there will be a survey on the use of the Park and the perception of ecosystem services by different stakeholders. With regard to the categories of stakeholders identified by us (see list at the end of the document), do you think there is some other unrepresented category that would be useful to consult (as well as categories not of interest to the Park)?
12)	How did you notice that the pandemic changed the attendance in the Park? Was there any noticeable effect on the quantity and attitude of tourists and/or residents?

Table S5.1.3. Stakeholders' categories identified through surveys with Park's managers. In bold, the main categories used for the analyses.

Stakeholders' categories:
• Workers in catering and/or tourism **Hut managers**

Hoteliers, bars/restaurants

- Tourism workers

Tourism agencies

- Tourists

Non-expert hikers

Expert hikers (trekking)

Cultural/museum/food and wine tourism

Alpinists

Climbers

Mountain biker

Canoeing/rafting

Photographers

Secondary residences

- Residents in the Park
- Residents outside the park but in neighbouring municipalities
- Park's workers
- Craftsman/Producer/Breeder

Shepherds/breeders

Local producers

- Researchers

Researcher with activities in progress or carried out in the Park

Table S5.1.4 Number of replies and percentage of biographical data. In columns gender, in rows age classes.

Adamello				Gran Paradiso			
F		M		F		M	
N of replies	%	N of replies	%	N of replies	%	N of replies	%
<20				<20			

104	10%	97	9%	127	5%	101	4%
21-30				21-30			
130	12%	88	8%	175	7%	169	7%
31-40				31-40			
54	5%	45	4%	151	6%	149	6%
41-50				41-50			
119	11%	81	8%	272	12%	175	7%
51-60				51-60			
97	9%	78	7%	274	12%	204	9%
61-70				61-70			
43	4%	46	4%	180	8%	184	8%
>70				>70			
34	3%	36	3%	79	3%	80	3%

TableS5.1.5 Description of frequency of visits at the PAs and type of activity carried out

Adamello	First time		Less than 3 times		More than three times		Usually (recurrent destination)		Total of replies
	N of replies	%	N of replies	%	N of replies	%	N of replies	%	
Relaxation	1	11	1	11	0	0	7	78	9
Cultural tourism	4	57	2	29	1	14		0	7
Cultural and naturalistic tourism	11	37	11	37	3	10	5	17	30
Cultural and sports tourism	5	17	12	40	3	10	10	33	30
Cultural and food tourism	2	67	1	33		0		0	3
Cultural tourism/food and wine/nature	9	26	10	29	4	11	12	34	35
Cultural/food and wine/sports tourism	8	38	7	33	4	19	2	10	21
Cultural/naturalistic/sports tourism	16	18	19	21	11	12	45	49	91
Food and wine tourism	1	33	1	33		0	1	33	3
Food and wine and nature tourism	2	14	7	50		0	5	36	14
Food and wine tourism and sports	1	5	9	41	7	32	5	23	22
Food and wine/nature/sport tourism	11	15	16	22	6	8	39	54	72
Nature tourism	7	32	5	23	4	18	6	27	22
Nature and sports tourism	21	19	20	19	25	23	42	39	108
Sports tourism	13	15	25	29	9	10	39	45	86
All categories	93	18	137	27	42	8	234	46	506
Gran Paradiso	N of replies	%	N of replies	%	N of replies	%	N of replies	%	Total of replies
Relaxation	0	0	0	0	0	0	4	100	4
Cultural tourism	4	44	2	22		0	3	33	9
Cultural and naturalistic tourism	6	60		0	1	10	3	30	10
Cultural and sports tourism	12	19	20	32	8	13	23	37	63
Cultural and food tourism	1	25	1	25		0	2	50	4
Cultural tourism/food and wine/nature	1	33		0	1	33	1	33	3
Cultural/food and wine/sports tourism	10	22	7	16	5	11	23	51	45
Cultural/naturalistic/sports tourism	66	19	67	19	53	15	169	48	355
Food and wine tourism	6	21	7	24	1	3	15	52	29
Food and wine and nature tourism	1	33		0		0	2	67	3
Food and wine tourism and sports	11	18	4	7	11	18	34	57	60
Food and wine/nature/sport tourism	52	17	50	17	43	14	155	52	300
Nature tourism	19	19	34	34	17	17	31	31	101
Nature and sports tourism	80	16	70	14	77	16	267	54	494
Sports tourism	43	15	36	13	45	16	163	57	287
All categories	129	23	98	17	77	14	259	46	563

Table S.5.1.6. Detailed table of how the frequency of visits changed in percentage, considering more or less visits, at the Adamello Regional Park. Percentages for Naturalistic Associations at PNGP and Iren Energy workers at AD are not available, due to the lack of the category at the specific PA.

	AD		PNGP	
Changes COVID AD	Less frequent visits	More frequent visits	Less frequent visits	More frequent visits
Artisan/Producer/Breeder	67%	33%	67%	33%
Employee of the Park	100%	0%	0%	100%
Naturalistic associations	100%	0%	NA	NA
Owner or user second home in the Park (or nearby)	68%	32%	71%	29%
Researcher with activities in progress or carried out in the Park	0%	100%	57%	43%
Resident (in the Park)	65%	35%	55%	45%
Resident (outside the Park but in neighbouring municipalities)	67%	33%	61%	35%
Tourism worker	100%	0%	88%	13%
Tourist	72%	28%	64%	35%
Worker in catering and/or tourism	65%	35%	59%	41%
Worker Iren Energy	NA	NA	50%	50%

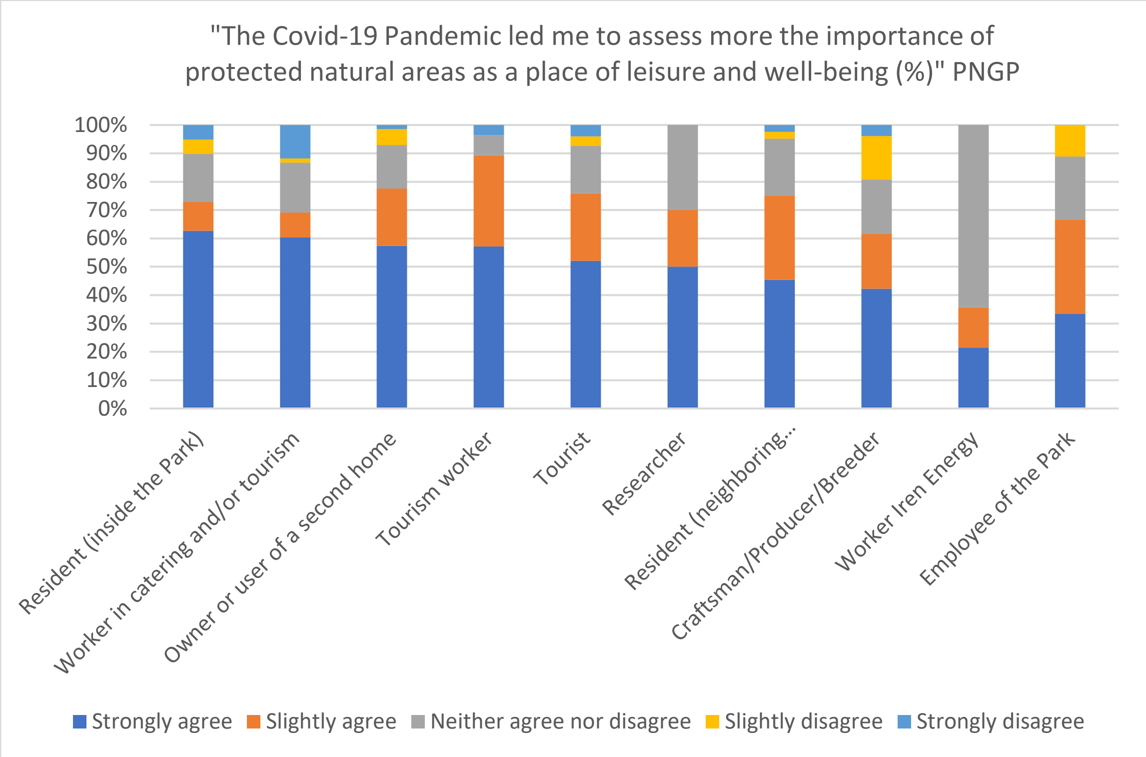

Fig. S5.1 Agreement (in percentage) of the development of a new perception of the PA as a place of leisure and well-being after the COVID-19 at the PNGP.

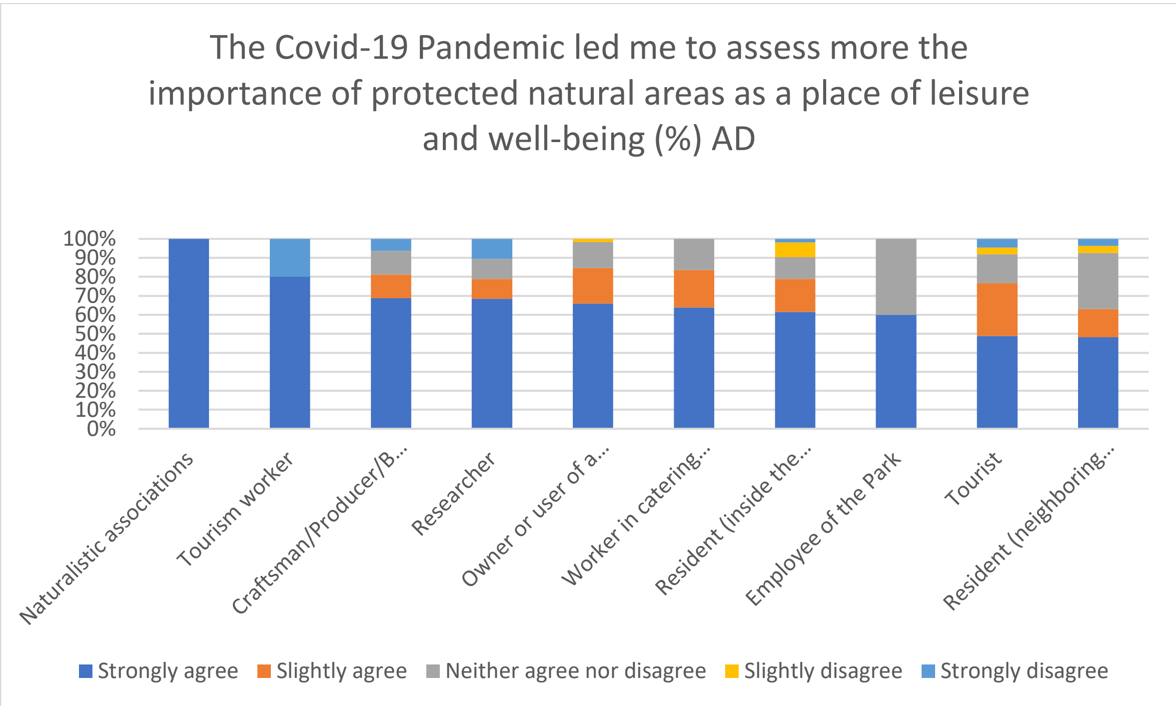

Fig. S5.1.2 Agreement (in percentage) of the development of a new perception of the PA as a place of leisure and well-being after the COVID-19 at the A

SUBCHAPTER 5.2

Ecosystem Services in the Alps: users' perceptions from the Adamello Regional Park and the Gran Paradiso National Park (Italy)

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Abstract

The evaluation of cultural ecosystem services in alpine protected areas is a powerful tool for helping managers and policy makers in understanding how users' value the provision of such important benefits. Urgent conservation efforts must be undertaken for reducing the impacts of climate change on such vulnerable areas, and understanding the relationships between visitors and natural areas can help in developing management strategies, also supported by the public acceptance. We administered 3399 questionnaires in two Italian alpine PAs to investigate how users perceived 21 critical alpine ES, assess their familiarity with the concept of ES and examine whether the COVID-19 changed their perception of these areas. Information on users' profiles were collected to examine the possible correlations with ES perception and to provide information on categories on which communication efforts should be made. The aesthetic value of the landscape was the most perceived service, followed by biodiversity conservation and nature observation. Users reported a general increase in positive appreciation of PAs post COVID-19. Interestingly, the higher perception of ES was positively correlated with female, senior and nature-related stakeholders. Additionally, we observed and enhanced perception of ES among users who had previously acknowledged their existence. Given these findings, we gave suggestions for communications strategies. These insights can aid managers and policymakers in understanding how the areas are perceived, and to whom they should direct the communication efforts for increasing public awareness of the benefits provided by the natural protected areas.

