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Assessing the carbon stock in the Alps: Considerations on three different approaches

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ABSTRACT

Alpine protected areas provide a wide range of ecosystem services, with climate regulation being one of the most significant. In line with the European Biodiversity Strategy for 2030, which emphasizes the conservation and enhancement of ecosystem services, 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 carbon storage, a widely used indicator of the climate regulation service. In this study three approaches were compared: fieldwork data collection, the Italian National Inventory and the TESSA toolkit. Discrepancies in the results emerged, in the Aosta Valley, TESSA reported 423 Gg for OC stock in mixed broadleaves, compared to 263 Gg from field data and 210 Gg from the National Inventory. Fieldwork data collection, while the most accurate, was the most time and resource intensive. The national inventory yielded values similar to fieldwork data; for example, in the Adamello spruce forest, the National Inventory reported 1838 Gg, while field data measured 1964 Gg. However, TESSA depicted qualitatively the same organic carbon stock distribution across the habitats compared to the other approaches. Based on the results, we propose different applications for these approaches, considering the advantages and disadvantages of each. Specifically, we suggest using the TESSA toolkit for preliminary and a qualitative screening of a study area to identify potential areas of interest for the carbon stock, while more precise but demanding approaches should be employed for local studies.

1. Introduction

The current geological epoch, known as the Anthropocene, is unequivocally having a negative impact on biodiversity and ecosystems. In response, the European Biodiversity Strategy for 2030 (European Commission, 2021a) proposes ambitious objectives for biodiversity and ecosystem conservation. Among these objectives, the need for restoring degraded ecosystems and protect the already existing carbon-storing ecosystems, such as forests and wetlands. The strategy aims to halt biodiversity loss, support the recovery of nature, and address key drivers of biodiversity loss (Hermoso et al., 2022). Specific goals include increasing the area of protected land and sea, reducing pollution, and integrating biodiversity considerations across all policy areas.

The Ecosystem Services (ES) concept is recognized as valuable support for policy makers and managers in decision-making and monitoring activities (Duarte et al., 2016; Goldman & Tallis, 2009; Goldman, Tallis, Kareiva, & Daily, 2008), promoting a more comprehensive understanding of ecosystems by incorporating multiple factors. Due to their relevance, there is a growing demand for their evaluation, even within national and local policies (Naturale, 2018; Maes et al., 2013). Hence, it is essential to understand how ES are provided and how to support and improve their supply, to aid in achieving the Biodiversity Strategy aims. Additionally, other initiatives are currently ongoing for the conservation and restoring of ecosystems, such as the EU Forest Strategy 2030 (European Commission, 2021b) – strictly linked European Biodiversity Strategy for 2030 and key initiative of the European Green Deal – that proposes to plant 3 billion additional trees and avoid poor land management, such as deforestation and unsustainable forestry practices, to enhance the organic carbon (OC) storage and its positive effects on biodiversity and ecosystems. However, before implementing these

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procedures, it is pivotal to understand the current knowledge of OC stock and its distribution among habitats and ecosystem services provision (Abeli & Di Giulio, 2023). In general, the European Green Deal (COM/2019/640), which targets European climate neutrality by 2050, emphasizes the importance of enhancing carbon sequestration and biodiversity. A key element in this effort is the use of carbon credits, which provide financial incentives for conservation and sustainable land management practices that increase OC storage and mitigate climate change (Alcasena et al., 2021), further underscoring the necessity for accurate carbon stock assessment.

Protected Areas (PAs) play a fundamental role in the supply of many Ecosystem Services (ES) (Eastwood et al., 2016; MEA, 2005). The European Alps span nearly 1,200 km across Europe, featuring mountain peaks that reach above 4,000 m, and their ecosystems are crucial for the provision of ES (Crouzat et al., 2019; Grêt-Regamey, Brunner, & Kienast, 2012a), but they are also highly vulnerable to the effects of climate change (IPCC, 2022). 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., in Prep).

Although ES were introduced to the public over two decades ago (Costanza et al., 1997), there is still 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; Czúcz et al., 2018; Egoh et al., 2012) and to uncertainties regarding the magnitude of ES supply. Particularly, 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. Field data collections are certainly fundamental for an appropriate description of the actual OC stocks of an area and their distribution, but these are generally time and resources consuming (Petrokofsky et al., 2012). In some cases, limited resources may hinder the choice of higher resolution for the studies (Peh, Balmford, Bradbury, Brown, Butchart, Hughes, Stattersfield, Thomas, & Walpole 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 aimed for each study, which may vary, either depending on the extent of the study area or the peculiarity of the study (Waage & Stewart, 2008). For policy makers, different methodologies may be better suited to specific objectives. For example, fieldwork approaches are particularly effective for reporting to National inventories or local decision making, as they provide high-resolution, accurate descriptions of OC stocks that are crucial for localized assessments. On the other hand, large-scale approaches such as remote sensing or estimation toolkits enable comparisons among wider areas, offering broader but less detailed insights that can be instrumental for international policy comparisons and large-scale monitoring efforts (Forkuor et al., 2017; Mulder et al., 2011).

In this study, we aimed to i) identify the differences in the OC stock using diverse approaches on different habitats within the study areas, and ii) to reach conclusions about the effort for obtaining the outcomes for each approach. We assessed 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 & Balmford et al., 2013a), a widely used toolkit for the rapid assessment of ES. We aimed to understand how different methodologies affect OC stock evaluations to informed assessment and monitoring strategies. Depending on the purpose and study area, one methodology might be more suitable than another within specific time and budget constraints. We investigated these diverse approaches to analyse their outcomes and provide recommendations for OC stock assessment, ensuring proper descriptions within available resources and time. We did not seek to evaluate which approach is superior in a general context, but rather to investigate the differences in 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. 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 belonging to a research line of the Laboratory of Landscape Ecology of the University of Milano Bicocca on the assessment of ES in mountain protected areas.

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, with the peak of Adamello being its highest point. The park, covering an area of 51,000 ha, 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 beyond 2,000 m.a.s.l of elevation. Unlike other sedimentary mountain complexes in the Southern Alps, the rocks of the Adamello Group have a magmatic, intrusive origin. The primary magmatic rocks found in the Adamello include quartz diorites, coarse-grained tonalites, and granodiorites. Based on the field data collected during the study, the main soil types of the Adamello are Cambisols, Histosols, Kastanozems, Luvisols, Phaenozems, Podzols, Regosols and Umbrisols. Temperatures vary significantly with altitude. In the lower areas, such as the lowlands of Valle Camonica, winters are cold but not extremely harsh, and summers are mild. At higher altitudes, very low temperatures and with heavy snowfalls are present during winters, while summers remain cool. The park's precipitation pattern is typical of the alpine areas, with abundant rainfall during the autumn and spring months.

