

Article

Aboveground Carbon Stocks and Soil Carbon Pools in Sub-Mediterranean Ecosystems of the Black Sea Coast of Russia: A Descriptive Case Study of Two Contrasting Plots

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Abstract

Sub-Mediterranean ecosystems along the northeastern Black Sea coast remain insufficiently studied despite their importance for the regional carbon cycle and their sensitivity to human disturbance. This study presents an exploratory case study of aboveground biomass carbon stocks in two contrasting plant communities at the carbon-monitoring supersite of the Southern Branch of the Shirshov Institute of Oceanology RAS in Gelendzhik, Russia. The aboveground observations were interpreted together with soil carbon stocks and greenhouse gas fluxes previously reported for the same permanent plots. The investigated communities comprised a terraced pine–oak plantation (SP1) and a natural pubescent-oak shiblyak (SP2). Vegetation was surveyed using the Braun-Blanquet approach. Tree biomass was estimated using the generalized allometric equation of Chave et al., while aboveground biomass was converted to carbon using carbon concentrations determined by elemental analysis of sampled plant tissues. Herbaceous vegetation and forest-floor material were quantified by elemental analysis. Within-plot spatial heterogeneity was visualized using Python-based radial-basis-function (RBF) interpolation for exploratory mapping of local carbon distribution. Because each vegetation type was represented by a single 400 m² plot, all comparisons are site-specific and exploratory and should not be extrapolated beyond the investigated communities. The aboveground carbon density was 64.1 t C ha^{−1} in the terraced pine–oak stand and 16.1 t C ha^{−1} in the natural shiblyak. Woody biomass dominated the plantation, whereas litter and herbaceous vegetation contributed proportionally more to the carbon pool in the shiblyak. Previously published soil organic carbon stocks at the terraced site exceeded the measured aboveground carbon pool, whereas the natural rendzinas were characterized by substantial carbonate-associated inorganic carbon stocks. C/N ratios of organic substrates ranged from 11 to 100, indicating a pronounced variation in substrate quality: higher C/N values in woody and coniferous fractions were consistent with slower decomposition, whereas lower C/N values in herbaceous material were consistent with faster mineralization. Exploratory spatial mapping revealed within-plot variation in aboveground carbon of up to two orders of magnitude. Together, these site-specific observations provide the first integrated description of aboveground biomass carbon together with previously reported soil carbon pools for contrasting sub-Mediterranean vegetation on the



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northeastern Black Sea coast. Despite its exploratory nature, this study establishes a baseline for future replicated, spatially explicit investigations of ecosystem carbon dynamics in sub-Mediterranean ecosystems along the northeastern Black Sea coast.

Keywords: carbon stocks; aboveground biomass; C/N ratio; sub-Mediterranean ecosystems; slope terracing; Black Sea coast

1. Introduction

In the context of global climate change and increasing anthropogenic pressure, quantifying carbon pools in terrestrial biomes is critical for understanding and predicting the Earth's climate system [1,2]. Forest ecosystems absorb up to ~30% of anthropogenic CO₂ emissions and are principal regulators of the global carbon cycle [3,4], with a large share of ecosystem carbon held in aboveground woody phytomass [5,6]. The sub-Mediterranean belt of the Russian Black Sea coast is a biogeographically distinctive transitional region combining xerophytic and mesophytic elements, including Crimean–Novorossiysk endemics and communities such as juniper woodlands, tomillyars, tragacanthic communities, and *Quercus pubescens* Willd. forests with *Carpinus orientalis* Mill. [7]. Despite their biogeochemical significance, these ecosystems are underrepresented in quantitative carbon assessments, limiting their integration into regional and global carbon models [8,9].