1. Introduction

The supply of Ecosystem Services (ES) - defined as the benefits that ecosystems provide to human well-being (MEA, 2005) - is subject to an increased demand by human population and a reduced supply capacity due to habitat fragmentation, loss, and climate change effects (Brockerhoff et al., 2017; Cairns, 2006; Mooney et al., 2009; Scholes, 2016). There is an urgent need to find solutions to reverse the current trend and preserve ES delivery, above all in alpine protected areas, which are fundamental for the provision of many ES, most of them being primary for human survival and wellbeing, such as freshwater regulation, food provision, pollination, climate regulation and habitat provision (Canedoli et al., 2020; Grêt-Regamey et al., 2012a; Mori et al., 2017; Rota N., Canedoli C., 2020; I. D. Thompson et al., 2011) and cultural ecosystem services (CES), ranging from the aesthetic perception of the landscapes to more introspective services, such as sense of belonging and artistic inspiration (Crouzat et al., 2022; Schirpke et al., 2018; Scolozzi et al., 2015). For this reason, alpine protected areas are destinations for hundreds of millions of tourists annually (The Guardian, n.d.), that benefit from the ES provided by the areas while doing many types of activities, from outdoor to relaxing activities (Rota et al., 2023). These areas are particularly vulnerable to climate change and human activities (Hock et al., 2019), and their deterioration will lead to a reduced capacity of ES provision. Therefore, it is crucial to take action to protect these areas, preserve their habitats and biodiversity, and ensure the supply of ecosystem services that result from ecosystem functions. Through the commitment of the users who frequent the alpine protected areas and their involvement in conservation activities, it may be possible to obtain better results in their safeguard. There is an urgent need for an integrated management, that takes into account both nature conservation and societies (Hummel et al., 2019), above all for what concerns PAs: without public acceptance, management strategies aiming to safeguard nature could be difficult to pursue (Schenk et al., 2007). PAs within the European boundaries are voluntarily valuating their ES supply for implementing their conservation and monitoring activities, for instance, the Gran Paradiso National Park, one of the area studied in this project, provided an EMAS certification (Parco Nazionale del Gran Paradiso, 2022), also accounting the cultural ecosystem services (CES) provision. ES can be considered as a holistic tool for PAs management (De Groot et al., 2010; Menzel & Teng, 2010), since they can comprehend environmental, social and economic aspects in their evaluations. Moreover, the concept of ES is closely linked to the presence of a beneficiary (Petter et al., 2013; Schulze &

Mooney, 2012), being the latter conscious or not (Brockerhoff et al., 2017). The development of an acknowledgement of ES and the explicit affirmation of the reliance of human beings upon healthy environments may be a useful tool to develop greater awareness of environmental issues, developing public participation in environmental activities, including stakeholders in the decision-making process (Menzel & Teng, 2010) and making them more likely to behave ecologically and in a sustainable way, and more prone to accept conservation activities that may limit some activities, i.e., outdoors sports. An assessment of the general public perception of ES could be useful for understanding which are the categories of users that are most likely to perceive the ES, and detect which ES are perceived in the specific area. Determining which services are mainly identified and valued, and which are neglected by various categories of users could result in important insights to design conservation approaches that incorporate a greater role for citizen participation in PAs safeguard (Ballantyne et al., 2009; Isager et al., 2001). Moreover, this information will aid in structuring appropriate, targeted, effective communication campaigns.

In this study, we assumed that users' profile can be related to perception of ES (Almeida et al., 2018), and we aimed to disentangle the factors linked to this possible relationship. Data collection took place in summer 2021 during a temporary ease of the COVID-19 restrictions: at that time people had previously undergone to strict lockdowns that caused a drop in nature experience in the everyday life (Colléony et al., 2022). For this reason, we considered that people's perceptions may be affected this nature deprivation and the experience of lockdowns, hence we included a specific part of the study concerning the change in the perception of PAs after COVID-19.

In this paper we aimed to investigate the perception of ES of different categories of users in alpine protected areas, examining 21 ES (identified from the literature review as especially significant for the Italian Alps and after interviews with parks' managers), focusing on the following topics:

a) determine how ES are perceived in two alpine PAs;
b) examine the users' familiarity with the concept of ES and the recognition of ES in the questionnaire's statements;
c) how PAs perception changed after COVID-19 pandemic;

d) determine the relationships between the average perception of ES and users' profile.

2. Material and methods

2.1. Study Areas

The study areas are two alpine protected areas situated in the North of Italy, namely the Adamello Regional Park (AD) and the Gran Paradiso National Park (PNGP) (Figure 5.2.1). We chose these areas as part of our broader project on the assessment of ES (Canedoli et al., 2020) and tourism in alpine areas (Rota et al., 2023). The PAs share similarities in the environmental features, such as elevation range, habitats composition, flora and fauna. Nevertheless, the areas are regulated under different laws, since the PNGP is a National park and the AD is a regional Park, hence we assume that differences in the management strategies may exist. The Gran Paradiso National Park was instituted in 1922, being the first Italian national park, it has an extension of 70.000 hectares, and it represents a popular destination for mountaineering due to the wide knowledge of his peaks among the outdoor sector, above all considering its highest peak, the Gran Paradiso, one of the most famous European mountains. Moreover, the PNGP is widely known for its conservation efforts in the preservation of *Capra ibex* (von Hardenberg, 2021), which avoided its extinction in late XIX century. The Adamello Regional Park (AD) was founded in 1983, it is located in between two important Italian National Parks (the Stelvio National Park and the Adamello-Brenta National Park), having a strategic bridging position for touristic activities and conservation projects. The AD has more local tourism than the PNGP (Rota et al., 2023), a smaller extensions (51.000 hectares) and the ISTAT touristic indicators shows that the touristic vocation of this area is lower than the PNGP (ISTAT, n.d.). Despite these factors there is an ongoing trend of outdoor and nature tourism in this area, which offers many possibilities in terms of nature sightseeing, cultural attractions (e.g., petroglyphs) and outdoor recreational activities.

Figure 5.2.1. Map of the study areas: on the left is the Gran Paradiso National Park and, on the right, the Adamello Regional Park.

2.2. Questionnaire's structure

A total of 3399 questionnaires (Supplementary materials, Table S.5.2.1) were administered, of which 2340 at the PNGP and 1059 at the AD. We used a random sampling design to involve different stakeholder categories to cover the variability of users that attended the PAs. Questionnaires were administered in the places of interest of the PAs such as the beginning of hiking trails, central squares, and information centres. Furthermore, we went to local businesses such as restaurants, producers and farmers, to gather information from categories that would have been overlooked if we only considered touristic attractions. Questionnaires were also published online to collect remotely data from users (Canedoli & Rota, 2021a; Canedoli & Rota, 2021b). The main sections were: (1) perception of ES and familiarity through statements, (2) biographical data, type of stakeholder's category (Supplementary materials, Table S.5.2.2), frequency, duration of visits at the PA and activities carried out, (3) familiarity with the concept of ES and its recognition (4) perception of PAs after COVID-19 and changes in attendance of PAs. The section two, related to users' profile, such as stakeholders' and activities categories, was analysed in a previous publication about touristic attitudes at the PAs (Rota et al., 2023), and was used here for the independent variables to disentangle the correlations to the perception of ES. The structure of the questionnaire encompassed both lists of closed answer questions to describe the users in categories and positive statements regarding the ES perception, ranging from strong agreement to strong disagreement and reported, for clarity purposes, in a Likert scale, ranging from 1 to 5 (1: “strong disagreement”, 5: “strong agreement”). Respondents were also asked whether they identified the ES in the previous part of the survey, to assess the recognition of the concept of ES. In this study, we addressed to the *perception* according to Sudarmady et al. (2001) (Tugaswati et al., 2001), hence as the ability to perceive environmental issues in the real world, based on memory and influenced by prior experience (Kuper, 2004). Perception is an individual and embodied process, inscribed in cultural and societal dynamics which affect the individual's mental and physical capacity and attitudes towards nature. Then we conceived the *familiarity with the concept of* ES in terms of acquaintance of the concept without an in deep scientific knowledge, and we investigated it in the two closed answered questions: a) “Have you ever heard of Ecosystem Services?” b) “If yes, have you recognised them in this questionnaire’s statements?” For clarity purposes, we will categorise the first question as familiarity with the concept of ES, and the second as recognition of ES.

2.2.1. List of values

We based our survey on ES on the methods proposed in Tessa Toolkit (Peh et al., 2013) Method M1c, specifically designed for surveys on perception of CES. To create the list of ES, we used as baseline the classification proposed in TESSA Annex. For clarity purposes we reported the TESSA classification categories, our statements, and the CICES V.5 classification (Supplementary Materials, Table S.5.2.3), which resulted in the more updated and comprehensive in range of categories. Our main aim was the evaluation of CES, however, we included statements for the provisioning and regulation categories as these were of particular interest in the PAs investigated. Based on the prior knowledge of the PAs, we selected the main services we encountered in alpine protected areas and the easiest to understand to the public, obtaining 21 ES (Fig. 5.2.2). Then, according to Method M1c, we expressed the concept of ES in simple statements, in order to readapt to the common language and limit misunderstanding by respondents (Tengberg et al., 2012).

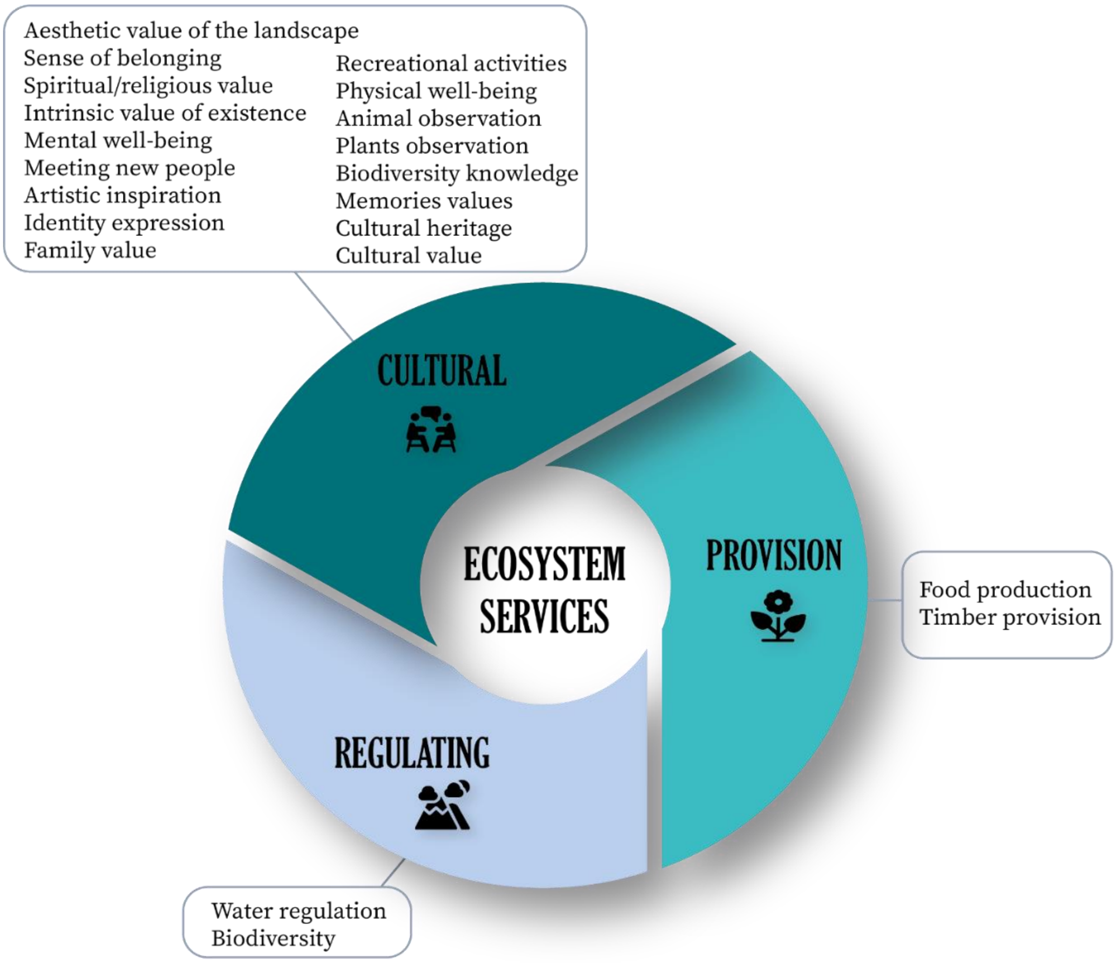

Figure 5.2.2. List of ES encompassed in the study using the abbreviated version.