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. It is regulated under the Framework Law 394/91. Its area is 71.043,79 ha, covering two regions – Piedmont (PDM) and the Aosta Valley (AV) – 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 for 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 forests, spruce forests, alpine grasslands, mixed coniferous forests, chestnut forests and mixed deciduous forests. The average climate of the area is typically alpine, characterized by low mean temperatures and annual rainfall regimes that ranges from about

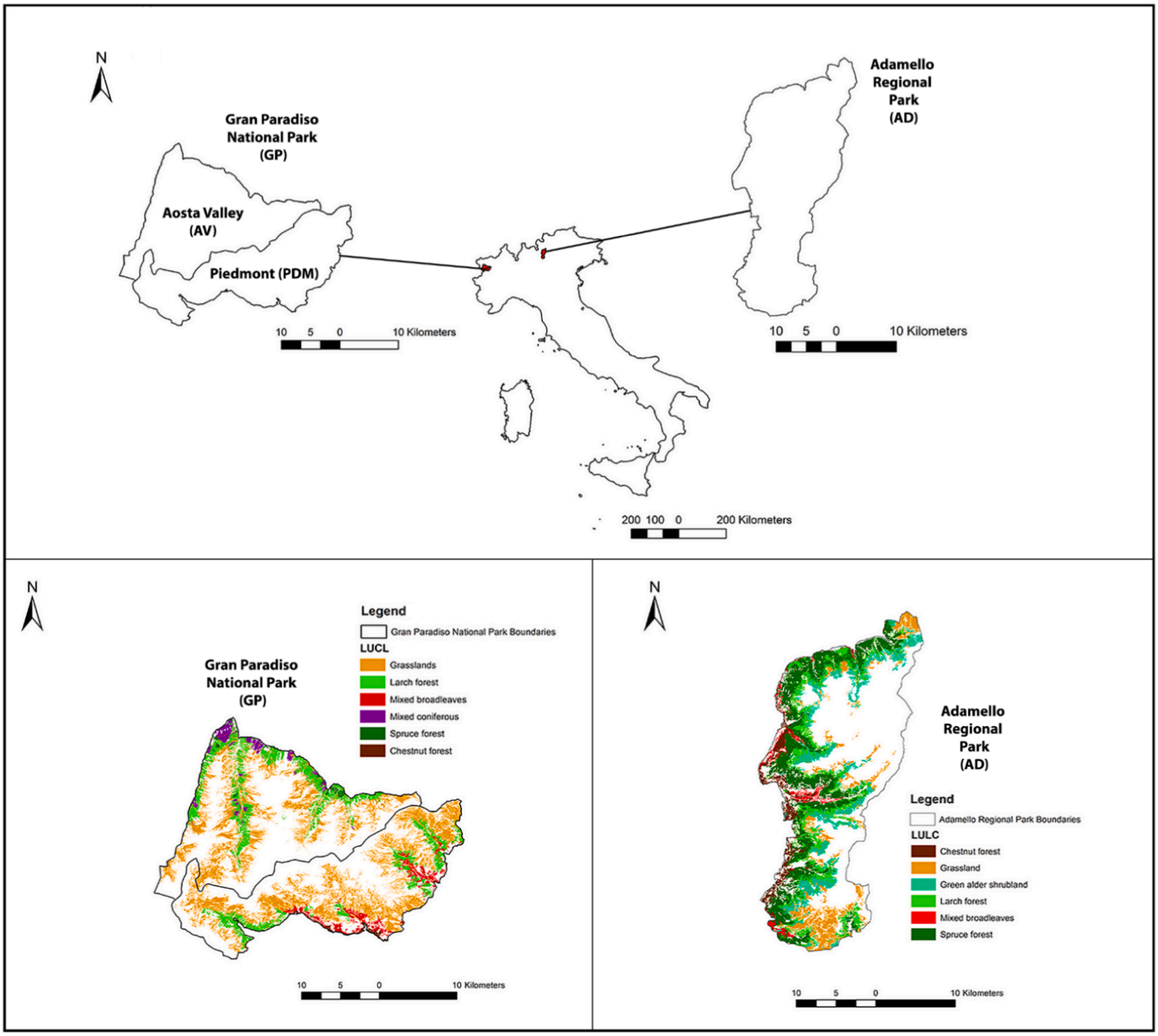

Fig. 1. Above: Maps of the study areas, with Gran Paradiso National Park to the west and Adamello Regional Park to the east. Below: Maps of the habitat types considered in the study.

550 mm in the continental Aosta Valley to 1200–1400 mm in Piedmont, influenced by Mediterranean humid air masses. The mountain range consists of various types of rocks, primarily metamorphic (gneiss and greenstones), along with glacial sediments (moraines). Based on the field data collected the soil types of the Gran Paradiso Nation Park are Cambisols, Fluvisols, Kastanozems, Leptosols, Phaenozems, Podzols, Regosols and Umbrisols.

In this study we 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 (PDM and AV), we will have diverse OC stock values for each carbon pools studied (soil, litter and above-ground biomass) (Gasparini & Tabacchi, 2011) and habitat since the regions of the Aosta Valley and the Piedmont 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, and from 2021 to 2022 at AD. 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 1), in order to yield a representative description of each PA, selecting only the habitats that covered at least 5 % of the total area, using the habitat area provided by the Land Use Land Cover (LULC) maps. The baselines for our selection were the habitat maps provided by the PAs (Nazionale, 2019b) and the regional geoportals. 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

Table 1
Description of the habitats sampled using the classification for TESSA, fieldwork and the INFC, and their extent in ha, obtained from the LULC maps.

IPCC, 2006 **Ecological Zone** (IPCC, 2006)	**FAO Ecological zone** (FAO, 2012)	**Type**	**Habitat type** (Nazionale, 2019b; Regione Lombardia, 2023)	**INFC habitat** (Gasparini & Tabacchi, 2011)	**Area AD (ha)**	**Area AV (ha)**	**Area PDM (ha)**
Cold temperate moist	**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

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 (Lombardia, 2023). 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 the AV (Fig. S2) and 114 in the AD (Fig. S1). Each plot was 30x30m in size, chosen through a stratified random sampling design.

Soil, tree aboveground biomass (AGB) and litter data were collected according to Canedoli et al. (2020). 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}).

At each plot, mineral soil samples were collected from three minipits at standard depths (0–10 cm, 10–20 cm, 20–40 cm) and combined to form a composite sample of each layer. For each layer, the volumetric rock fragment content was estimated visually. Soil samples were air dried, sieved through a 2 mm mesh, crushed, sieved to a finer mesh (0.5 mm) and analysed for total carbon (TC) using an elemental analyser (Flash EA 1112 NCSoil, Thermo Fisher Scientific, Pittsburgh, PA, USA). To account for soil organic carbon (SOC), we measured total inorganic carbon (TIC) in samples with pH > 7.0 using the volumetric gas method (Dietrich-Frühling calcimeter; Swift, 1996). SOC was then calculated as the difference between TC and TIC.

Volumetric samples (volume 100 cm^3) of undisturbed soil were also collected for bulk density (BD) determination; the collected volumetric samples were placed in an oven at 105 °C for 24 h and weighed. In the presence of rock fragments, the volume and mass of the soil were reduced proportionally to obtain the BD of fine soil ($<$ 2 mm diameter). Where the bulk density samples were could not be collected, BD was estimated using pedotransfer functions (Ferré et al., 2023; Fig. S3). The SOC content (%) was converted to SOC stock (kg m^{-2}) considering the soil BD and the mean percentage volume of rock fragments in each layer (Agaba et al., 2024).

Corresponding to each minipit, organic samples were also collected from an area of 18x18 cm in three horizons: OL, OF and OH. The organic samples were oven dried at 70 °C for 48 h and then weighed; the organic carbon content was determined using the NC elemental analyzer and converted to content on an area basis (kg m^{-2}).

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 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., 2006). For the Lombardy region 74 plots were sampled, 36 for Aosta Valley and 123 for Piedmont (Gasparini & Tabacchi, 2011).The methods used for the quantification of organic carbon stored in the INFC were comparable to the methods we used during our field activities, since we used the INFC protocol as reference, 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. We identified the model that best interpreted our data points – primarily linear, power and logarithmic – for the SOC content. Our results were reported 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 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, Balmford, Bradbury, Brown, Butchart, Hughes, Stattersfield, Thomas, & Walpole et al., 2013).