The carbon storage in these landscapes is associated with multiple interacting environmental and site-specific factors that have been reported to affect biomass accumulation and the accumulation and distribution of soil organic carbon (SOC). Previous studies have identified parent material, carbonate content, slope position, terracing, stand origin and age, species composition, canopy structure, and land-use history as potentially important controls on carbon storage in Mediterranean and sub-Mediterranean rendzina ecosystems [10,11]. Previous work at the Gelendzhik supersite described soil carbon dynamics, reporting higher SOC in terraced soils (up to 25 kg m⁻², or up to 250 t C ha⁻¹ total soil carbon) than in natural rendzinas. In these soils, CO₂ is emitted as a net source, while CH₄ is emitted as a stable sink. However, this previous work did not quantify aboveground biomass, precluding an integrated ecosystem-level assessment of vegetation and soil carbon pools [11].

Reliable estimates of aboveground biomass depend on the use of allometric models appropriate for local vegetation characteristics [12,13]. This is particularly important in shiblyak communities, a xerophytic open woodland typical of the sub-Mediterranean Black Sea region, where drought-tolerant deciduous trees and shrubs frequently develop multi-stemmed growth forms and validated species-specific allometric equations are largely unavailable [11]. Consequently, generalized allometric models provide a practical alternative where validated species-specific equations are unavailable, although their application should be interpreted with appropriate caution. Beyond biomass quantity, the biochemical quality of litter, commonly characterized by the C/N ratio, is widely considered an important factor influencing decomposition, mineralization, and long-term SOC accumulation [14,15], an effect that may be modified in carbonate rendzinas through Ca²⁺/Mg²⁺-mediated organo-mineral interactions [11,16]. Because carbon pools are also spatially heterogeneous within stands, exploratory two-dimensional interpolation (e.g., RBF) can also help illustrate within-plot heterogeneity, although such approaches require cautious interpretation [17].

Against this background, the objective of the present study was not to test statistical relationships between vegetation and soil carbon pools but to provide a descriptive

comparison of two contrasting sub-Mediterranean plant communities using newly measured aboveground carbon stocks together with previously published soil-carbon data from the same plots. Given that only one plot per community was available, the study is explicitly designed as a descriptive, exploratory case study; it does not test statistical relationships between aboveground and soil carbon, and its comparisons are not intended for regional extrapolation.

To address this question, the study (1) characterized the two communities geobotanically (Braun-Blanquet method) and quantified aboveground carbon in the tree, herb-dwarf-shrub, and forest-floor components, including C/N of the main organic fractions; (2) explored the spatial structure of tree-layer carbon within plots using RBF interpolation; and (3) qualitatively compared the aboveground estimates with previously published soil organic/inorganic carbon and greenhouse gas flux data for the same plots [11].

2. Materials and Methods

2.1. The Study Area

The study was conducted at the carbon supersite of the Southern Branch of the P.P. Shirshov Institute of Oceanology RAS (SBIO RAS) in Gelendzhik, Krasnodar Krai, Russia (44°32' N, 37°58' E). Under the Köppen–Geiger scheme, the area is transitional between humid subtropical (Cfa) and Mediterranean (Csa) types; the mean annual air temperature is +13.7 °C, and mean annual precipitation is ≈788 mm [11,17]. The site occupies a 15–20° coastal slope facing Gelendzhik Bay, up to ~150 m a.s.l. Phytogeographically, it belongs to the Utrish–Tuapse unit of the Crimean–Novorossiysk orobiome within the Mediterranean Region [7]. Parent material is carbonate rock (marls and limestones); soils are natural rendzinas and their anthropogenically transformed skeletal analogues.

Two field plots (SPs) were established to study the effects of habitat and anthropogenic transformation. SP1 was located on an artificially terraced site with a plantation forest, and SP2 was located on a natural, undisturbed, south-facing slope. Each plot measured 400 m² (20 m × 20 m), which is consistent with standard geobotanical practices for forest communities [18]. SP1 is a ~70-year-old oak–pine plantation dominated by *Pinus brutia* var. *pityusa* (Steven) Silba and *Quercus petraea* (Matt.) Liebl. SP2 is a natural downy oak shiblyak dominated by *Quercus pubescens* with a xerophytic herb layer on a stony substrate. The locations of the two sample plots within the SBIO RAS carbon supersite are shown in Figure 1.