2.3. Data analysis

Analyses were conducted using the software IBM SPSS version 29.0.0 (Verma, 2012), and graphics data visualisation were obtained using R Software. A Pearson Correlation matrix was undertaken to understand the correlations among ES perceptions, and plotted as correlograms with corrplot package in R. We undertook Chi^2 Test to evaluate the independency among the categorical values of familiarity with the concept of ES, recognition of ES, appreciation after COVID-19, and PAs. We clustered the ES into three categories, namely provision, regulating and cultural ES, and an Analysis of Variance (ANOVA) was carried out to identify statistically significant variance between the ES perception of the three categories, and the respondents' profile, considering as features age, gender, stakeholders' category, activities carried out, frequency and duration of the stay. We created heatmaps of the perception of ES among the diverse stakeholders' categories using the package ggplot in R software. Eventually, a Multivariate Regression Analysis was performed to detect significant relationships between the variables related to users' profile, using the forward stepwise method to select the significant variables. The analysis was carried out for each PA separately, the dependent variable was the average ES appreciation, and the independent variables were stakeholders' category, age group, gender, activities category, previous knowledge of ES, recognition of ES in the questionnaire, frequency and duration of visits.

3. Results

3.1.Perception of ES and respondent's categories

The most perceived ES in both PAs was the aesthetic value of landscape (Fig.5.2.3). At the AD we detected an overall agreement of users' also regarding the biodiversity conservation, whereas at PNGP people were more engaged with fauna observation. In general, similar scores were found among the two areas, indicating values related to mental and physical well-being, and nature observation and conservation as the most important after the aesthetic value. Provisioning services reached the lowest values in both PAs, with the exception of timber provision with was perceived slightly differently in the two areas, with higher values at the AD. The least considered values along with provision services were CES related to introspective services, such as spiritual value, memories value, and the social value. At the PNGP we identified higher scores than the AD for biodiversity-related values, recreation, personal well-being and the intrinsic value of existence, whereas at the AD services such as the freshwater regulation, food production and timber provision had higher scores than the PNGP.

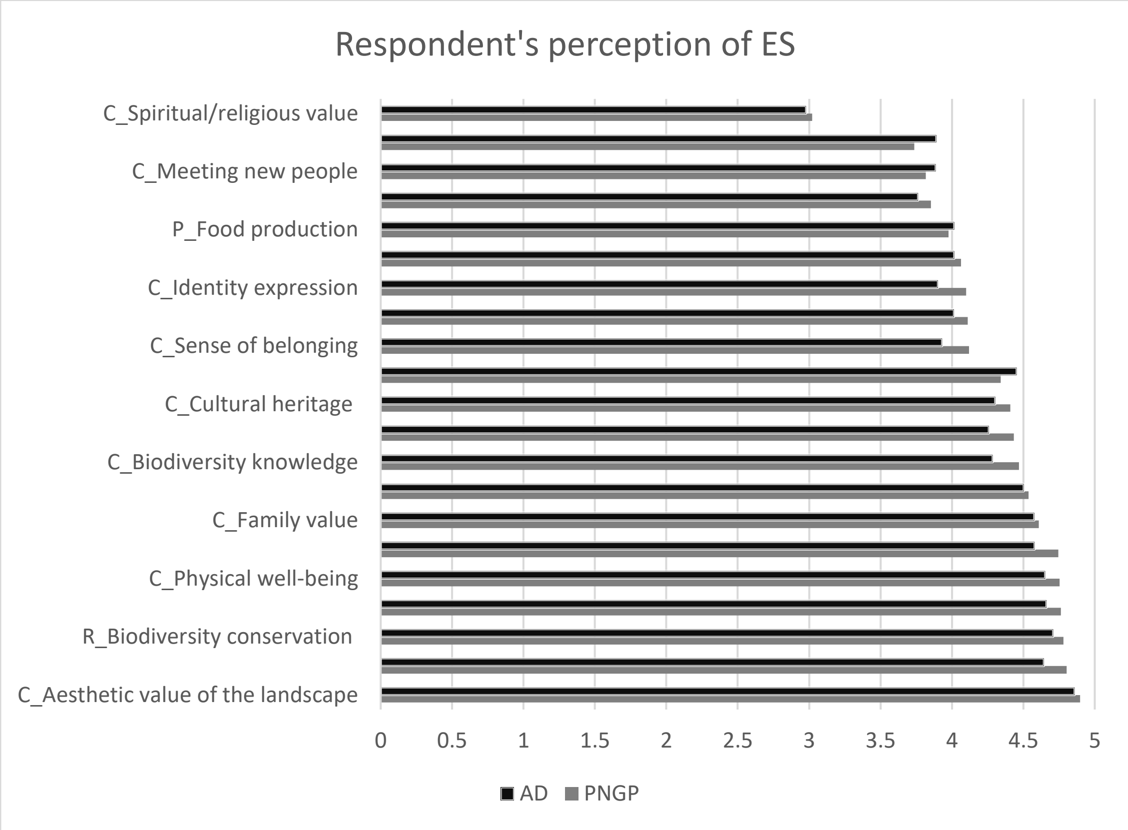

Figure 5.2.3. Average value of perception of ES at the Adamello (AD) and Gran Paradiso National Park (PNGP), the prefix indicates the category of ES (C: cultural, R: regulating, P: provisioning).

From the Pearson Correlation it emerged that most of the ES were correlated to each other, depending of the PA showing peculiar synergies and no negative correlation was detected among the ES. At the PNGP (Fig.5.2.4) it resulted that the aesthetic appreciation was highly positively correlated with flora and fauna observations, and mental and physical well-being. This output was present but with less strength at the AD (Fig.5.2.5). In both PAs there was a significant positive correlation between introspective ES, being the sense of belonging was correlated both with memories and identity services. Interestingly, we found also that there was a correlation in both PAs for provision ecosystem services, such as timber, food and water supply.

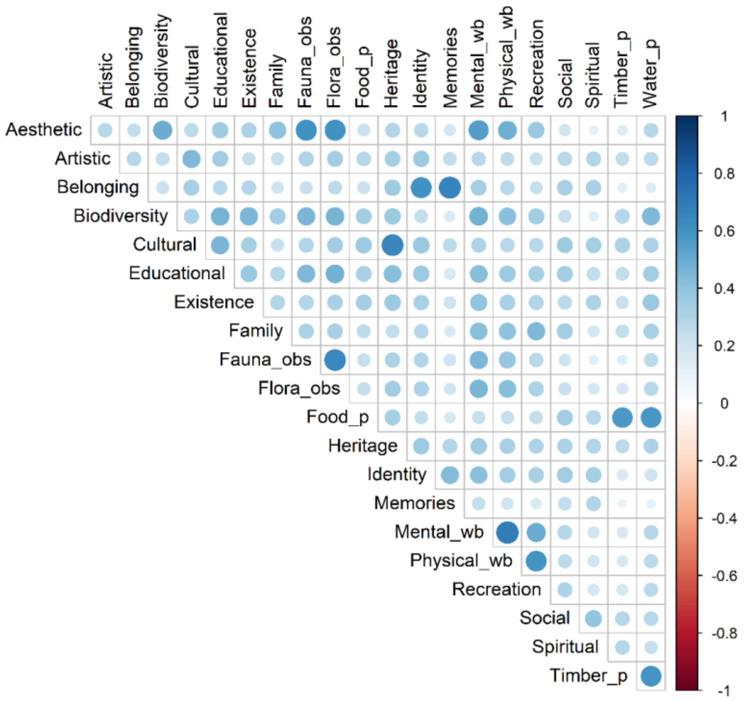

Figure 5.2.4. Pearson's Correlation at PNGP among ES with a significance level of p≤ 0. 05. Size of the circles represent the strength of the correlation, the gradient represents the type of correlation (positive: blue, negative: red). The abbreviation "obs" means "observation", "wb" means "well-being", and "p" means "provision".

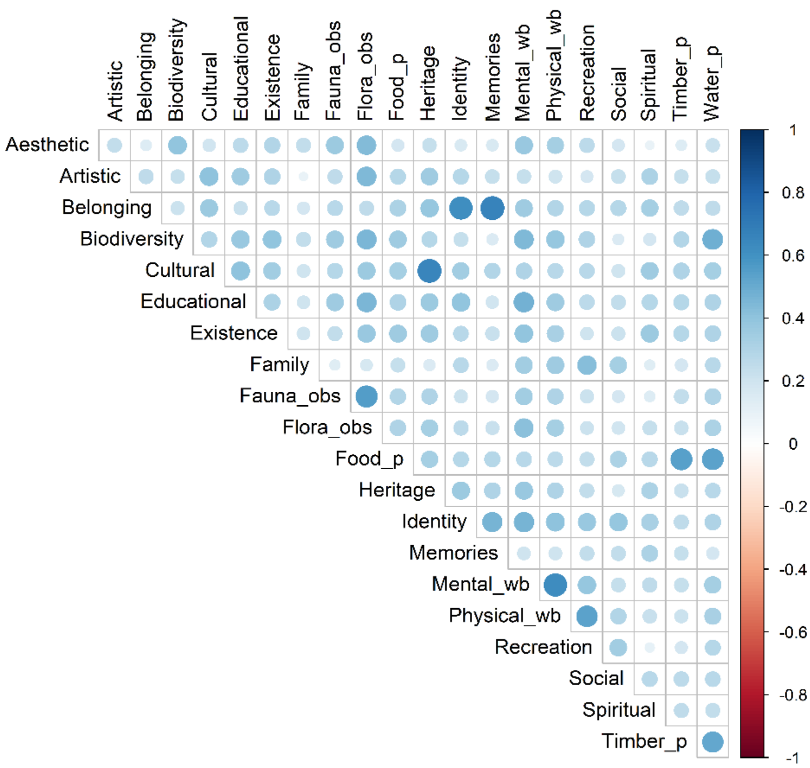

Figure 5.2.5. Pearson's Correlation at AD among ES with a significance level of p≤ 0.05. Size of the circles represent the strength of the correlation, the gradient represents the type of correlation (positive: blue, negative: red). The abbreviation "obs" means "observation", "wb" means "well-being", and "p" means "provision".

3.2. Familiarity with the concept of ES

Within the two PAs we obtained significant different values (p<0.001) in the overall familiarity with the concept of ES. At the PNGP, nearly half of the participants (43%) demonstrated a strong familiarity, while at the AD, only a small proportion (15%) exhibited a very low level of familiarity. Moreover, we investigated how the results were spread in the stakeholders' categories at the PAs (Supplementary materials, Table S.5.2.4). At the AD (Fig.5.2.6) the familiarity with the concept of ES was mostly higher in respondents related to the environmental field (e.g., Naturalistic associations and parks' workers). This result was found at the PNGP (Fig.5.2.7) as well, having environmental-related stakeholders were more familiar with ES. Other categories non-directly related to the environmental field, such as tourism workers and residents in the PA, resulted in more than 50% of users having a familiarity with the concept of ES. In both study areas users' that had familiarity with the concept, generally also recognised as ES the statements of the survey, reaching the recognition percentage around 83% of users at the PNGP and 81% at the AD.

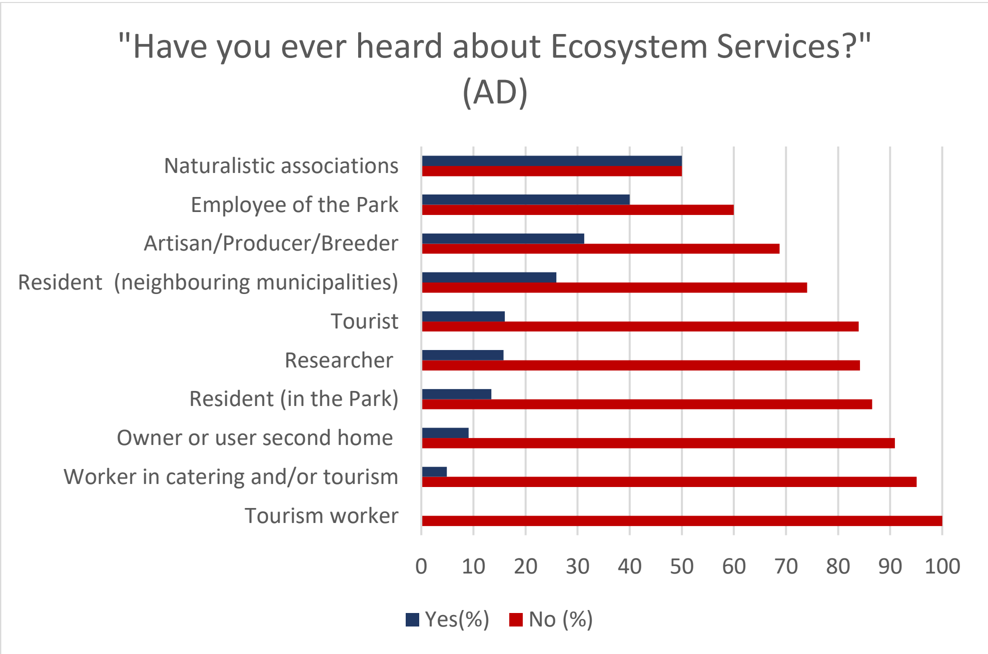

Figure 5.2.6. Percentages of familiarity with ES concept at the AD.