The toolkit multiplies the values of OC stock for the specific LULC class by the area. First, we converted our LULC classification into TESSA habitat types, according to the IPCC (2006) and FAO Ecological Zones

(Table 1) (FAO, 2012). 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 (15 Mg ha^{-1}). All the AGB values were referenced to IPCC (2003). For broadleaves forests and chestnut forests the values were 200 Mg ha^{-1}, while larch forest, mixed coniferous and spruce forest had 175 Mg ha^{-1} of biomass values. To calculate the total above-ground live biomass carbon stock (Mg ha^{-1}) of each 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 for broadleaves and 26 Mg/ha 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), referenced from Jobbágy and Jackson (2000) and Bernoux et al. (2002). The soil types we collected were identified as High Activity Clay (HAC; Leptosols, Phaeozems, Cambisols, Umbrisols, Regosols) and Spodic soils (Podzols). Values for HAC OC stock in 0–30 cm depth were 95 Mg ha^{-1} and 155 Mg ha^{-1} in Spodic soils. 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

Statistical analyses were conducted using non-parametric analyses since the normal distribution was not met for all the methods and pools. We utilized the Mann-Whitney *U* test, also known as the Wilcoxon rank sum test, to assess differences between two independent groups (Mann & Whitney, 1947). 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. To determine the minimum number of plots required for fieldwork suggestions, 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), which is an indicator of how much the error in predicting a value compared to the real value, and we aimed to evaluate the change in the error with an increasing sampling effort.

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 Version 10.8 (Booth & Mitchell, 2001), one for each approach, assigning to each LULC class the corresponding average OC stock value. 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

3.1. TESSA toolkit

Concerning AGB, the TESSA method (Table S2) consistently estimated 87.5 Mg ha^{-1} for coniferous forest and 100 Mg ha^{-1} for broadleaves forest, except for *Alnus viridis* shrubland in AD (Fig. 4) with 7.5 Mg ha^{-1}. For soil OC stock, TESSA estimated 95 Mg ha^{-1} for grasslands, mixed coniferous forest, and larch forest, and 115 Mg ha^{-1} for spruce forest. In PDM (Fig. 2), TESSA consistently estimated soil OC stock at 95 Mg ha^{-1} across all forest types. In AD, TESSA consistently estimated soil OC stock at 95 Mg ha^{-1} for all habitats except larch forest, which was estimated at 115 Mg ha^{-1}. Litter OC stock was estimated at 26 Mg ha^{-1} for coniferous forests and 16 Mg ha^{-1} for broadleaves forests.

3.2. Fieldwork Data

Fieldwork data (Tables S2 and S3) in the AV (Fig. 3) measured AGB OC stock at 63.7 Mg ha^{-1} for larch forest, 95.2 Mg ha^{-1} for spruce forest, and 90.1 Mg ha^{-1} for mixed coniferous forest. Soil OC stock was measured at significantly lower values, with 28.8 Mg ha^{-1} for spruce forest. Litter OC stock showed 7.4 Mg ha^{-1} for larch and mixed coniferous forests, and 12.4 Mg ha^{-1} for spruce forest. In PDM (Fig. 2) fieldwork data measured AGB OC stock at 70.3 Mg ha^{-1} for larch forest, 95.7 Mg ha^{-1} for chestnut forest, and 70.2 Mg ha^{-1} for mixed broadleaves. Soil OC stock was 36.3 Mg ha^{-1} for larch forest and 42.9 Mg ha^{-1} for chestnut forest. Litter OC stock was 6.7 Mg ha^{-1} for larch forest and lower values for other forest types. In AD (Fig. 4), fieldwork data measured AGB OC stock at 115 Mg ha^{-1} for mixed deciduous forest and 113 Mg ha^{-1} for spruce forest. Soil OC stock showed 51.6 Mg ha^{-1} for chestnut forest and 76.5 Mg ha^{-1} for larch forest. Litter OC stock was 20.5 Mg ha^{-1} for spruce forest, and the lowest value was found for mixed deciduous forest (5.3 Mg ha^{-1}). Fieldwork data also reported maximum, minimum, and standard deviation values (Table S3) for each study area and habitat type.

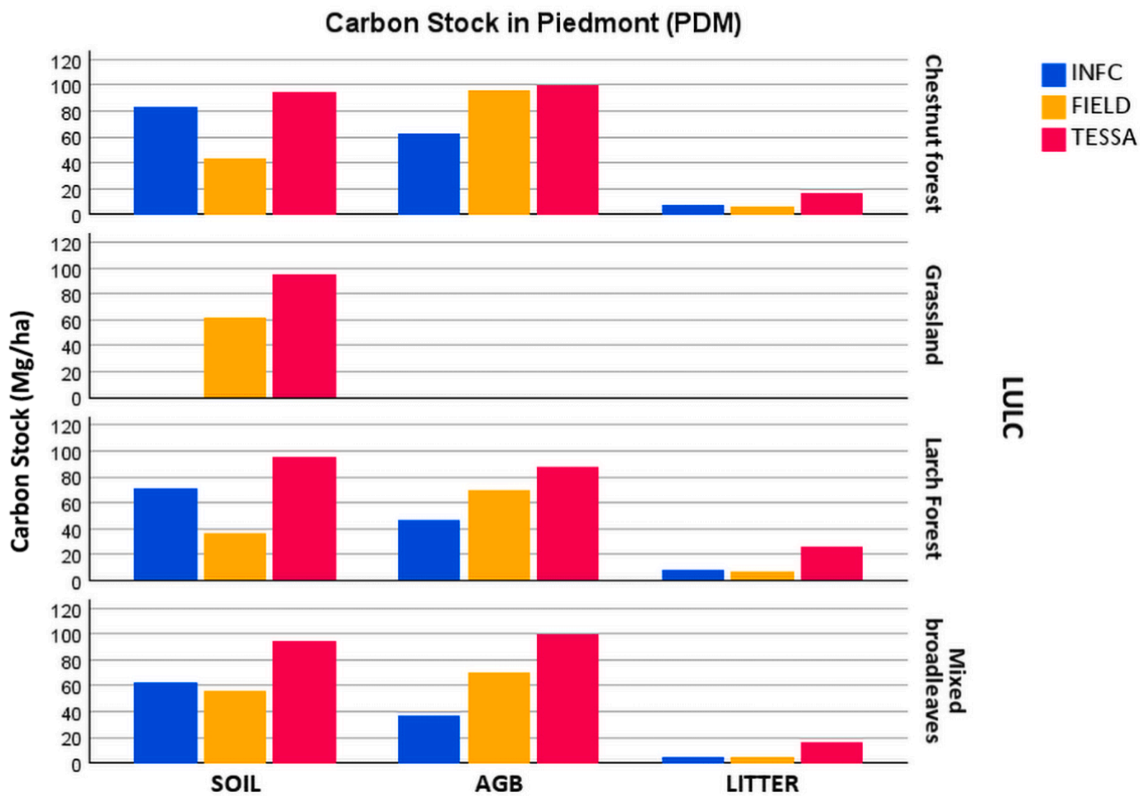

Fig. 2. Output from each methodology (fieldwork, INFC and TESSA) of the average OC stock (Mg/ha) per each pool and habitat type in Piedmont.