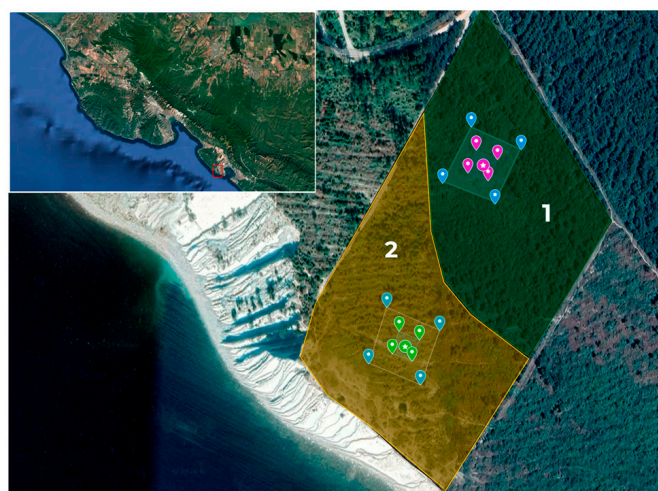


Figure 1. Satellite image of the study area showing the locations of the sample plots (1 = SP1—terraced oak–pine forest; 2 = SP2—downy oak shiblyak) within the SBIO RAS carbon supersite (Gelendzhik, Krasnodar Krai). The inset map in the upper left corner shows the location of the study area.

2.2. Geobotanical Investigations

Plant communities were described with the Braun-Blanquet method within the 20 × 20 m plots, characterizing vertical structure, species composition, and cover of each layer, using the Braun-Blanquet cover-abundance scale. Structural characterization included mean layer height, cover, and Raunkiær life-form spectra. Sites were georeferenced with Google Earth (Google LLC, Mountain View, CA, USA) imagery and GPS. Species identification followed contemporary floras for the Caucasus and Black Sea coast [7,19]; syntaxonomy followed the Braun-Blanquet system [18,20].

2.3. Assessment of Aboveground Carbon Stocks

2.3.1. Tree Layer

The aboveground biomass (AGB) of individual trees was estimated using the generalized allometric model proposed by Chave et al. [12]:

$$\text{AGB} = 0.0673 \times (\rho \times D^2 \times H)^{0.976} \quad (1)$$

where AGB is aboveground dry biomass (kg), D is stem diameter at breast height (DBH) (cm), H is tree height (m), and ρ is wood density (g/cm^3). This model was selected because it explicitly accounts for differences in wood density and tree architecture among species by incorporating species-specific wood density values while requiring only standard forest inventory measurements (DBH and height). Species-specific wood density values were obtained from the Global Wood Density Database. When species-level data were unavailable, values reported for the corresponding genus were used [21].

The study plots contained several Mediterranean and sub-Mediterranean woody taxa (e.g., *Carpinus orientalis* and *Paliurus spina-christi* Mill.), for which species-specific allometric equations are currently unavailable or underrepresented in European biomass databases. Using a single generalized allometric model ensured methodological consistency across all tree species and avoided potential biases associated with combining equations from different regions, datasets, and sampling protocols.

The model was originally developed using a broad pantropical dataset; however, its structure is based on fundamental scaling relationships among stem diameter, tree height, wood density, and biomass. This makes the model suitable for comparative biomass assessments when local, species-specific equations are lacking. Similar generalized allometric approaches have been widely adopted in forest carbon studies and are compatible with the IPCC framework for estimating aboveground biomass and carbon stocks.

Aboveground biomass (AGB) was converted to carbon stocks using carbon fractions determined by analyzing the chemical composition of the sampled plant material. This approach permitted the use of site- and component-specific carbon concentrations rather than the default conversion factors recommended by IPCC guidelines.