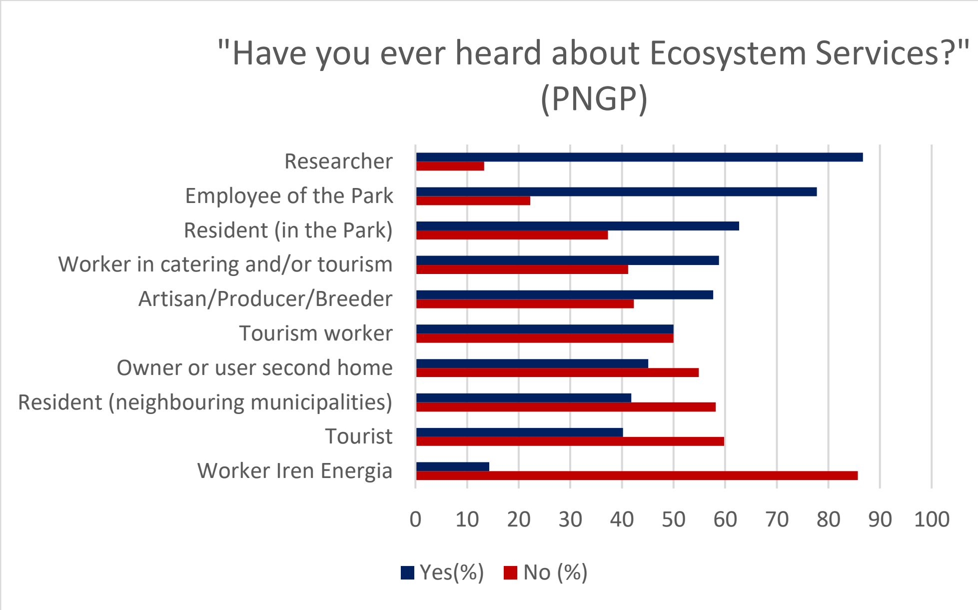

Figure 5.2.7. Percentages of familiarity with ES concept at the PNGP.

3.3. How the perceptions of PAs changed after COVID-19

In both PAs there was a very positive response to how the pandemic shaped their perception associated to the frequentation of PAs (Fig.5.2.8), with an emerging overall strong agreement of a new appreciation of natural areas. Z scores (Supplementary materials, Fig.S.5.2.1) showed an overlap of the results in both the PAs, indicating a similar trend of appreciation. From this, we can affirm that regardless of the area, the COVID-19 pandemic led users to appreciate PAs more. We performed a Chi^2 to assess whether there were significant differences between the two PAs, and we had no statistically significant results, confirming that both the areas had similar trends of variation in users change in perception after COVID-19 pandemic.

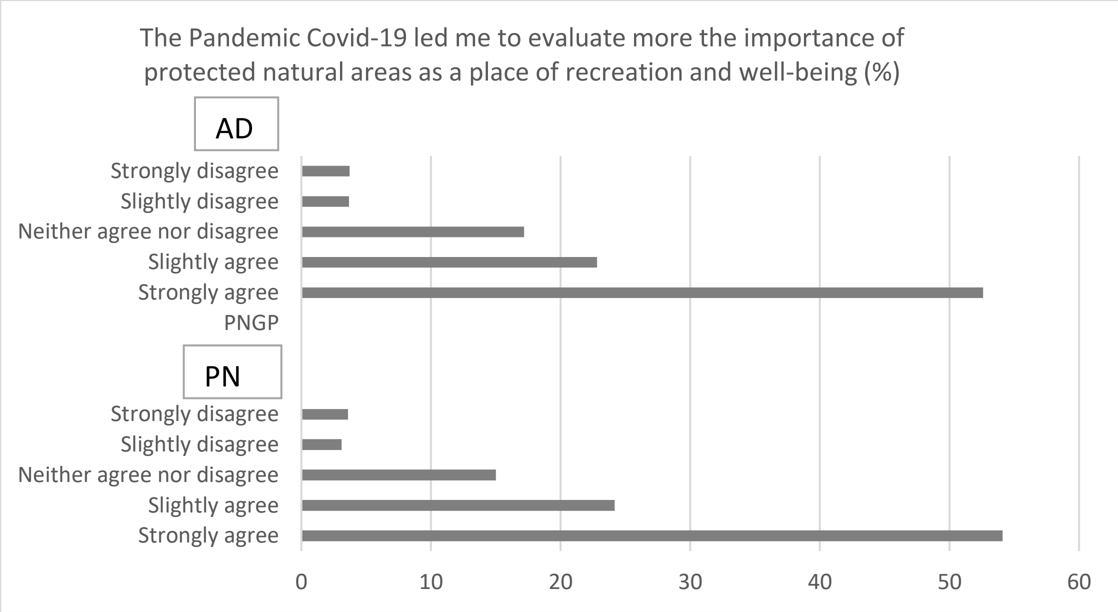

Figure 5.2.8. Results of changes in the perception of the importance of natural areas after COVID-19 pandemic

Considering the stakeholders' category, we found that at the AD there was an overall agreement reaching almost 50% of strong agreement answer in each stakeholder's category (Supplementary materials Table S.5.2.5), and 80% of total agreement, considering strong and slight agreement together. However, the category "employees of the park", showed a 40% of unchanged perception of the benefits. The highest agreement was found at the AD in the naturalistic association category (100% of strong agreement), while the lowest values were recorded in residents (48% of strong agreement). Interestingly, along with residents, tourists were the second group of stakeholders which declared lower scores for the development of a new positive perception. Regarding the PNGP, we did not have a complete agreement as for the AD considering the stakeholders' categories. Users that mostly appreciated nature after the pandemic were residents inside the park, with a strong agreement of 63%. Concerning the total agreement, the tourism worker category reached values close to 90% of consensus. The stakeholders that least perceived a change in the perception of nature were the ones that visit the park for working purposes that were not related to tourism, such as IREN Energy Workers, with a strong agreement only around the 20%, and 64% of a neutral response, but no strong disagreement was detected. Employees of the park reached an overall 67% of total agreement (strong and slight agreement). The highest percentages of strong disagreement were expressed by workers in restoration and tourism, reaching the 12% of their category.

3.4. Relationships between ES perception and users' profile

Depending on the stakeholders' categories a different perception of ES was found. The heatmaps (Fig.5.2.9) showed the average appreciation of ES ranging from 1 to 5, from low to high perception, clustering hierarchically the outcomes. It was interesting to note that there was an overall appreciation in all the stakeholders' categories of mental well-being, physical wellbeing, flora and fauna observation, biodiversity conservation and recreational values. Some services resulted to be more marginalised and perceived mostly by one category, this was the case of educational, artistic and cultural services at the AD, perceived mostly by naturalistic associations, or educational and existence value at the PNGP, perceived mostly by researchers. With this approach we could also note that some stakeholders' categories poorly perceive the ES provided by the PA, for instance, IREN energy workers gave the lowest ratings to ES at PNGP, with the exception of physical well-being.

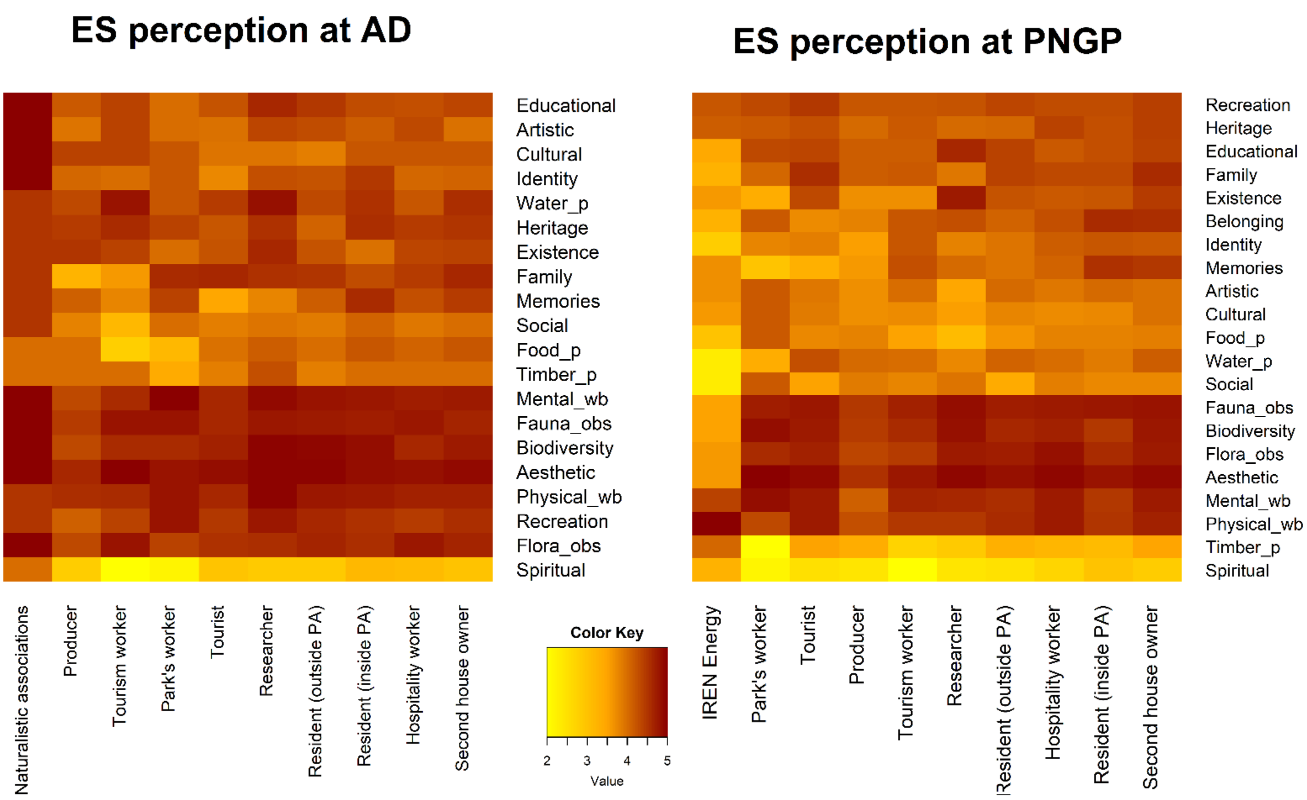

Figure 5.2.9. Heatmaps showing the perception of ES from the diverse categories of stakeholders on average, ranging from 1 (low perception) to 5 (high perception).

The ANOVA (Supplementary materials, Table S6, Table S7, Table S8) was carried out to detect significant differences in the perception of ES among users' biographical profiles and the perception of ES clustered into provisioning, regulating and cultural. It resulted that the ES perception varied among all the different profiles' features, in particular for cultural and provisioning services. At the AD we detected that profile features, such as age and gender, resulted in significant differences among all the three categories of ES (e.g., female and senior users stated an overall perception higher than males). The stakeholders' category resulted in significant values only for the CES. At the PNGP we detected similar trends than at AD, with significant variance between users' profile features, such as age, gender, stakeholders' and activities categories.

The forward stepwise multiple linear regression was undertaken to detect the relationships with the average perception of ES. The R^2 scores were 0.220 at the AD (Table 5.2.1) and 0.221 at PNGP (Table 5.2.2) indicating that the 22% of variance can be explained by our predictor variables in both PAs. The results showed that there was a positive significant relationship between a higher agreement in the perception of ES at the AD and senior visitors, recurrent visitors and female gender, whereas interesting negative relationships emerged within categories such as sport and enogastronomic mixed categories of activity. Remarkably, we detected a positive relationship in both the PAs with users that identified ES, indicating that users that were already familiar with the concept of ES also perceived ES more. Moreover, positive relationship was found with categories related to higher agreement in a new perception of PAs after the COVID-19, in fact a positive perception of the PAs after COVID (Likert_afterCovid) was one the second most important variable at the AD and first at the PNGP, suggesting a relevant relationship with the appreciation with ES. Regarding stakeholders' category, we detected positive relationship with researchers at the AD and tourists at the PNGP, a negative relationship as found at PNGP for IREN energy category.

Table 5.2.5.2.1. Results of multivariate linear regression analysis using the average ES appreciation as dependent variable at the AD. The codes "Likert_afterCovid" represented the positive appreciation after COVID, "Stk" represented the stakeholder category, "Act" referred to the activity type and "Recognition ES" referred to a positive reply to the recognition of ES in questionnaire.

AD

	B	Standard error	Beta	t	Sign.
Constant	3,352	0,074		45,158	0,000
Age	0,072	0,008	0,254	8,839	0,000
Likert_afterCovid	0,105	0,014	0,208	7,366	0,000
Frequency of visits	0,061	0,014	0,138	4,510	0,000
Gender	-0,109	0,030	-0,103	-3,659	0,000
Act_sport	-0,192	0,053	-0,100	-3,624	0,000
Duration	0,030	0,011	0,084	2,687	0,007
Stk_researcher	0,256	0,109	0,064	2,342	0,019
Act_food/sport	-0,234	0,101	-0,063	-2,308	0,021
Act_nature	-0,222	0,101	-0,060	-2,189	0,029
Recognition ES	0,091	0,042	0,060	2,149	0,032

R^2 score: 0.220

Table 5.2.2. Results of multivariate linear regression analysis using the average ES appreciation as dependent variable at the PNGP. The codes "Likert_afterCovid" represented the positive appreciation after COVID, "Stk" represented the stakeholder category, "Act" referred to the activity type and "Recognition ES" referred to a positive reply to the recognition of ES in questionnaire.