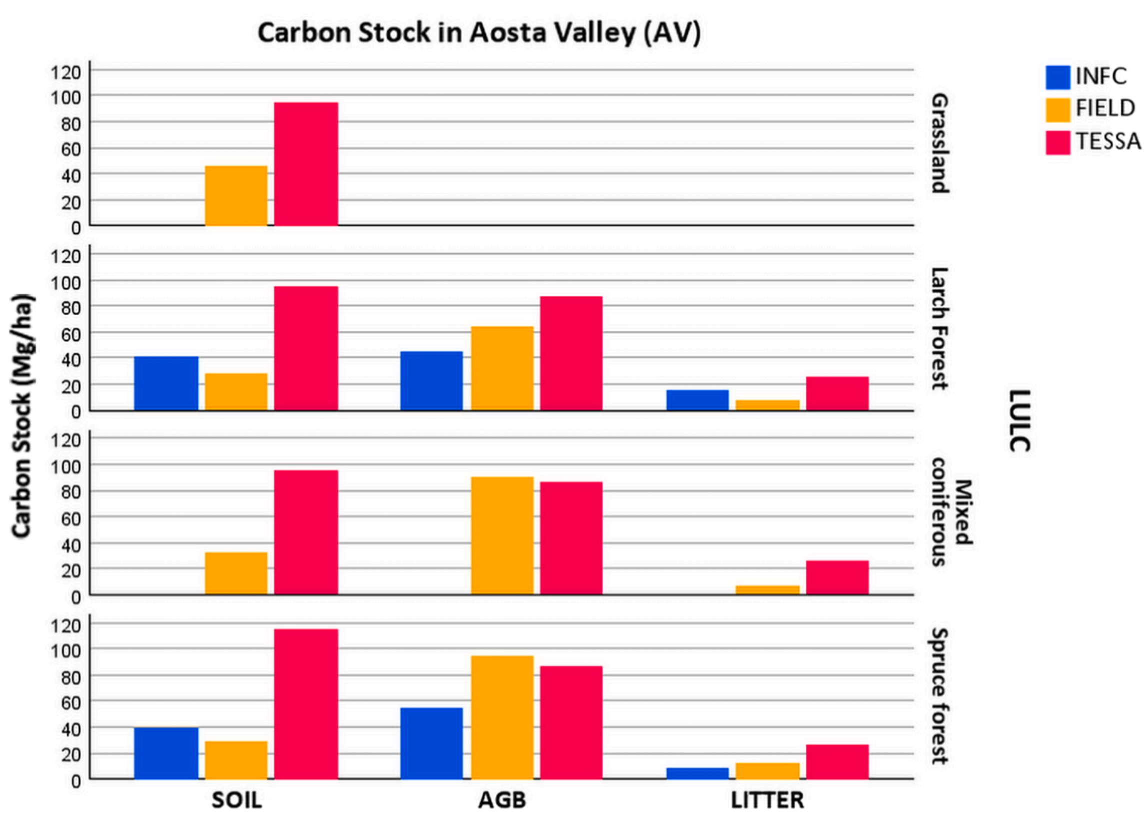

Fig. 3. Output from each methodology (fieldwork, INFC and TESSA) of the average OC stock (Mg/ha) per each pool and habitat type in the Aosta Valley.

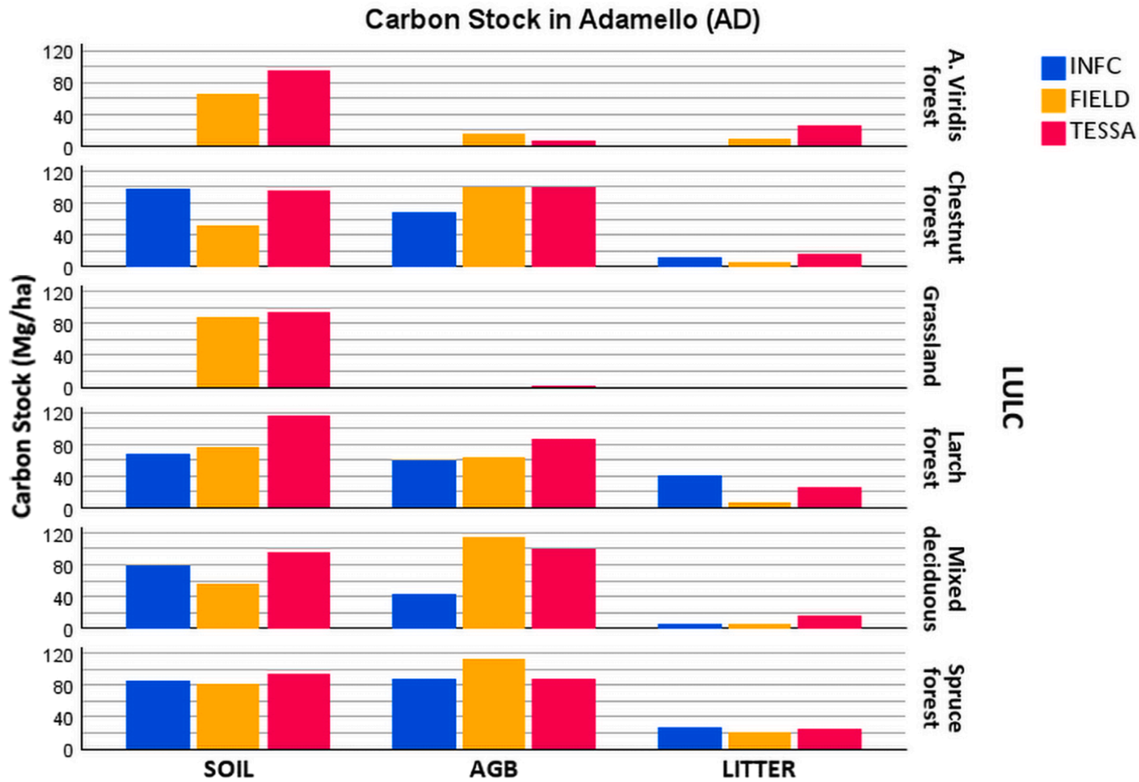

Fig. 4. Output from each methodology (fieldwork, INFC and TESSA) of the average OC stock (Mg/ha) per each pool and habitat type at the Adamello.

3.3. INFC

In the AV (Fig. 3) the INFC method showed lower values for AGB OC stock, with 55 Mg ha^{-1} for spruce forest and 45 Mg ha^{-1} for larch forest. Soil OC stock was 40 Mg ha^{-1} for spruce forest. Litter OC stock measurements were diverse, with 9 Mg ha^{-1} for spruce forest and 16 Mg ha^{-1} for larch forest. In PDM (Fig. 2) the INFC resulted in lower AGB OC stock values compared to the other approaches, particularly for larch forest (47 Mg ha^{-1}) and mixed broadleaves (37 Mg ha^{-1}). Soil OC stock was 83 Mg ha^{-1} for chestnut forest, 71 Mg ha^{-1} for larch forest, and 63 Mg ha^{-1} for mixed broadleaves. Litter OC stock resulted 8 Mg ha^{-1} for larch forest.

In AD (Fig. 4) the INFC recorded lower AGB OC stock values compared to field data, with 44.1 Mg ha^{-1} for mixed deciduous forest and 88 Mg ha^{-1} for spruce forest. Soil OC stock showed 96.7 Mg ha^{-1} for chestnut forest and 66.8 Mg ha^{-1} for larch forest. Litter OC stock was higher for spruce forest (26.8 Mg ha^{-1}) and for mixed deciduous forests (6.4 Mg ha^{-1}).