To illustrate carbon storage within the mapped vegetation units, plot-level carbon stocks were proportionally scaled to the corresponding vegetation areas. This extrapolation assumes homogeneous stand structure and biomass distribution within each vegetation type. It is intended solely for visualizing potential carbon storage, not for statistically representative regional estimation.

2.3.2. Herb–Dwarf Shrub Layer and Forest Floor

Herb-layer biomass was estimated by clipping four 0.25 m² (50 × 50 cm) subplots per plot [22]; material was oven-dried to constant mass, weighed, and separated into forbs, standing dead matter, grasses, and legumes. Forest-floor samples were collected from 0.25 m² frames using the same design. Carbon and nitrogen of all forest-floor and herb-layer samples were determined by high-temperature catalytic combustion (Elementar

Vario EL Cube, Elementar Analysensysteme GmbH, Langenselbold, Germany; TNM-L nitrogen module). Carbon stock per unit area (g C m^{-2}) was determined as follows:

$$C = m \times f(C) \times S^{-1} \quad (2)$$

where m is oven-dried mass (g), $f(C)$ is the carbon concentration (fraction of dry mass), and S is the sampling area (0.25 m^2). Values were converted to t C ha^{-1} and, where climate-accounting comparison was needed, to CO_2 -equivalent using $44/12 = 3.67$ [23,24].

2.4. Determination of C/N Ratios

In addition to the quantitative assessment of carbon stocks, the qualitative characteristics of organic matter were evaluated using the C/N ratio as an indicator of decomposition intensity and substrate quality.

The total carbon (C) and total nitrogen (N) contents of the plant material samples, including branches, leaves, needles, herbaceous vegetation, and forest floor fractions, were determined using an Elementar Vario EL Cube analyzer, as described in Section 2.3.2. Sample types (leaves, branches, and stems) were collected and analyzed separately for each tree species. No composite or homogenized samples combining tissues from different species were prepared for carbon and nitrogen analysis.

The C/N ratio was calculated by dividing the mass concentration of carbon by the mass concentration of nitrogen in oven-dried samples.

2.5. Previously Published Soil Carbon Dataset Used for Comparison

Soil organic carbon (SOC) data used in this study were derived from our previously published investigation conducted at the same carbon supersite under identical sampling locations and field conditions [11]. Full-profile soil pits were excavated within each monitoring plot, and soil samples were collected separately from each genetic horizon. Soil organic carbon stocks were calculated for the entire depth of each soil profile, which ranged from approximately 40 to 100 cm depending on soil thickness, rather than being standardized to a common reference depth. Bulk density was determined from undisturbed core samples of known volume. Corrections for coarse fragments and anthropogenic inclusions were applied using a stoniness correction factor. Total carbon (TC) and inorganic carbon (IC) were measured by dry high-temperature catalytic combustion using a Shimadzu TOC-L (Shimadzu Corporation, Kyoto, Japan) CPN analyzer equipped with an SSM-5000A solid-sample module, and total organic carbon (TOC) was calculated as the difference between TC and IC. Organic carbon stocks were calculated for each horizon according to the following equation:

$$\text{Carbon Stock} = \text{TOC} \times H \times \text{BD} \times \text{AI}, \quad (3)$$

where TOC is the organic carbon concentration (%), H is the horizon thickness (cm), BD is the bulk density (g cm^{-3}), and AI is the correction factor accounting for coarse fragments and anthropogenic inclusions. Profile carbon stocks were obtained by summing horizon-specific stocks. A detailed description of soil sampling procedures, analytical methods, and quality control is provided in Gorbov et al. [11].

As reported there, soils were characterized from five soil pits (Pits 1–3 on the terraced/anthropogenically transformed skeletal rendzinas associated with SP1; Pits 4–5 on the natural rendzinas associated with SP2), with total organic carbon (TOC) and inorganic carbon (IC) determined by depth through the profile (to ≥ 60 cm), and microbial biomass carbon (MBC), basal respiration (BR), the metabolic quotient ($q\text{CO}_2$), and CO_2/CH_4 fluxes measured over 2024–2025. Reported profile pools reach $12\text{--}25 \text{ kg m}^{-2}$ TOC

(120–250 t C ha^{−1}) in terraced soils, 6–7 kg m^{−2} TOC (60–70 t C ha^{−1}) with 15–28.7 kg m^{−2} IC in natural rendzinas, and a mean MBC of 411 µg C g^{−1} in the top 40 cm.