PNGP

	B	Standard error	Beta	t	Sign.
Constant	3,083	0,060		51,073	0,000
Likert_afterCovid	0,146	0,009	0,307	16,378	0,000
Frequency of visits	0,064	0,009	0,150	6,918	0,000

Age	0,043	0,006	0,147	7,745	0,000
Act_sport	-0,148	0,029	-0,095	-5,049	0,000
Recognition ES	0,088	0,020	0,084	4,490	0,000
Duration of stay	0,033	0,007	0,098	4,774	0,000
Act_nature	-0,199	0,047	-0,079	-4,275	0,000
Gender	-0,068	0,019	0,066	3,542	0,000
Stk_IREN energy worker	-0,385	0,124	-0,058	-3,097	0,002
Stk_tourist	0,068	0,022	0,063	3,054	0,002

R^2 score: 0.221

4. DISCUSSION

4.1.Perception of ES

Through the valuation of how visitors perceive ES provided by a natural protected area, managers could benefit by understanding visitors' preferences (Weixin Zhang et al., 2020), having insights of how people perceive the area, and on what to implement for resources allocation and management strategies. Moreover, it is expected that people that highly perceive ES in the area are more likely to support the management strategies (Whittaker et al., 2011), to enhance and safeguard the benefits provided. Hence, we aimed to identify which were the ES that mostly were perceived in two alpine PAs. The most perceived ES resulted to be the aesthetic value of the landscape, supporting evidences from literature regarding CES mountain area (Zoderer et al., 2016). The result is likely to be related to the provision of scenic landscape in mountain areas, generally more perceived in natural landscapes rather than in settlements and urban areas (Schirpke et al., 2016), and for the remoteness of the area (Schirpke, Tasser, et al., 2021). The aesthetic value was perceived even more than biodiversity conservation value, which ranked as second most perceived ES. Further research is needed to understand which landscape type could be considered as aesthetically beautiful for users, nevertheless this result must be carefully evaluated before being implied in the decision-making process. Moreover, it is important to note that the aesthetic value fundamentally rely on other categories of ES, and a management targeted on scenic beauty only could lead to an overall reduction in ES provision (Gamfeldt et al., 2013), affecting the entire ecosystem. Biodiversity conservation and observation values were notably perceived in both the PAs. This expected result aligns with the PAs objectives, underscoring that users were also conscious of the purpose of PAs and the supply of benefits related to biodiversity during their visits. This outcome highlighted that users not only are conscious of the crucial role of PAs in nature conservations, but also highly perceive these benefits, ranking them as the second most important, even more the outdoor and recreational services. This outcome holds the potential for a communication between managers and users concerning the need of nature conservation and management, using CES for making the public acceptance of management strategies easier (Peña et al., 2015; Qiu et al., 2013; Schenk et al., 2007), even when this implies limitations in human activities due to the possible conflicts with nature conservation (Bell et al., 2007). We partly confirmed the results of many studies which identify the recreational value of outdoor experiences in nature as one of the most perceived ES (Liu et al., 2017; Malchrowicz-Mośko et al., 2019; Schirpke, Scolozzi, et al., 2021) , however we identified a better agreement in the perception of other CES, more related to nature for its intrinsic value or the respondents' wellbeing (e.g., mental and physical wellbeing). Mental and physical well-being were widely perceived, reflecting the ongoing trend of visiting the natural areas for activities in natural landscapes (Bratman et al., 2019; Farkić & Taylor, 2019; Howell & Passmore, 2012; Malchrowicz-Mośko et al., 2019), considering them beneficial for personal well-being. Moreover, we detected that there were synergies between all the ES studies, showing an overall agreement in their perception, but some synergies resulted to be stronger, such as the inner ES (memories, belonging) or provisioning ES, suggesting that there could be the possibility of developing perceptions subordinate to the development of the perception of an ES, thus reducing the effort for communication strategies which could target on specific ES only.

It is widely acknowledged that CES are more perceived than regulating and provisioning services (García-Llorente et al., 2020), and the questionnaire confirmed this result, above all at the PNGP where the majority of regulating and provision values appeared in the ten least perceived. This result could be due to multiple factors, for instance, cultural values may be easier to perceive and understand by the public, whereas provision and regulating services might be considered abstract (Wei Zhang et al., 2015), or even difficult to understand. Another possibility could be related to the fact that the majority of respondents were tourists, thus these areas were mostly perceived as a supplier of recreation activities, instead of productive activities (e.g., timber production). Eventually, the spiritual value was mostly considered as a subordinate ES, again confirming the already existent literature (Zoderer et al., 2016), however we did not detect a sharp strong disagreement, we assume that some users' might perceive spirituality in these areas, perhaps due to the presence of sanctuaries on high elevations.

4.2. Familiarity with the concept of ES correlates with their recognition

This study showed significant differences between PAs, and user categories in the familiarity with the concept of ES. We detected that users related to environmental careers the most familiar with ES, and this was an expected result since we assume that during their activities they were related and worked the topic of ES, but it was interesting to note that depending on the PA, the percentage of familiarity changed; at PNGP most of park's workers had already heard about ES, whereas at the AD less than a half of the park's workers did. Lewan & Söderqvist, (2002), stated that without a wider recognition of ES in the public, we would not achieve an inclusion of the ES in policy making, hence it is crucial to widespread the concept of ES and develop divulgation campaigns that explain to the broader audience the concept ES and its advantages. The effectiveness of these communication campaigns could be increased focusing on the categories that do not acknowledge the concept of ES (Beery et al., 2016; Paul & Nagendra, 2017). Also, we detected that at the PNGP both local stakeholders and tourists were more likely to be familiar with the concept of ES, rather than the AD where the percentage dropped. We assume that the differences between the percentages of the PAs may be related to events carried out by the Parks and the presence of widespread information points on the park's area. As already stated, the PNGP has a wider popularity for being the first Italian National park and during time it has developed many divulgation events, in which residents were one of the main targets (Parco Nazionale del Gran Paradiso, n.d.). Even the AD has developed communication events, but the magnitude of these and the time lapse are reduced, hence we assume that this could be one of the factor affecting the different outcomes. Since the familiarity with the concept of ES is known as an efficient tool for supporting decision making (Breure et al., 2012), being useful for encompassing the natural capital into the decision-making process (Daily & Matson, 2008), and to help stakeholders in the management process (Daily et al., 2009), we stress the necessity of developing a more stratified communication strategy using ES as an educational tool for raising an awareness towards environmental topics (Beery et al., 2016), above all in smaller areas, aiming to engage also the marginalised stakeholders categories, such as people that visit the area for non-leisure purpose. This was evident for the category of IREN Workers, which attend the area mainly for working purposes, and recorder the lowest perception and familiarity of ES at the PNGP. It is fundamental to involve into these topics these other users' categories, and since ES are easy to understand even in people that do not have a prior knowledge of the topic (Lewan & Söderqvist, 2002b), we consider them as the tool for developing an awareness of the benefits provided (Beery et al., 2016) and to reinforce the current support of forest, having an higher engagement in conservation actions (Grêt-Regamey et al., 2012b).

4.3. Change after COVID

Due to the COVID-19 pandemic travel restrictions and lockdowns were undertaken, and this unequivocally led to a reduced possibility of people to experience nature, and the development of a nature deprivation (Colléony et al., 2022; Tomasso et al., 2021). We observed that users had an overall increased appreciation of natural areas after pandemic, considering them as places for leisure and well-being. Natural areas were places related to well-being even before the pandemic (Berman et al., 2008; Frumkin et al., 2017; Hartig et al., 2014; Rejeski, 1982), but through this study we could confirm the literature that states that after this particular period people felt an enhanced benefit from them (Beckmann-Wübbelt et al., 2021; Grima et al., 2020; Zhai & Lange, 2021). Categories related to attendance of PAs for leisure activities and environmental careers generally appreciate them more than people that visit the areas for working purposes, confirming that the appreciation could be affected by the stakeholders' category. We assume that users in an environmental career that declared a neutral change might be referring to a prior strong appreciation of the PAs value, thus no change was related to the pandemic. We would like to remark that other events of nature deprivation can occur, not only related to pandemics but also due to the vulnerability of these areas against climate change and the biodiversity reduction, that will lead to irrevocable changes of these environments (IPCC, 2022). This result was an interesting proxy on how the deprivation of nature rises in people an important reaction to feeling more connected to nature. This must be a fundamental point to appeal to the public consciousness during communication, trying to remind them of the feeling of deprivation of the benefits provided by these areas and pushing them to act sustainably, reflecting on the past crisis to act for a better future.

4.4. Perception of ES changes depending on the users' profile

We obtained significant differences in the perception of ES related to users' profile characteristics such as frequency of visits, duration of the stay, age, gender, stakeholder category and activities category, for both PAs, remarking that the appreciation of ES is linked with users' profile (Schirpke et al., 2022; Scolozzi et al., 2015; Small et al., 2017). We acknowledge that the perception of ES is a complex topic, and more variables are needed to have a fulfilling explanation, however we believe that our analysis has contributed meaningfully to our understanding of the topic and will help to make informed decisions and target actions to spread the knowledge of ES. We determined that age resulted to be one of the variables mostly positively related with higher values of ES perception, noting that older users perceived more the ES than younger users, and confirming the evidences in environmental psychology in which ecological awareness and behaviours were correlated to the age (Olli et al., 2001; Otto & Kaiser, 2014). Furthermore, also gender was positively related to the ES perception showing that women were more likely to perceive more ES rather than men, confirming this recurrent result in literature (Nowak-Olejnik et al., 2020; Plieninger et al., 2013; Schirpke et al., 2022). These aspects were fundamental to understand to whom environmental communication should target. For instance, we suggest engaging more young generations in the ES communications, such as promoting events that are likely to be appealing for young people, trying to find specific communications formats (Corner et al., 2015). The most interesting result concerned the positive appreciation of ES and the familiarity, both with the area and the concept of ES. Users that were recurrent visitors and staying for longer visits, could be considered as familiar with the PA (Rota et al., 2023), and were positively related with a positive perception of ES. Eventually, users' that developed a new positive perception of the natural area were also positively related with higher values in the perception. We can remark that the nature deprivation due to the COVID-19 may have led people to develop a new appreciation of the areas along with a new perception of them (Pichlerová et al., 2023; Tomasso et al., 2021) , resulting in higher scores in our questionnaires.

This study allowed to understand that familiarity with the concept of and their perception were correlated factors, and since through an awareness and perception of role played by the environment in our well-being, people could feel more involved in environmental issues and act more ecologically. We underline the need for communication that also involves the non-scientific community, ranging from managers to the public (Cartwright et al., 2016) . The correlations identified could be a guiding tool to target the audience that needs to be encompassed in such activities, for instance, trying to engage more young people and specific stakeholders' categories that still poorly perceive ES in the PAs, using ES knowledge as a tool for raising an improved environmental awareness. The concept of ES might have some uncertainties in its understanding by policy-makers and non-scientific audience, and being misunderstood could lead in the development of a sense of mistrust (Norgaard, 2010), for this reason scientist must communicate efficiently to the audience the topic of ES, leading the comprehension of complex ecological topics (Cartwright et al., 2016), using a facilitated language for non-scientific audiences (Heath & Heath, 2007; J. L. Thompson et al., 2016). Due to the many possibilities of using ES as a tool (Mckenzie et al., 2014), we believe that through the development of familiarity with ecosystem services, and environmental topics in general, users will develop an improved environmental awareness (Paul & Nagendra, 2017) and a pro-active behaviour in environmental safeguard (Kaiser et al., 1999), which are crucial aspects for the fight against the changes induced by human activities.

5. Conclusions

This project valuated the familiarity with the concept the ES concept and their perception by users attending two alpine protected areas, considering users' profiles, and additionally evaluating the effects of the COVID-19 pandemic on their appreciation of ES. In this study, it was possible to identify the most perceived ES in these protected areas, which resulted to be mostly related to the aesthetic value of landscape and biodiversity. Moreover, we detected that ES perception was dependent on users' categories, noting that some characteristics, such as the familiarity with the concept of ES, age, and gender were related to higher ratings in user perception of ES. This could be an incentive for targeting communication activities in the PAs, focusing on new formats and specific categories, to expand the perception potential of users visiting the areas and to develop awareness towards environmental topics, targeting the audience that had the most urgent need to be engaged.

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Supplementary materials

Table S.5.2.2. Stakeholders' categories and number of users.