3.4. Differences among the methods

Our analysis revealed significant differences in carbon stock estimates between the methods used: fieldwork, INFC, and TESSA. The fieldwork and INFC approaches demonstrated greater similarity in their outcomes. In contrast, the TESSA method consistently led to an overestimation of the OC stock results. Using the Mann-Whitney *U* test, we found no statistically significant differences between the INFC and fieldwork data for each carbon pool. In contrast, TESSA showed statistically significant differences when compared to both INFC and fieldwork data concerning soil carbon stock. Specifically, significant differences were observed at $p < 0.05$ for AV and PMT, and at $p < 0.005$ for AD (Table S4).

We produced three maps of the total OC stock for every PA, each corresponding to a different approach (Figs. 5 and 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 represented field data, the second referred to INFC data and focused only on forested habitats, 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 in most of the forest habitats, 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. 5), 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. 6), 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.

Furthermore, we were interested in calculating the total OC stock in Gg, 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 S5). The results showed that TESSA at the AD overestimated the total OC stock to a lesser extent compared to the GP (PDM and AV). At the AV (Fig. 8) we found that the larch forest stored the highest amount of OC, primarily due to its extensive coverage of 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 Gg, the INFC provided a slightly higher value with 432 Gg and TESSA yielded almost double with 883 Gg. In PDM (Fig. 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,

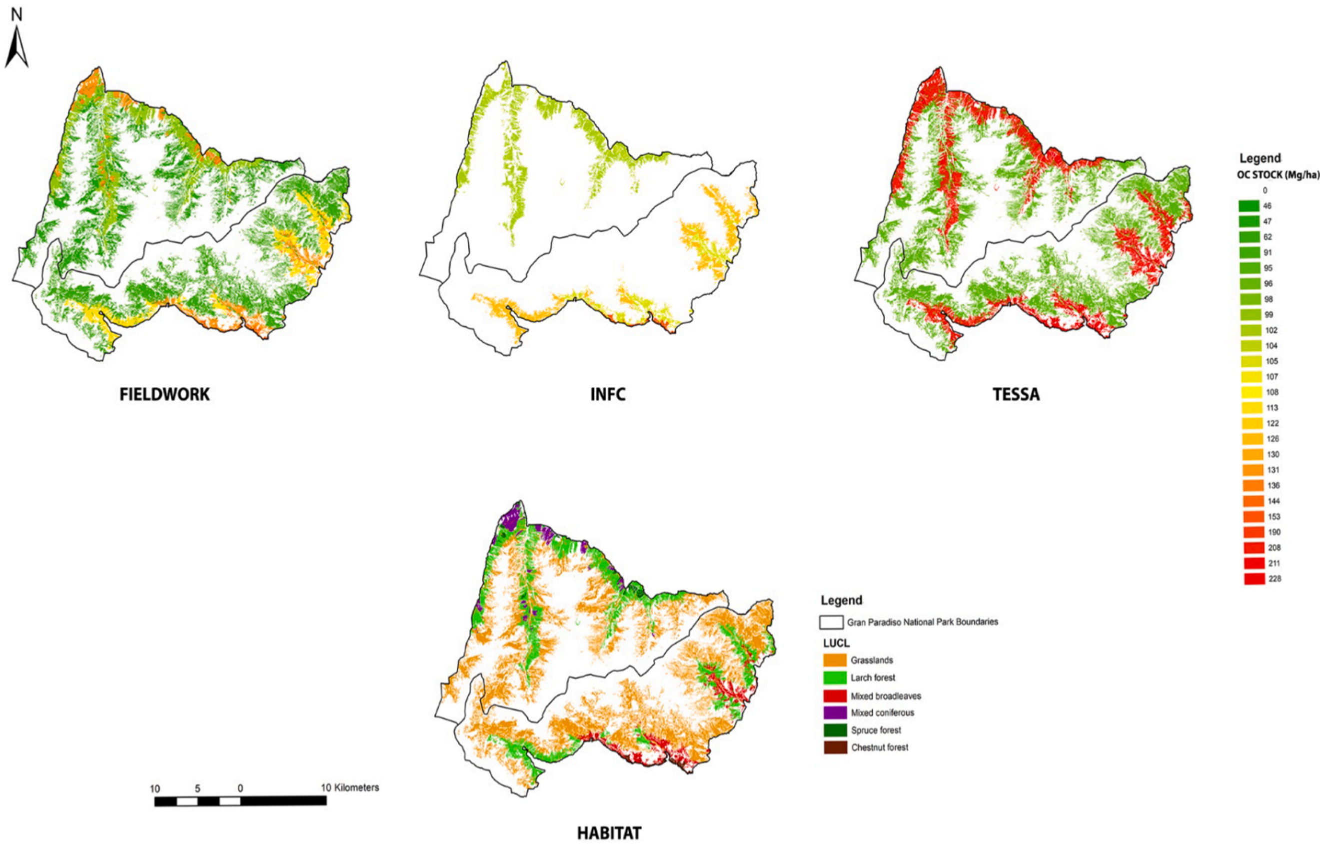

Fig. 5. Maps of the total OC stock summed across three pools (soil, litter, and above-ground biomass) assessed using the three different approaches: Fieldwork, INFC, and TESSA. Each map represents the distribution of OC stock in the Gran Paradiso National Park, with values expressed in Mg/ha. The color gradient indicates the OC stock levels, ranging from green (low values) to red (high values). The bottom map shows the LULC classes within the park providing context for the OC stock distribution observed in the other maps.

TESSA overestimated the values compared to the fieldwork data, with respective totals with all the habitat summed of 892 Gg for TESSA and 579 Gg for fieldwork. The differences were slightly less pronounced than in the AV. At the AD (Fig. 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 for spruce forest in the AD. The INFC yielded a total of 1838 Gg, the fieldwork data resulted in 1962 Gg, and TESSA estimated a total of 1906 Gg.

To better understand the differences between the methods we calculated the ratio of values using fieldwork data as the baseline reference (Table S5), since we assumed that data collected in the field were the closest to the actual values of the area. 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.

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. We then calculated the MAPE for each habitat, and evaluated the trend obtained through a regression analysis (Fig. 10, Table S6), and showed that increasing the number of plots there is a reduction of the error. The acceptable MAPE depends on the parameter studied and the purpose of the study (Corti et al., 2023). Considering our parameter, the OC stock, we aimed to achieve a low error and it emerged that in each PA more samples were necessary for grasslands compared to the other habitats. This was due to the broad classification of the LULC provided, which included diverse grassland types (e.g., acidic grasslands, calcicolous grasslands). Larch forest gave different values between AD and AV. Spruce forest and mixed coniferous forests, where present, resulted lower sampling effort reaching the same threshold.