To facilitate comparison with vegetation carbon pools, the main characteristics of the soil carbon stocks included in the present analysis are summarized in Table 1.

Table 1. Soil carbon pools of the two study plots (modified from Ref. [11]).

Carbon Pool	SP1 (t C ha ^{−1})	SP2 (t C ha ^{−1})
Organic carbon (TOC)	120–250	60–70
Inorganic carbon (IC)	10–70	167–287
Total soil carbon	130–240	227–357

2.6. Spatial Analysis and Visualization of Carbon Distribution

The within-plot spatial structure of tree-layer carbon was explored using two-dimensional heat maps built from individual tree GPS coordinates and their computed carbon stocks. Processing used a custom Python 3.11.7. script (NumPy 1.26.4, SciPy Rbf 1.12.0, and Matplotlib 3.9.3): (1) import of coordinates and carbon values; (2) a regular 0.5 m interpolation grid within plot boundaries; (3) RBF interpolation of point values; (4) rendering as a gradient heat map with isolines and tree markers; and (5) exporting as a 300 dpi PNG.

For the spatial distribution maps (see Section 3.6), carbon density is expressed in g C m^{−2} because interpolation was performed on raster cells defined in square meters. This unit directly represents the carbon density assigned to each cell and is therefore more appropriate for spatial visualization than t C ha^{−1}. Converting between the two units is straightforward (1 t C ha^{−1} = 100 g C m^{−2}).

These maps are exploratory visualizations only. With ~19–30 measurement points per 400 m², the interpolated surface may imply a level of precision that exceeds the information content of the raw data. Therefore, smoothed gradients and isolines should not be interpreted as validated quantitative predictions. No geostatistical error assessment was performed (e.g., cross-validated kriging variance), and a comparison of RBF against geostatistical alternatives, as well as the incorporation of topography, is deferred to future work. RBF interpolation may produce overshooting in areas with sparse observations, resulting in negative estimates. These values are numerical artifacts of the interpolation algorithm and should not be interpreted as negative carbon stocks. The maps are used solely to identify qualitative within-plot patterns and do not support ecosystem- or landscape-scale quantitative conclusions.

2.7. Statistical Data Processing

Data are summarized with descriptive statistics means and SDs (see dendrometric characteristics in Section 3.2) using Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA) and Python 3.11.7 (NumPy 1.26.4, SciPy, 1.12.0 and Pandas 2.1.4). Because only one plot per community was available, between-community differences are reported descriptively and are not subjected to inferential hypothesis tests at the ecosystem level. Any exploratory correlations within plots (e.g., carbon stock vs. stem size) are presented as such, with the tree as the unit of observation. These correlations are not interpreted as generalizable relationships at the ecosystem level.

3. Results

3.1. Floristic Composition and Structure of Plant Communities

Two contrasting plant communities were identified. Both have a three-layered structure with Mediterranean floristic elements and a high proportion of xerophytes but differ

in canopy architecture, composition, and total vegetation cover, reflecting local topography, moisture, and land-use history.

SP1 (artificial oak–pine forest) has a well-developed three-layer structure. The tree layer (Layer I, ~12 m) comprises *Pinus brutia* var. *pityusa* (8% canopy cover) and *Quercus petraea* (14%). The shrub layer (Layer II, ~2.2 m) is weakly developed (*Paliurus spina-christi* and *Carpinus orientalis*). The dwarf-shrub–herb layer (Layer III, ~0.8 m) includes *Sideritis taurica* Steph. ex Willd., *Jasminum fruticans* L., *Xeranthemum annuum* L.; herbaceous cover is dominated by *Achnatherum bromoides* (L.) P. Beauv. (up to 15%) with *Stipa pulcherrima* K. Koch and *Asphodeline lutea* (L.) Rchb. Total vegetation cover $\approx$ 90% (closed canopy, strong stratification).