Stakeholder category	Users AD	Users PNGP
Artisan/Producer/Breeder	16	26
Naturalistic associations (Botanica Rhaetica, etc)	2	0
Employee of the Park	5	9
Worker Iren Energia	0	14
Tourism worker	5	28
Worker in catering and/or tourism	61	68
Invalid reply	3	10
Owner or user second home in the Park (or nearby)	176	357
Resident (in the Park)	52	59
Resident (outside the Park but in neighbouring municipalities)	27	165
Researcher with activities in progress or carried out in the Park	19	30
Tourist	693	1574
Total	1059	2340

Table S.5.2.3. List of values considered in the study, in particular main category classification (category), ES as stated in the questionnaire (statement), class according to CICES V5.1 (class), code according to CICES V5.1 (Code) and the abbreviation of the class used along the paper (abbreviation)

Category	Statement	Explanation (CICES)	CICES Code	Abbreviation
Provision	For me it is important that the Park produces food (e.g. registered trademark products, local products)	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	1.1.1.1 - 1.1.6.1	**Food production**
	For me it is important that the Park produces wood	Cultivated plants (including fungi, algae) grown as a source of energy	1.1.1.3	**Timber provision**
Cultural	The Park gives me the opportunity to do recreational activities (sports, relaxation...)	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	3.1.1.1	**Recreational activities**
	These places contribute to my physical well-being (it allows me to do activities that make me feel physically better, breath pure air, ...)		3.1.1.1	**Physical well-being**
	In the Park I like to observe animals	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	3.1.1.2	**Animal observation**
	In the Park I like to observe plants and flowers		3.1.1.2	**Plants observation**

	The Park helps me to know better the flora and fauna and to understand the ecosystems	Characteristics of living systems that enable education and training	3.1.2.2	**Biodiversity knowledge**
	I have memories of life linked to these places that are very important to me	Characteristics of living systems that are resonant in terms of culture or heritage	3.1.2.3	**Memories values**
	The Park contains a cultural heritage that I consider very important (traditions, customs, history, ...)		3.1.2.3	**Cultural heritage**
	The Park allows me to know the culture and history of my country		3.1.2.3	**Cultural value**
	In the Park I like to observe the beauty of the landscape	Characteristics of living systems that enable aesthetic experiences	3.1.2.4	**Aesthetic value of the landscape**
	These places arouse in me a sense of belonging (I feel 'at home', I have a deep sense of familiarity)	Elements of living systems that have symbolic meaning	3.2.1.1	**Sense of belonging**
	This place is important for me from a spiritual/religious point of view (it allows me to pray, it has spiritual symbolic elements)	Elements of living systems that have sacred or religious meaning	3.2.1.2	**Spiritual/religious value**
	This place has an intrinsic value to the fact that it exists, no matter what I or others get out of it. I value the fact that it exists and will exist in the future.	Existence/bequest values	3.2.2.1	**Intrinsic value of existence**
	These places contribute to my mental well-being (it makes me feel good)	Others	3.3.X.X	**Mental well-being**
	These places allow me to create new social relationships (e.g. meeting new people)		3.3.X.X	**Meeting new people**
	The Park for me is an important source of artistic inspiration (photography, painting, music...)		3.1.X.X	**Artistic inspiration**
	These places allow me to express my identity (here I feel myself, I can express who I am through the activities I can carry out)		3.3.X.X	**Identity expression**
	These places allow me to spend time with my family/friends		3.3.X.X	**Family value**
Regulation	For me it is important that the Park preserves the biodiversity of fauna and flora	Maintaining nursery populations and habitats (Including gene pool protection)	2.2.2.3	**Biodiversity conservation**
	For me it is important that the Park contributes to providing drinking water	Ground (and subsurface) water for drinking	4.2.1.1	**Fresh water regulation**

Table S.5.2.4. Results of users' familiarity with the concept of ES in percentage and number of respondents (in brackets).

	AD		PNGP	
Have you ever heard of "Ecosystem services" ?	**Yes**	**No**	**Yes**	**No**
Artisan/Producer/Breeder	31% (5)	69% (11)	58% (15)	42 % (11)
Naturalistic associations	50% (1)	50% (1)	\	\
Employee of the Park	40% (2)	60% (3)	78% (7)	22% (2)
Worker Iren Energia	\	\	14% (2)	86% (12)
Tourism worker	0	100% (5)	50% (14)	50 % (14)
Worker in catering and/or tourism	5% (3)	95% (58)	59% (40)	42% (28)
Owner or user second home in the Park (or nearby)	9% (16)	91% (160)	45% (161)	55 % (196)
Resident (in the Park)	13% (7)	87% (45)	63% (37)	37% (22)
Resident (outside the Park but in neighbouring municipalities)	26% (7)	74% (20)	42% (69)	58% (96)
Researcher with activities in progress or carried out in the Park	16% (3)	84% (16)	87% (26)	13% (4)
Tourist	16% (111)	84% (582)	40% (633)	60% (941)
Total	15% (155)	85% (901)	43% (1004)	57% (1326)

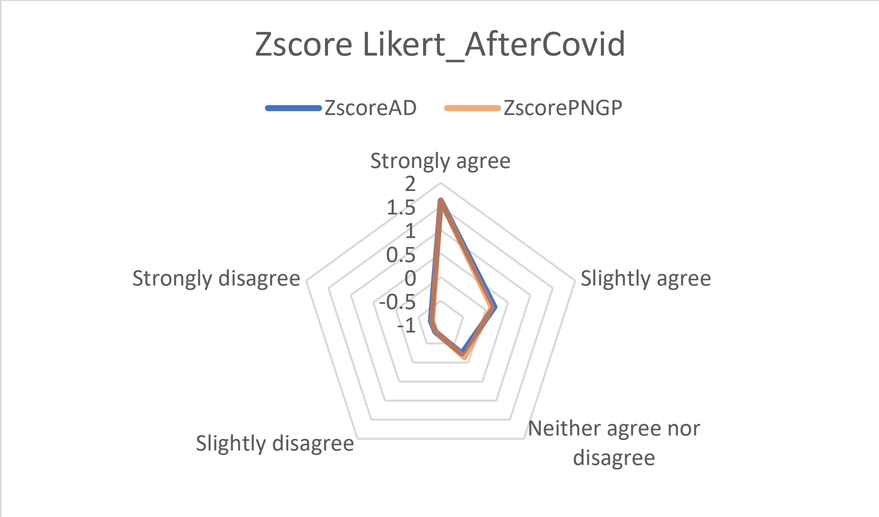

Figure S.5.2.1. Zscores of average values of the appreciation of PAs after the COVID-19 pandemic, in blue the AD and in orange the PNGP.

Table S.5.2.5. Results of users' changes of appreciation of natural protected areas after covid (in percentage).

	PNGP					AD				
The Pandemic Covid-19 led me to evaluate more the importance of protected natural areas as a place of recreation and well-being (%)	**Strongly agree**	**Slightly agree**	**Neither agree nor disagree**	**Slightly disagree**	**Strongly disagree**	**Strongly agree**	**Slightly agree**	**Neither agree nor disagree**	**Slightly disagree**	**Strongly disagree**
Artisan/Producer/Breeder	42%	19%	19%	15%	4%	69%	13%	13%	0%	6%
Employee of the Park	33%	33%	22%	11%	0%	60%	0%	40%	0%	0%
Naturalistic associations (Botanica Rhaetica, etc)	\	\	\	\		100%	0%	0%	0%	0%
Worker Iren Energia	21%	14%	64%	0%	0%	\	\	\	\	
Tourism worker	57%	32%	7%	0%	4%	80%	0%	0%	0%	20%
Worker in catering and/or tourism	60%	9%	18%	1%	12%	64%	20%	16%	0%	0%
Owner or user second home in the Park (or nearby)	57%	20%	15%	6%	1%	66%	19%	14%	2%	0%
Resident (in the Park)	63%	10%	17%	5%	5%	62%	17%	12%	8%	2%
Resident (outside the Park but in neighbouring municipalities)	45%	30%	20%	2%	2%	48%	15%	30%	4%	4%

Researcher with activities in progress or carried out in the Park	50%	20%	30%	0%	0%	68%	11%	11%	0%	11%
Tourist	52%	24%	17%	3%	4%	49%	28%	15%	3%	5%

Table S.5.2.6. Results of the ANOVA and significance at AD and PNGP

		Variables AD		Variables PNGP	
		F	Sig.	F	Sig.
Frequency					
	Cultural	18.571	0.000	49.209	0.000
	Provision	7.932	0.000	2.128	0.095
	Regulating	1.572	0.194	0.810	0.488
Duration					
	Cultural	13.026	0.000	20.718	0.000
	Provision	7.774	0.000	2.448	0.044
	Regulating	2.969	0.019	1.994	0.093
Age					
	Cultural	21.168	0.000	21.433	0.000
	Provision	8.506	0.000	2.381	0.027
	Regulating	6.619	0.000	11.201	0.000
Gender					
	Cultural	16.510	0.000	18.904	0.000
	Provision	9.580	0.002	6.197	0.002
	Regulating	12.315	0.000	4.845	0.008
Stakeholder					
	Cultural	3.847	0.000	4.901	0.000
	Provision	1.377	0.185	7.655	0.000
	Regulating	1.525	0.125	1.998	0.030

Activities					
	Cultural	3.643	0.000	8.054	0.000
	Provision	1.942	0.019	7.839	0.000
	Regulating	1.159	0.302	11.172	0.000

Table S.5.2.7. Descriptive statistics for the ANOVA at the AD.

DESCRIPTIVE STATISTICS ANOVA ADAMELLO

			N	Average	Standard Deviation	Standard Error
Frequency						
	C_aver	First time	205	4,050	0,562	0,039
		Less than 3 times	283	4,151	0,522	0,031
		More than 3 times	119	4,212	0,522	0,048
		Recurrent	452	4,353	0,506	0,024
	P_aver	First time	205	3,746	1,112	0,078
		Less than 3 times	283	3,894	0,884	0,053
		More than 3 times	119	3,870	0,960	0,088
		Recurrent	452	4,106	0,890	0,042
	R_aver	First time	205	4,541	0,684	0,048
		Less than 3 times	283	4,569	0,613	0,036
		More than 3 times	119	4,504	0,817	0,075
		Recurrent	452	4,628	0,639	0,030
Duration						
	C_aver	Overnight	395	4,107	0,553	0,028
		Two days	110	4,196	0,573	0,055
		One week	262	4,220	0,482	0,030
		Two weeks	102	4,390	0,540	0,053
		More than 2 weeks	190	4,402	0,478	0,035
	P_aver	Overnight	395	3,791	1,000	0,050
		Two days	110	4,118	0,848	0,081
		One week	262	3,895	0,930	0,057
		Two weeks	102	4,216	0,776	0,077
		More than 2 weeks	190	4,134	0,958	0,069
	R_aver	Overnight	395	4,496	0,699	0,035
		Two days	110	4,623	0,640	0,061

		One week	262	4,626	0,558	0,034
		Two weeks	102	4,701	0,577	0,057
		More than 2 weeks	190	4,611	0,760	0,055
Age						
	C_aver	<20	202	3,948	0,557	0,039
		21-30	219	4,091	0,567	0,038
		31-40	100	4,264	0,509	0,051
		41-50	200	4,345	0,422	0,030
		51-60	175	4,372	0,497	0,038
		61-70	89	4,449	0,410	0,043
		<70	70	4,397	0,529	0,063
	P_aver	<20	202	3,671	0,951	0,067
		21-30	219	3,790	0,959	0,065
		31-40	100	3,910	0,962	0,096
		41-50	200	4,100	0,884	0,063
		51-60	175	4,097	1,022	0,077
		61-70	89	4,337	0,726	0,077
		<70	70	4,093	0,910	0,109
	R_aver	<20	202	4,403	0,753	0,053
		21-30	219	4,493	0,747	0,050
		31-40	100	4,610	0,571	0,057
		41-50	200	4,643	0,548	0,039
		51-60	175	4,609	0,692	0,052
		61-70	89	4,809	0,508	0,054
		<70	70	4,800	0,469	0,056
Gender						
	C_aver	Female	588	4,284	0,520	0,021
		Male	471	4,150	0,547	0,025
	P_aver	Female	588	4,034	0,946	0,039
		Male	471	3,852	0,953	0,044
	R_aver	Female	588	4,645	0,638	0,026
		Male	471	4,502	0,687	0,032
Stakeholder						
	C_aver					
		Artisan/Producer/Breeder	16	4,125	0,904	0,226
		Naturalistic associations (Botanica Rhaetica, etc)	2	4,735	0,374	0,265
		Employee of the Park	5	4,306	0,192	0,086
		Tourism worker	5	4,153	0,359	0,161