4. Discussion

This study aimed to compare three different approaches (TESSA, fieldwork data and INFC) 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 (Kotlarski et al., 2023), there is an urgent need to evaluate the ES provided (Elkin et al., 2013; Grêt-Regamey, Brunner, & Kienast, 2012b; Zlatanov et al., 2017). Moreover, there is a lack of robust information based on field collected data on OC stock in alpine environments, particularly on soils, 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 could be achievable. The three approaches (fieldwork, INFC and TESSA) had differences in the outputs and the effort required 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

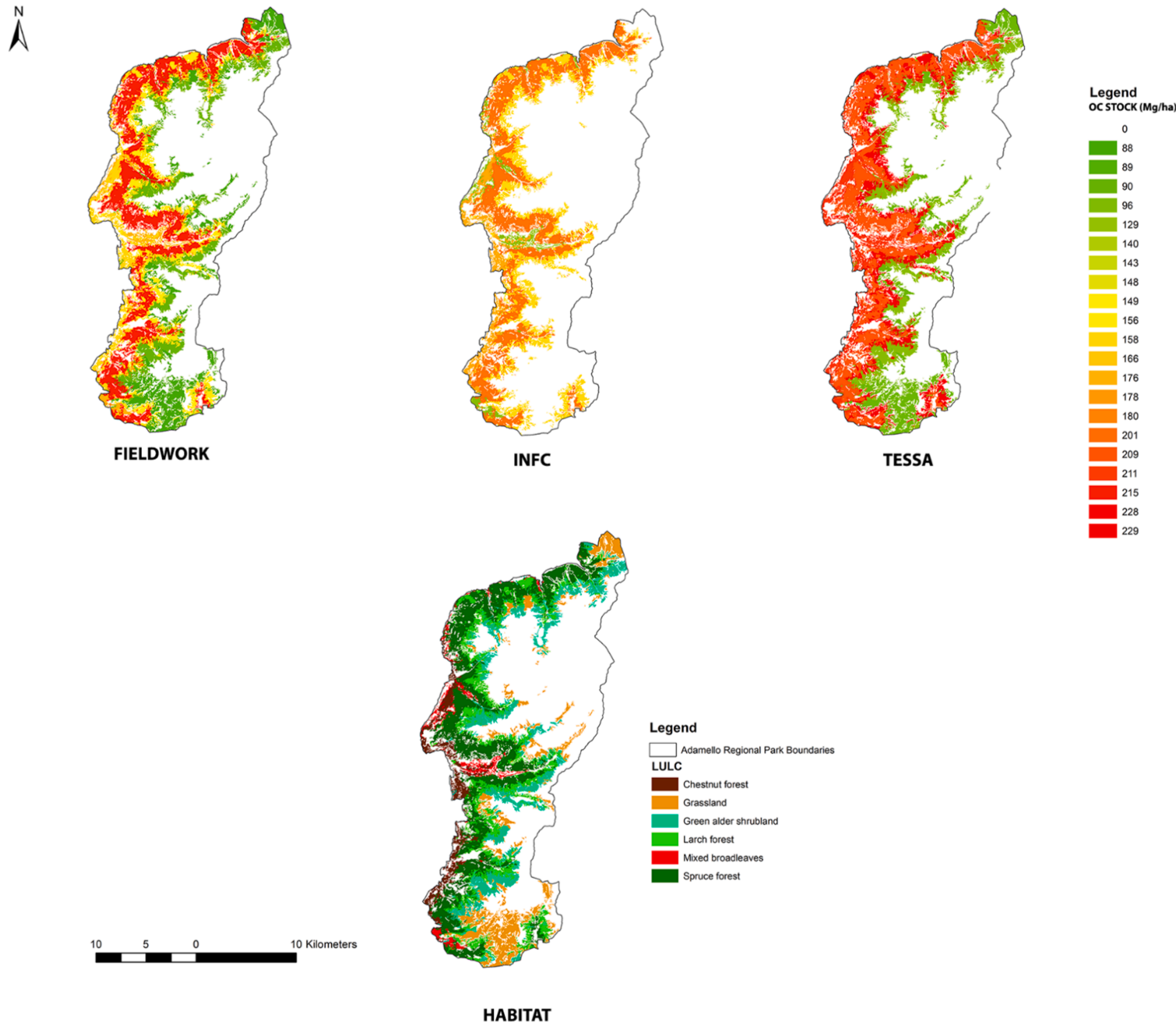

Fig. 6. Maps of the total OC stock summed across three pools (soil, litter, and above-ground biomass) assessed using the three different approaches: Fieldwork, INFC, and TESSA. Each map represents the distribution of OC stock in the Adamello Regional Park, with values expressed in Mg/ha. The color gradient indicates the OC stock levels, ranging from green (low values) to red (high values). The bottom map shows the land use and land cover LULC classes within the park providing context for the OC stock distribution observed in the other maps.

fieldwork campaigns and laboratory analyses, involving a team of more than ten collaborators. Conversely, the TESSA toolkit was the most time and resources efficient, 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. This aggregation flattened the results and led to statistically significant differences compared to the INFC and field data. We attribute these differences to the huge differences in carbon storage of the merged WRB classes in the HAC (e.g. Umbrisols and Regosols). Therefore, a potential improvement for TESSA would be to provide separate values for each WRB classification. 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 and with a higher plots' density, 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. The few discrepancies between INFC and fieldwork data 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 grasslands constituted one of the most widespread habitats in the total area, and they are now a habitat of interest, after that their carbon storage potential was for long overlooked (Bai & Cotrufo, 2022; 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

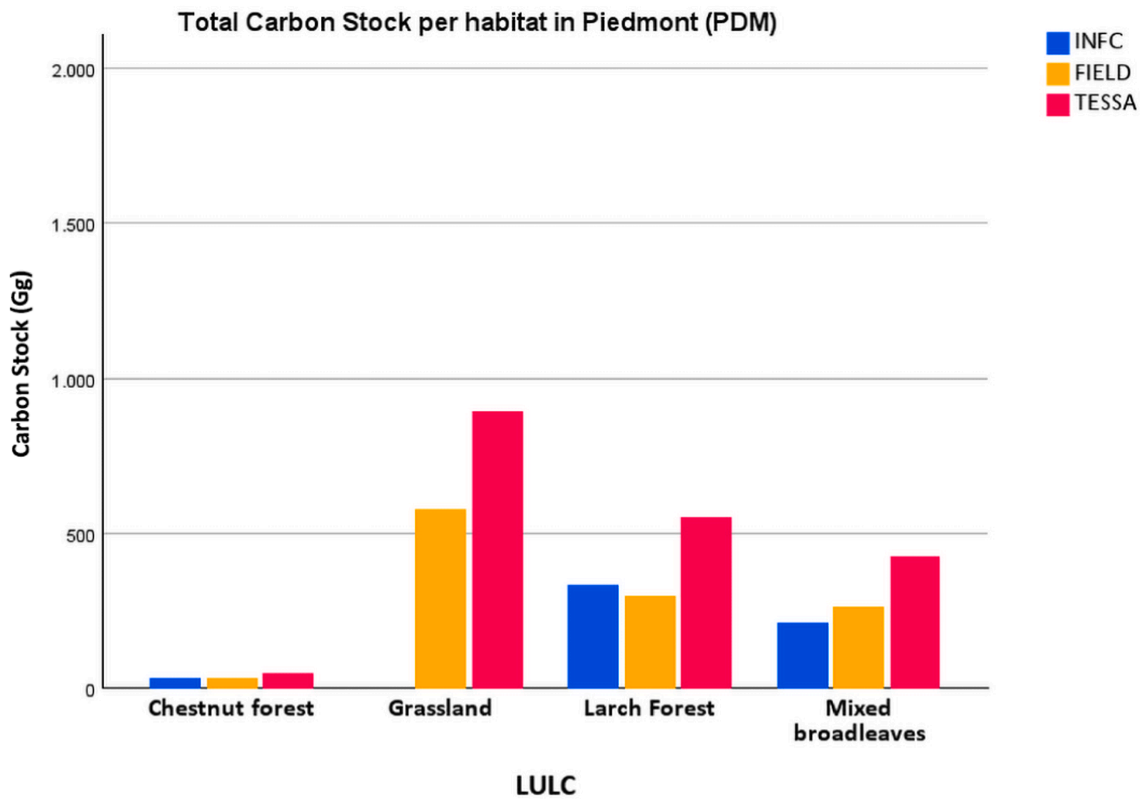

Fig. 7. Total Carbon Stock in Gigagrams (Gg) per habitat type in Piedmont (PDM) using INFC, field data and TESSA. The carbon stock values were calculated by multiplying the organic carbon stock value per hectare by the area of each habitat type.