SP2 (natural downy oak shiblyak) is lower and more open. Layer I is *Quercus pubescens* (22%, ~3 m). Layer II (~1.5 m) is *Paliurus spina-christi* (18%) and *Cotinus coggygria* Scop. Layer III (~0.8 m) includes *Ruscus aculeatus* L. and *Jasminum fruticans*; the herb layer is mainly *Bothriochloa ischaemum* (L.) Keng and *Dictamnus albus* L., with *Ruscus aculeatus* L. up to 25%. Total vegetation cover $\approx$ 78%.

A detailed overview of this layer stratification can be seen in Figure 2, which provides a schematic representation of the vertical layer structure of plant communities SP1 and SP2, indicating the heights of layers and the dominant species.

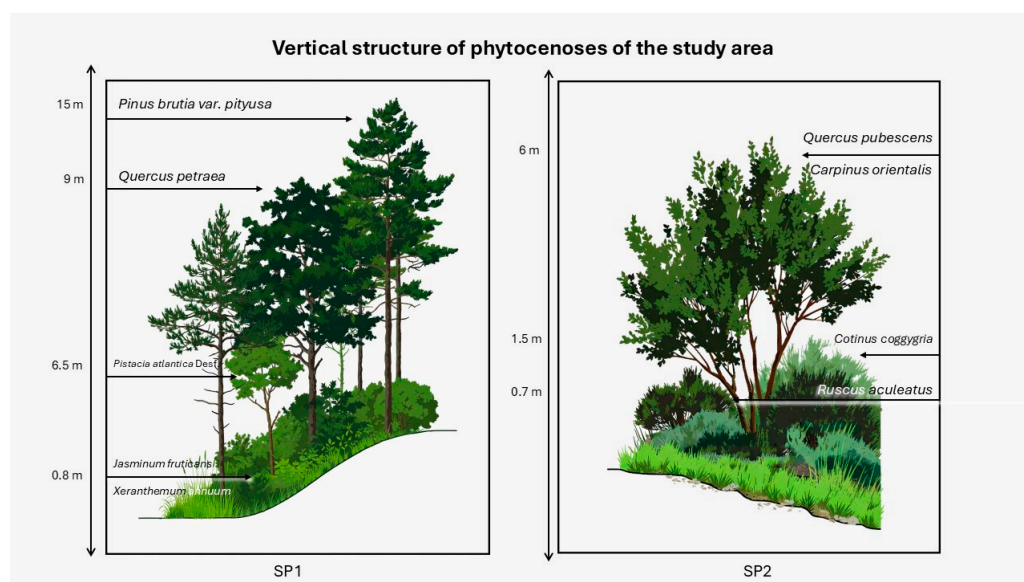


Figure 2. Schematic representation of the vertical layer structure of plant communities SP1 (oak–pine forest) and SP2 (downy oak shiblyak). It indicates the heights of the layers and the dominant species.

According to the Braun-Blanquet syntaxonomic system, the plant community of SP1 belongs to the *Quercion pubescenti–petraeae* alliance (class *Quercetea pubescentis*), and the vegetation of SP2 belongs to the *Paliuro–Quercion pubescentis* shiblyak alliance. The floristic composition of both sample plots, based on original Braun-Blanquet relevés, is presented in Tables 2 and 3.

These syntaxa correspond to well-described vegetation alliances previously reported for the Black Sea coast of the Caucasus [7].

Thus, SP1 shows greater vertical differentiation and canopy closure, whereas SP2 has a lower woody canopy and stronger shrub/xerophytic development (Figure 2). Syntaxonomically, SP1 belongs to the *Quercion pubescenti–petraeae* alliance (class *Quercetea pubescentis*) and SP2 to the *Paliuro–Quercion pubescentis* shiblyak alliance—both typical sub-Mediterranean syntaxa of the Caucasian Black Sea coast [7], although the present observations remain specific to the investigated plots.