	Worker in catering and/or tourism	61	4,352	0,570	0,073
	Owner or user second home in the Park (or nearby)	176	4,368	0,486	0,037
	Resident (in the Park)	52	4,395	0,416	0,058
	Resident (outside but neighbouring municipalities)	27	4,325	0,539	0,104
	Researcher with activities in progress or carried out in the Park	19	4,378	0,394	0,090
	Tourist	693	4,157	0,536	0,020
P_aver					
	Artisan/Producer/Breeder	16	4,000	1,438	0,359
	Naturalistic associations (Botanica Rhaetica, etc)	2	4,000	0,000	0,000
	Employee of the Park	5	3,300	0,837	0,374
	Tourism worker	5	3,400	0,652	0,292
	Worker in catering and/or tourism	61	4,041	1,112	0,142
	Owner or user second home in the Park (or nearby)	176	4,099	0,826	0,062
	Resident (in the Park)	52	4,096	0,913	0,127
	Resident (outside but neighbouring municipalities)	27	3,926	1,191	0,229
	Researcher with activities in progress or carried out in the Park	19	4,211	0,713	0,164
	Tourist	693	3,900	0,953	0,036
R_aver					
	Artisan/Producer/Breeder	16	4,313	1,153	0,288
	Naturalistic associations (Botanica Rhaetica, etc)	2	4,750	0,354	0,250
	Employee of the Park	5	4,400	0,418	0,187
	Tourism worker	5	4,700	0,447	0,200
	Worker in catering and/or tourism	61	4,426	0,836	0,107
	Owner or user second home in the Park (or nearby)	176	4,645	0,624	0,047
	Resident (in the Park)	52	4,702	0,478	0,066

		Resident (outside but neighbouring municipalities)	27	4,630	0,614	0,118
		Researcher with activities in progress or carried out in the Park	19	4,895	0,209	0,048
		Tourist	693	4,565	0,665	0,025
Activity						
	C_aver	Relaxing	9	4,261	0,614	0,205
		Cultural tourism	7	4,261	1,071	0,405
		Cultural and nature tourism	30	4,147	0,535	0,098
		Cultural and sports tourism	30	4,257	0,486	0,089
		Cultural and gastronomic tourism	3	4,373	0,148	0,085
		Cultural/gastronomic/naturalistic tourism	35	4,197	0,386	0,065
		Cultural/food and wine/sports tourism	21	4,045	0,498	0,109
		Cultural/naturalistic/sports tourism	91	4,282	0,523	0,055
		Food and wine tourism	17	3,990	0,512	0,124
		Gastronomic and naturalistic tourism	23	3,944	0,510	0,106
		Food and wine/ nature/ sports tourism	72	4,077	0,457	0,054
		Nature tourism	22	4,019	0,629	0,134
		Natural tourism and sport	107	4,184	0,610	0,059
		Sport tourism	86	4,032	0,550	0,059
		All categories	506	4,316	0,511	0,023
		Totale	1059	4,225	0,536	0,016
	P_aver	Relaxing	9	3,944	0,982	0,327
		Cultural tourism	7	4,071	1,058	0,400
		Cultural and nature tourism	30	3,817	0,942	0,172
		Cultural and sports tourism	30	4,050	0,986	0,180
		Cultural and gastronomic tourism	3	4,333	0,577	0,333
		Cultural/gastronomic/naturalistic tourism	35	3,929	0,940	0,159
		Cultural/food and wine/sports tourism	21	3,881	0,947	0,207
		Cultural/naturalistic/sports tourism	91	3,692	1,102	0,116

	Food and wine tourism	17	3,824	0,900	0,218
	Gastronomic and naturalistic tourism	23	4,065	0,921	0,192
	Food and wine/ nature/ sports tourism	72	3,785	0,813	0,096
	Nature tourism	22	3,977	0,945	0,201
	Natural tourism and sport	107	3,734	1,106	0,107
	Sport tourism	86	3,890	1,102	0,119
	All categories	506	4,083	0,866	0,039
	Totale	1059	3,953	0,953	0,029
R_aver	Relaxing	9	4,611	0,601	0,200
	Cultural tourism	7	4,143	1,029	0,389
	Cultural and nature tourism	30	4,700	0,407	0,074
	Cultural and sports tourism	30	4,700	0,596	0,109
	Cultural and gastronomic tourism	3	4,833	0,289	0,167
	Cultural/gastronomic/naturalistic tourism	35	4,571	0,596	0,101
	Cultural/food and wine/sports tourism	21	4,500	0,548	0,120
	Cultural/naturalistic/sports tourism	91	4,560	0,691	0,072
	Food and wine tourism	17	4,500	0,468	0,113
	Gastronomic and naturalistic tourism	23	4,500	0,657	0,137
	Food and wine/ nature/ sports tourism	72	4,514	0,628	0,074
	Nature tourism	22	4,500	0,772	0,164
	Natural tourism and sport	107	4,519	0,749	0,072
	Sport tourism	86	4,436	0,804	0,087
	All categories	506	4,637	0,638	0,028

Table S.5.2.8. Descriptive statistics for the ANOVA at the PNGP.

DESCRIPTIVE STATISTICS ANOVA PNGP

			N	Average	Standard Deviation	Standard Error
Frequency						
	C_aver	First time	441	4,133	0,517	0,025
		Less than 3	397	4,246	0,471	0,024
		More than 3	341	4,249	0,576	0,031
		Recurrent	1161	4,444	0,483	0,014
	R_aver	First time	441	4,619	0,640	0,030
		Less than 3	397	4,582	0,602	0,030

		More than 3	341	4,506	0,718	0,039
		Recurrent	1161	4,548	0,692	0,020
	P_aver	First time	441	3,847	1,027	0,049
		Less than 3	397	3,845	0,966	0,048
		More than 3	341	3,789	0,992	0,054
		Recurrent	1161	3,882	1,004	0,029
Duration						
	C_aver	Overnight	766	4,216	0,568	0,021
		Two nights	349	4,315	0,485	0,026
		One week	473	4,302	0,465	0,021
		Two weeks	229	4,418	0,426	0,028
		More than two weeks	523	4,464	0,505	0,022
	R_aver	Overnight	766	4,532	0,707	0,026
		Two nights	349	4,563	0,641	0,034
		One week	473	4,604	0,583	0,027
		Two weeks	229	4,657	0,561	0,037
		More than two weeks	523	4,522	0,754	0,033
	P_aver	Overnight	766	3,807	1,016	0,037
		Two nights	349	3,784	1,045	0,056
		One week	473	3,884	0,942	0,043
		Two weeks	229	3,967	0,930	0,061
		More than two weeks	523	3,902	1,022	0,045
Age						
	C_aver	<20	230	4,081	0,574	0,038
		21-30	346	4,185	0,489	0,026
		31-40	302	4,257	0,478	0,027
		41-50	451	4,383	0,422	0,020
		51-60	481	4,412	0,511	0,023
		61-70	369	4,414	0,533	0,028
		>70	161	4,457	0,594	0,047
	R_aver	<20	230	4,496	0,671	0,044
		21-30	346	4,517	0,637	0,034
		31-40	302	4,488	0,681	0,039
		41-50	451	4,560	0,654	0,031
		51-60	481	4,603	0,655	0,030
		61-70	369	4,606	0,695	0,036
		>70	161	4,661	0,762	0,060
	P_aver	<20	230	3,685	0,969	0,064
		21-30	346	3,689	0,984	0,053
		31-40	302	3,699	1,027	0,059
		41-50	451	3,785	1,033	0,049
		51-60	481	3,944	0,938	0,043
		61-70	369	4,069	0,971	0,051
		>70	161	4,199	0,991	0,078

Gender						
	C_aver	F	1258	4,382	0,510	0,014
		M	1062	4,252	0,519	0,016
		Rather not reply	20	4,459	0,399	0,089
	R_aver	F	1258	4,606	0,653	0,018
		M	1062	4,508	0,696	0,021
		Rather not reply	20	4,600	0,447	0,100
	P_aver	F	1258	3,915	0,983	0,028
		M	1062	3,786	1,018	0,031
		Rather not reply	20	3,800	0,834	0,186
Stakeholder						
	C_aver	Artisan/Producer/Breeder	26	4,111	0,815	0,160
		Employee of the Park	9	4,248	0,667	0,222
		Worker Iren Energia	14	3,861	0,690	0,184
		Tourism worker	28	4,258	0,772	0,146
		Worker in catering and/or tourism	68	4,369	0,470	0,057
		Owner or user second home in the Park (or nearby)	357	4,462	0,520	0,028
		Resident (in the Park)	59	4,395	0,548	0,071
		Resident (outside the Park but in neighbouring municipalities)	165	4,301	0,553	0,043
		Researcher	30	4,310	0,376	0,069
		Tourist	1574	4,301	0,492	0,012
	R_aver	Artisan/Producer/Breeder	26	4,365	0,807	0,158
		Employee of the Park	9	4,278	0,939	0,313
		Worker Iren Energia	14	3,286	1,340	0,358
		Tourism worker	28	4,429	0,900	0,170
		Worker in catering and/or tourism	68	4,456	0,776	0,094
		Owner or user second home in the Park (or nearby)	357	4,566	0,656	0,035
		Resident (in the Park)	59	4,331	0,968	0,126
		Resident (outside the Park but in neighbouring municipalities)	165	4,473	0,714	0,056
		Researcher	30	4,417	0,644	0,118
		Tourist	1574	4,604	0,621	0,016
	P_aver	Artisan/Producer/Breeder	26	3,846	0,946	0,186
		Employee of the Park	9	3,444	0,982	0,327
		Worker Iren Energia	14	3,786	0,671	0,179
		Tourism worker	28	3,464	1,045	0,197
		Worker in catering and/or tourism	68	3,772	1,186	0,144
		Owner or user second home in the Park (or nearby)	357	3,908	0,955	0,051
		Resident (in the Park)	59	3,737	1,233	0,161
		Resident (outside the Park but in neighbouring municipalities)	165	3,739	1,015	0,079

		Researcher	30	3,367	1,098	0,200
		Tourist	1574	3,886	0,985	0,025
Activities						
	C_aver	Relaxing	4	3,838	0,807	0,404
		Cultural tourism	9	3,935	1,223	0,408
		Cultural and nature tourism	10	4,329	0,342	0,108
		Cultural and sports tourism	63	4,270	0,422	0,053
		Cultural and gastronomic tourism	4	4,074	0,757	0,378
		Cultural/gastronomic/naturalistic tourism	3	4,137	0,434	0,250
		Cultural/food and wine/sports tourism	45	4,403	0,437	0,065
		Cultural/naturalistic/sports tourism	355	4,424	0,443	0,023
		Food and wine tourism	29	4,197	0,409	0,076
		Gastronomic and naturalistic tourism	3	4,333	0,238	0,137
		Food and wine tourism and sports	60	4,144	0,559	0,072
		Food and wine/ nature/ sports tourism	300	4,328	0,397	0,023
		Nature tourism	101	4,104	0,674	0,067
		Nature and sports tourism	494	4,288	0,490	0,022
		Sports tourism	287	4,169	0,630	0,037
		All categories	563	4,453	0,494	0,021
		Relaxing	4	4,125	0,854	0,427
	R_aver	Cultural tourism	9	4,111	1,294	0,431
		Cultural and nature tourism	10	4,700	0,675	0,213
		Cultural and sports tourism	63	4,413	0,704	0,089
		Cultural and gastronomic tourism	4	4,125	1,436	0,718
		Cultural/gastronomic/naturalistic tourism	3	4,667	0,577	0,333
		Cultural/food and wine/sports tourism	45	4,578	0,630	0,094
		Cultural/naturalistic/sports tourism	355	4,662	0,535	0,028
		Food and wine tourism	29	4,466	0,706	0,131
		Gastronomic and naturalistic tourism	3	4,833	0,289	0,167
		Food and wine tourism and sports	60	4,408	0,710	0,092
		Food and wine/ nature/ sports tourism	300	4,655	0,530	0,031
		Nature tourism	101	4,436	0,839	0,083
		Nature and sports tourism	494	4,474	0,681	0,031
		Sports tourism	287	4,331	0,870	0,051
		All categories	563	4,723	0,547	0,023
		Invalid	10	2,400	1,410	0,446

		Relaxing	4	3,250	1,323	0,661
	P_aver	Cultural tourism	9	3,778	1,253	0,418
		Cultural and nature tourism	10	4,100	0,810	0,256
		Cultural and sports tourism	63	3,563	1,057	0,133
		Cultural and gastronomic tourism	4	3,625	1,548	0,774
		Cultural/gastronomic/naturalistic tourism	3	3,667	0,289	0,167
		Cultural/food and wine/sports tourism	45	4,133	0,822	0,122
		Cultural/naturalistic/sports tourism	355	3,934	0,932	0,049
		Food and wine tourism	29	4,069	0,842	0,156
		Gastronomic and naturalistic tourism	3	3,667	1,528	0,882
		Food and wine tourism and sports	60	3,808	0,992	0,128
		Food and wine/ nature/ sports tourism	300	3,972	0,901	0,052
		Nature tourism	101	3,713	1,152	0,115
		Nature and sports tourism	494	3,554	1,055	0,047
		Sports tourism	287	3,618	0,996	0,059
		All categories	563	4,192	0,871	0,037

CHAPTER 6

CONCLUSION AND FUTURE PERSPECTIVES

Synthesis and future perspectives

The protection of mountain regions has been the focus of increasing attention in recent years due to their vulnerability to climate change. Ecosystem services have emerged as a comprehensive tool for evaluating the benefits provided by ecosystems and for further supporting their protection by quantifying their material and non-material values, including their economic worth. Ecosystem services are considered a holistic tool, as they include social, economic and environmental valuations, taking into account the complex interactions that exist in ecosystems. In addition, these services introduce a novel perspective, incorporating cultural benefits that individuals experience and non-material benefits that are of fundamental importance, particularly in the management of protected areas. In fact, cultural ecosystem services have been observed to cultivate a sense of belonging among individuals, potentially resulting in increased engagement with nature conservation efforts.