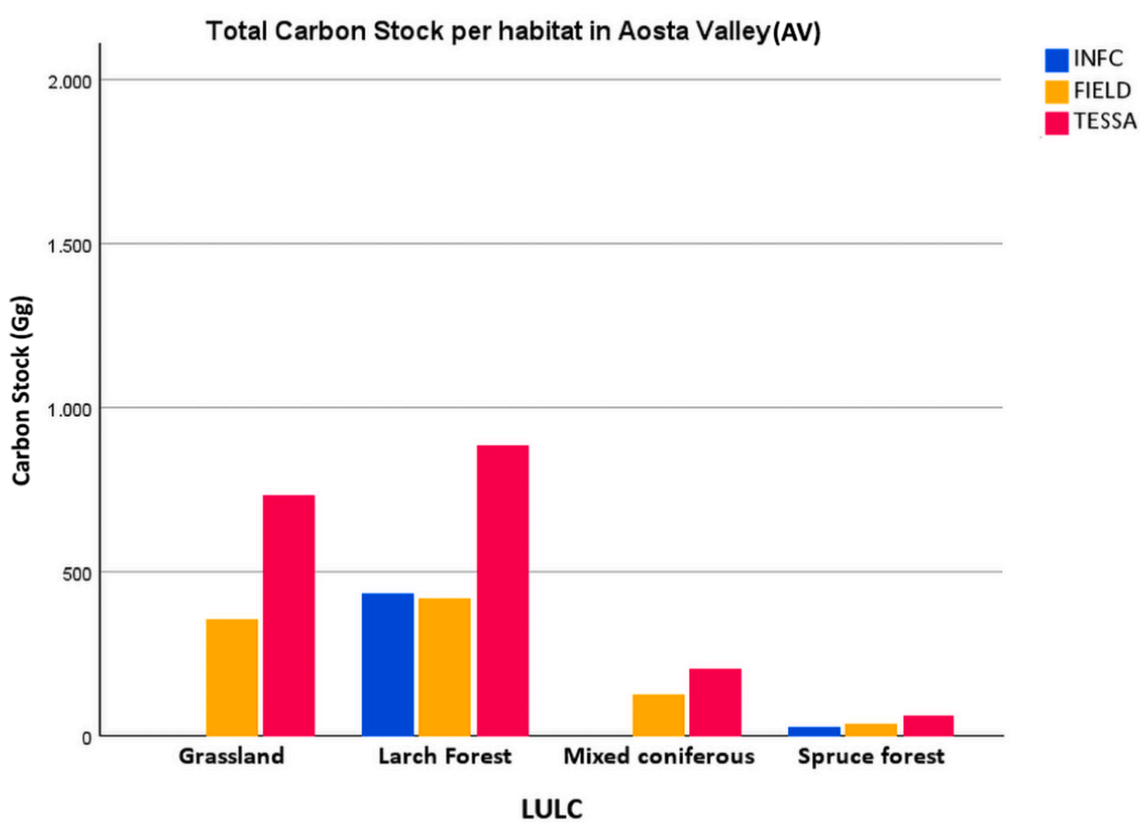

Fig. 8. Total Carbon Stock in Gigagrams(Gg) per habitat type in Aosta Valley (AV) using INFC, field data and TESSA. The carbon stock values were calculated by multiplying the organic carbon stock value per hectare by the area of each habitat type.

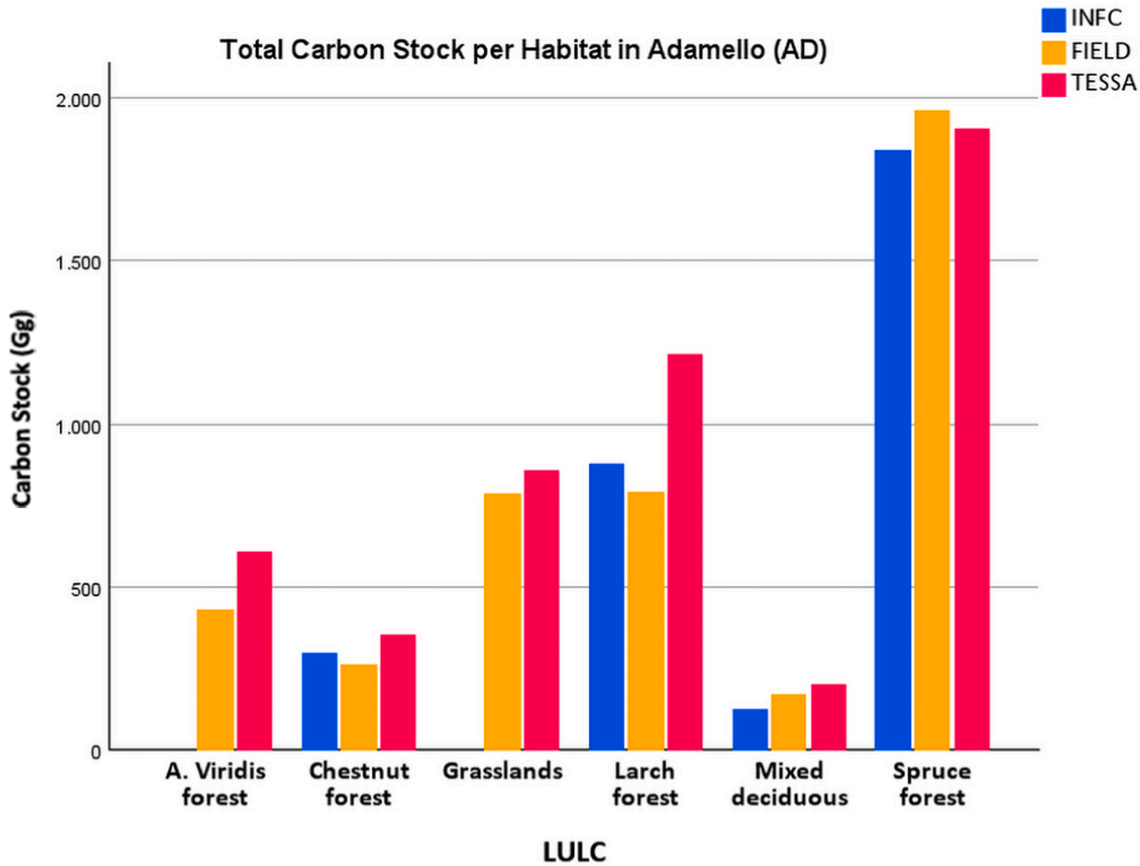

Fig. 9. Total Carbon Stock in Gigagram (Gg) per habitat type in Adamello (AD) using INFC, field data and TESSA. The carbon stock values were calculated by multiplying the organic carbon stock value per hectare by the area of each habitat type.

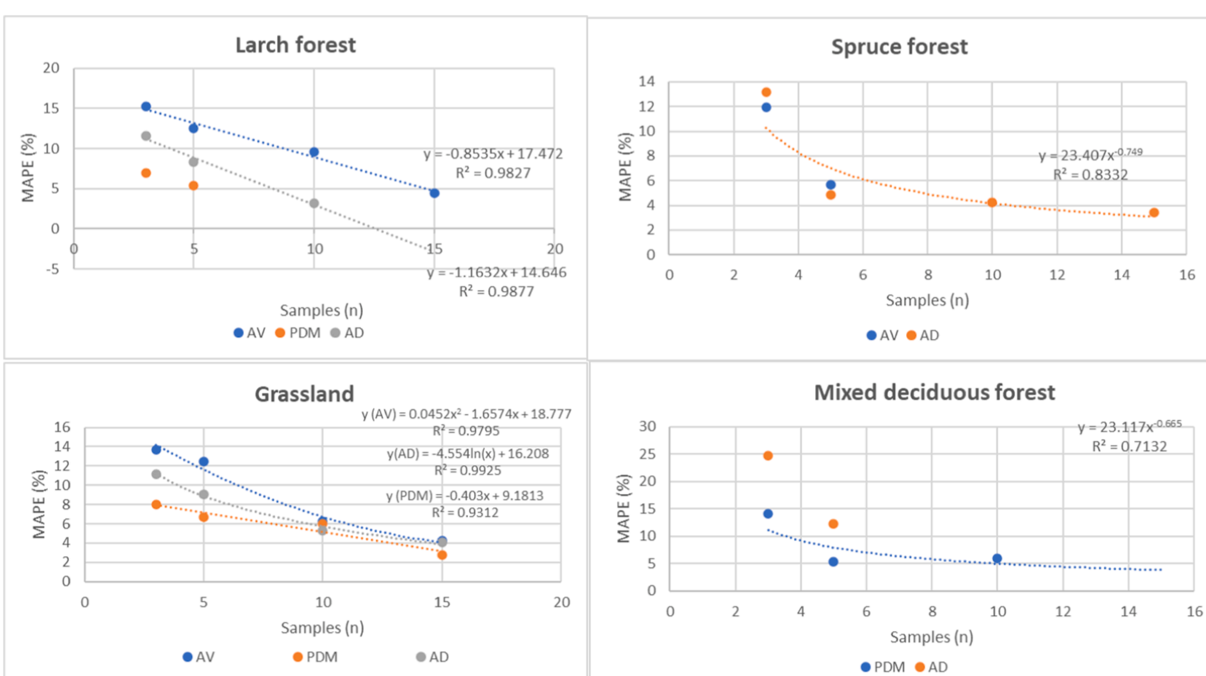

Fig. 10. Regression analysis for the evaluation of the minimum number of samples for reducing the MAPE (%), their equation and r-squared value.

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. Hence, we consider that an integration of the existing inventories with the alpine grasslands data could be a useful step for the description of such important habitats. 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.

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 site was an outlier in the qualitative analysis, showing discrepancies with both INFC and TESSA. This difference is probably related to the fact that the larch forests in this PA were particularly sparse, which resulted from our analyses in lower basal area and stem density compared to larch forests in other regions (SIFOR, 2020). Since basal area and tree density directly impact allometric equations, this sparsity likely explains the lower values obtained in the analysis.

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; Blaen et al., 2015; Liu et al., 2017; Manolaki & Vogiatzakis, 2017; Peh & Balmford et al., 2014; 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 carbon storage. For instance, maps can be used to qualitatively identify the distribution of OC stock. These maps can help researchers understand how OC is distributed in the area and determine where validation points should 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). 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 do not exist. 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 (Duvemo & Lämås, 2006; Nystrom & Stahl, 2001) and grasslands. Moreover, having updated, time-referred, and accurate data could help in the monitoring the gains and losses in carbon, aiding in the creation of historical trends of carbon changes by maintaining a consistent 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 scarcity of field data on the OC stock in alpine habitats 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, providing information on the factors affecting 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, 2019a, 2022), with the OC stock assessment based on the fieldwork activities of Canedoli et al. (2020). Hence, due to this widespread evaluation of ES within PAs, we highly recommend undertaking fieldwork activities to evaluate the carbon stock in PAs.

The importance an effective carbon storage assessment methodology extends beyond its immediate findings, playing a crucial role in supporting key European environmental initiatives. Within the framework of the European Green Deal, sustainable forest management is essential for carbon sequestration and climate regulation and for the carbon credits market. The European Biodiversity Strategy for 2030 emphasizes the need to protect and restore environments for biodiversity conservation. Additionally, the European New Forest Strategy 2030 outlines a vision for multifunctional forests that contribute to biodiversity, climate resilience, and human well-being. By offering recommendation on the assessment of OC stock, our study aligns with and supports the goals of these pivotal European strategies. For instance, 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 related to the EU Green Deal 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, we encourage that the baseline of each carbon pool is substantially set through fieldwork activities, above all for soil data. Using an accurate approach for these evaluations is fundamental since many management consequences and economic issues can emerge from inaccuracies. If an economic assessment of the organic carbon (OC) stock in an area results in values that are twice the actual amount due to the methodology used, this discrepancy can cause significant issues. Overestimations can lead to problems with fund allocation in the context of carbon credits or international grants for OC stock. Consequently, in the logic of carbon credits, uncertainties must be accurately accounted for to prevent these issues (Yanai et al., 2020). Furthermore, inaccurate evaluations can lead to a biased selection of intervention priorities, affecting the choice of degraded areas to restore or urgent areas to protect. It can result in a misallocation of resources for conservation, undermining the effectiveness of conservation efforts and potentially neglecting areas that need immediate attention.

However, 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. In some cases these can negatively affect the OC stock and other factors, 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 and biodiversity must be valuated during these monitoring activities.

We propose as a possible framework, that after a screening of the possible priority areas for the OC stock and other ES with TESSA and the existence of inventories, data in the field must 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 suggested 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 lower plots were suitable for the homogeneous habitats, predominantly composed by one species, such as spruce forests, and a higher number of 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 in 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 with less plots would have been sufficient, reducing our sampling effort: 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.

This study's objectives align closely with E.O. Wilson's Half-Earth concept (Wilson, 2016), which proposes preserving half of the planet to protect biodiversity. This concept is intrinsically linked to ecosystem services, which could serve as crucial tools for environmental protection. Our research examined the climate regulation service provided by alpine areas, specifically through OC stock measurement, demonstrating how the assessment of this ecosystem service could support conservation goals in mountain regions. To maintain essential ecosystem services, it is fundamental to properly manage and safeguard high mountain regions and carbon-rich environments, such as the Adamello Regional Park and the Gran Paradiso National Park. Hence, to develop an effective strategy for achieving the Half-Earth goals, a comprehensive understanding of ecosystem services - obtained through common methodologies - is crucial. This paper mirrored the challenges faced in finding widely applicable and common approaches for the ecosystem services assessment, a pivotal step to develop a shared framework to identify and protect key areas. Although a rapid assessment tool like TESSA provides a large amount of information quickly, including resource-intensive data to evaluate in the field (e.g. belowground biomass), quantitative and unbiased data are needed for 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, there is 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 between the areas and the habitats were observed, 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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CRediT authorship contribution statement

Noemi Rota: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Claudia Canedoli:** Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Chiara Ferré:** Data curation, Formal analysis, Methodology, Writing – review & editing. **Roberto Comolli:** Data curation, Formal analysis, Methodology, Writing – review & editing. **Davide Abu El Khair:** Investigation, Methodology. **Emilio Padoa-Schioppa:** Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2024.126746.

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