One of the critical ecosystem services provided by mountain regions is the climate regulation service, usually valued using the carbon stock as indicator. However, often valuations of carbon stock are carried out using inventory data, coarse dataset or indirect measurements. Through fieldwork activities it was possible to quantify the organic carbon stock in two mountain protected areas, giving a quantitative description of how this stock changed among habitats. The collection of metadata during fieldwork activities resulted fundamental for the valuation of correlations with the stocks, to provide a description of the environmental features that may be critical for the carbon stock accumulation. Overall, forested habitats, particularly coniferous forests, resulted to be the most stocking habitats of both our study areas. Nonetheless, important contributions were found in alpine grasslands, habitats that often are overlooked in the accounting of carbon stock and resulted to be an extremely important carbon sink, beyond being fundamental for biodiversity conservation. From the literature review, it emerged that studies on the evaluation of the carbon stock are carried out using indirect approaches, and a lack of in situ data regarding carbon stock quantities among habitats exists, particularly regarding soils, that were found to be the highest stocking carbon pool in the Alps. This study demonstrated their high importance in providing the climate regulation service, and more attention should be given to in situ measurement of carbon stock. Moreover, a huge number of approaches that exist for the evaluation of ecosystem services, and even for the same ES multiple indicators and output can be found, as described in the literature review. This leaves an uncertainty in the possible comparisons and shareability of the results. To be able to demonstrate how different approaches for the same ecosystem service can give very different outcomes, a comparison of three approaches (fieldwork data, national inventory, TESSA) was undertaken, and it was confirmed that the outcome had very diverse magnitudes in some cases. A common agreement on how to evaluate ecosystem services must be found. As widely mentioned, forests resulted to be the most important habitats for the provision of the climate regulation service, and for this reason it emerged the interest in exploring how forests changed over time in the main study area, the Adamello regional park. There is a common agreement regarding the increase of forested areas in the northern hemisphere, mostly due to land abandonment for high elevation agriculture. However, the change of forested coverage directly impacts the provision of ecosystem services, hence the trends of forest cover dynamics in the local area were studied, and hypothesis regarding the provision of ES. The study confirmed that the trends occurring in the study area were similar to the trends occurring in all the Alps, with an increase in forested habitats. At a glance this result seemed to be a positive result, but going deeply into the possible explanations, one main reason could be the increase of a fast-growing shrubs, as the *Alnus viridis*, and the changes in the provision of ES should be investigated. As ecosystem services encompass not just biophysical evaluations, but also social values, a study on the cultural ecosystem services in two protected areas in the Alps was conducted. Tourism is one important occupation of these areas and can be considered both as an opportunity for generating an economic income for the development of the area, and a driver of pressure on these fragile environments. Again, metadata was fundamental to profile the users and to understand users' attitudes towards the attendance of the protected area and their perception of ES. First, through the study of managers perceptions using semi-structured interviews, it was discovered that the issue of mass tourism is a matter of concern for them. Then, from the questionnaire and the metadata collected, it resulted that users are actually carrying out short term stays and increasing the pressure on these areas, and mass tourism was confirmed as an ongoing trend. Then, correlations between the features that characterize mass tourism and users' profile were found, generally correlated with young visitors and on their first visit at the area. Hence, an investigation on the perception of 21 ecosystem services (cultural, provisioning, regulating) was carried out. The aesthetic value of the landscape was the most perceived ecosystem service, and the result was attended since the study took place in a natural protected area and prior study demonstrated its high perception.

However, biodiversity conservation emerged as second main perceived ecosystem service, even more than recreational value, opening to the consideration of a protected area that goes beyond the personal and anthropic usage. This results suggest that people may be ready to understand that in some cases to preserve biodiversity and the integrity of ecosystems, some waivers may be done, such as the limitation of outdoor activities in reproductive season. However, regulating and provisioning services were poorly perceived, and some communication efforts must be done to explain that these services are fundamental for human existence. Also, it resulted that a higher overall perception of ecosystem services was found in users that already acknowledged the concept of ES, and in stakeholders that have environmental-related jobs, whereas poor perception of ecosystem services was found in young and male users. These results can help in targeted communication strategies and are reinforced by the outcome that through knowledge also the perception can improve, leading to an improved environmental awareness.

In conclusion, the research presented here enhances the knowledge of ecosystem services in mountain protected areas and serves for further research questions. Some of the future research directions are detailed below:

a) *Development of a model that estimates the carbon stock in mountain areas*: fieldwork data were fundamental for having a description of the current status of a Mediterranean and an Alpine protected area, as seen in Chapter 2 and 3. However, there is a need to extend this type of study also to other protected areas, and in the surrounding areas, to better detect the current supply of carbons stock in mountain areas. Fieldwork data collection is time and resources intensive, and the feasibility of undertaking such studies in all the mountain regions is very low. By using the fieldwork data and the relative metadata on the study area as training points, the development of a model using machine learning could be an option, and fieldwork activities will be more related to the gathering of training data and measuring the accuracy of the model using validation data.
b) *Estimation of biomass using fine-resolution satellite data:* remote sensed imagery resulted fundamental for describing the trends of land cover change in terms of forest a non-forest, as discussed in Chapter 4. Landsat data were utilised due to their vast temporal resolution, allowing a decadal change study since the establishment of the protected area at the Adamello. However, through finer-resolution satellite data it will be possible to describe the vegetation cover more accurately. As data on biomass were

collected in Chapter 2, these could be the training set for a biomass study, in which through random forest regression on maps with a correct vegetation cover, it will be possible to estimate the biomass changes and to describe the hierarchical correlations with the metadata. If any correlation with the Landsat data will emerge, there will be the possibility to carry out a decadal change of biomass on the Adamello, hence, to estimate the aboveground biomass carbon stock.

c) *Implement the understanding of cultural ecosystem services:* mountain areas are hotspots for the provision of multiple cultural ecosystem services, and as described in Chapter 5, most of the user's perceived the aesthetic value of the landscape as the most present ES in the study areas. It will be of a great importance to carry out monitoring of the perception and attitudes of users in protected areas over time. Along with proper communication strategies, as suggested in Subchapter 5.2., the monitoring through questionnaires would be of a great importance to comprehend if users' are progressing in the ES perception and knowledge, or if a diverse strategy could be carried out. An idea could be the development of an online application, that also collects the GPS location of the respondents in order to create maps of the supply areas in the PAs.

Figure 6.1.. Resume of the contribution of the current thesis to the topic of ecosystem services in mountain protected areas

Annex I

A review of methods and indicators for the evaluation of mountain ecosystem services

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Abstract

Ecosystem services (ES) assessment is a fundamental subject in ecology, and there is a proliferation of studies worldwide aiming toward ES valuation and assessment. Although a copious variety of methods and indicators exists to assess ES, there is a lack of shared standardization that greatly limits our capacity to produce comparable studies and thus advance ES understanding and monitoring. The aim of this paper is to conduct a literature review of the current indicators and methods used to evaluate mountain ES. Moreover, we examined whether the most used indicators are also the 'better' indicators by their compliance with the following parameters: i - significance, and representativeness; ii - simplicity and cost; iii – replicability and reliability; iv - ease of interpretation; v - policy relevance. Using ISI Web of Knowledge we selected published papers between 2015-2020 containing the words "ecosystem services" and "mountains" and resulting in 965 papers; of them, only 350 effectively applied at least one indicator to evaluate ES. For each article, we extracted the following information: type of ES evaluated, indicator(s) used, input data used, type of valuation (whether ecological, economic or social – and the indication of the method for economic and social valuation, i.e. market price method), the scale of analysis (local, regional, national, global), country, mapping (yes/no) and finally we indicated if the paper provides solutions or suggestions for management based on the ES valuation. Results showed that the most frequently measured ES are regulating and provisioning services. Europe and Asia were the most frequent continent studied and the scale of analysis was mainly local or regional. The most frequently used indicators were evaluated through an expert-based analysis to detect their suitability. Generally, there was a high heterogeneity of indicators used for the same ES and in nomenclature, highlighting the necessity of finding a standardization of the methods used to assess ES.

Appendix A

1. Peer reviewed publications

- **Rota, N.,** Canedoli, C., Fava, M., & Padoa Schioppa, E. (2023). Introducing children in the primary school to the concept of ecosystem services. VISIONS FOR SUSTAINABILITY, 2023(19).
- **Rota, N.,** Canedoli, C., Azzimonti, O. L., & Padoa-Schioppa, E. (2023). How Do People Experience the Alps? Attitudes and Perceptions in Two Protected Areas in Italy. Sustainability, 15(4), 3341.
- Bonardi, A., Ficetola, G. F., Razzetti, E., Canedoli, C., Falaschi, M., Lo Parrino, E., **... Rota. N** & Sindaco, R. (2022). ReptIslands: Mediterranean islands and the distribution of their reptile fauna. Global Ecology and Biogeography, 31(5), 840-847.

2. National and international conferences

- Presentation at *Ecologia del paesaggio oltre i confini. Teoria e pratica nel governo del territorio tra norme vincoli e piani* , Stia (AR) 28-30 settembre 2023, "The decadal forest-nonforest changes at the Adamello Regional Park using LANDSAT scenes", **N.Rota**, N. Neeti, H. Nagendra, C.Canedoli, E. Padoa-Schioppa.
- Presentation at XXXII° Congresso della Società Italiana di Ecologia, "Carbon stock evaluation in a Mediterranean mountainous area: the case of the Troodos massif, Cyprus" **N. Rota**, P. Manolaki, I.N. Vogiatzakis , C. Ferré, R. Comolli, D. Abu El Khair, C. Canedoli, E. Padoa-Schioppa.
- Presentation at *IALE World Congress 11th IALE World Congress – 2023,* Nairobi, Kenya, 10th – 15th, July 2023, "The evaluation and mapping of ecosystem services in a mountain protected area: the case of the climate regulation service at the Adamello Regional Park (Italy)", **N. Rota.,** C. Canedoli, C. Ferré, R. Comolli, D. Abu El Khair, E. Padoa-Schioppa.

- Presentation at *4th ESP Europe Conference,* Heraklion, Greece, 10-14 October 2022, "Evaluation of Carbon Stock in alpine protected areas: a comparison of different methods" **N. Rota ,** C. Canedoli , I. N. Vogiatzakis, E. Padoa-Schioppa.
- Presentation at *XXXI° Congresso della Società Italiana di Ecologia, Adattamenti degli Ecosistemi alle Pressioni dell'Antropocene*, "Evaluation and mapping of Ecosystem Services in alpine protected areas: the cases of the Gran Paradiso National Park and Adamello Regional Park (Italy)", **N. Rota**, C. Canedoli, E. Padoa-Schioppa.
- Presentation at *IALE 2022 European Landscape Ecology Congress*, Poland (online), 11-15 July 2022, "Soil biodiversity conservation: evaluation of the alpine edaphic soil fauna using eDNA metabarcoding", **N.Rota**, C.Canedoli, E.Padoa-Schioppa
- Presentation at *I paesaggi italiani verso il 2030: identità, cura e prospettive* SIEP-IALE national congress, Palermo, 25-27 November 2021, "Valutazione dei servizi ecosistemiciculturali in aree alpine protette" **N.Rota**, C.Canedoli, E. Padoa-Schioppa
- Presentation at *Sustainable Biomasses and Climate Change* summer school, Milan, 19-22October 2021, "Evaluation of the climate regulation ecosystem service in an alpine protected area" **N.Rota**, C. Canedoli, E. Padoa-Schioppa.
- iPoster presentation: "Disentangling the linkages between forest attributes, biodiversity and ecosystem services", *2020-IALE North America Annual Meeting Virtual Remote*, **N.Rota,** C.Canedoli, E.Padoa-Schioppa. ConferenceURL: https://2020toronto-ialena.ipostersessions.com/default.aspx?s=9C-51-98-CAD8-33-28-75-09-E6-25-70-62-03-AD-80