Table 2. Floristic composition of the two study plots (SP1 and SP2) based on the original Braun-Blanquet relevés.

Species	Growth Layer	SP1	SP2
<i>Achnatherum bromoides</i>	Herb	+	–
<i>Allium rotundum</i>	Herb	–	r
<i>Asparagus verticillatus</i>	Herb	1	1
<i>Asphodeline lutea</i>	Herb	–	r
<i>Bothriochloa ischaemum</i>	Herb	+	+
<i>Bupleurum tenuissimum</i>	Herb	–	1
<i>Carpinus orientalis</i>	Tree/Shrub	2	2
<i>Dictamnus albus</i> var. <i>gymnostylis</i>	Herb	–	+
<i>Fibigia clypeata</i>	Herb	–	r
<i>Globularia punctata</i>	Herb	–	r
<i>Jasminum fruticans</i>	Shrub	–	2
<i>Ligustrum vulgare</i>	Shrub	–	+
<i>Luzula sylvatica</i>	Herb	+	–
<i>Paliurus spina-christi</i>	Shrub	+	–
<i>Pinus brutia</i> var. <i>pityusa</i>	Tree	+	r
<i>Prospero autumnale</i>	Herb	+	–
<i>Quercus petraea</i>	Tree	+	–
<i>Quercus pubescens</i>	Tree	–	2
<i>Rhus coriaria</i>	Shrub	+	–
<i>Rosa agrestis</i>	Shrub	r	–
<i>Rubus occidentalis</i>	Shrub	r	–
<i>Ruscus aculeatus</i>	Shrub	2	2
<i>Scariola viminea</i>	Herb	–	r
<i>Sorbus torminalis</i>	Tree	–	+
<i>Teucrium chamaedrys</i>	Herb	–	+
<i>Teucrium polium</i>	Herb	2	–
<i>Xeranthemum annuum</i>	Herb	2	2

Note: “–” indicates species not recorded in the respective plot. Braun-Blanquet scale: r = solitary individual; + = few individuals with negligible cover (<1%); 1 = numerous individuals, cover <5%; 2 = 5%–25% cover.

Table 3. Summary characteristics of the vegetation plots in the two study areas (SP1 and SP2).

Parameter	SP1	SP2
Plot size	400 m ²	400 m ²
Total species richness	15	17
Tree layer richness	3	3
Shrub layer richness	5	4
Herb layer richness	7	10
Moss/Lichen layer	Absent	Absent
Total vegetation cover	90%	78%

3.2. Carbon Stocks in the Tree Layer

The tree layer is the dominant aboveground carbon component in both communities. Tree-layer carbon was estimated from allometric equations and individual mensuration; values varied strongly with species, DBH, and height (Table 4). The highest per-tree stocks were large *P. brutia* var. *pityusa* and *Q. petraea* in SP1; SP2 showed markedly lower accumulation because of low-statured, multi-stemmed forms.

Table 4. Dendrometric characteristics and aboveground carbon stocks of trees in sample plots SP1 and SP2. Values are presented as mean $\pm$ SD.

Sample Plot	Species	No. of Trees	DBH, cm	Height, m	AGB, kg Tree ⁻¹	C Stock, kg Tree ⁻¹
SP1	<i>Pinus brutia</i> var. <i>pityusa</i> (Steven) Silba	15	27.4 $\pm$ 10.4	12.5 $\pm$ 4.8	289.3 $\pm$ 202.5	130.1 $\pm$ 91.1
SP1	<i>Quercus petraea</i> (Matt.) Liebl.	3	22.7 $\pm$ 3.1	9.6 $\pm$ 1.3	159.5 $\pm$ 68.2	74.5 $\pm$ 31.9
SP1	<i>Carpinus orientalis</i> Mill.	1	8.0	3.4	9.0	4.1
SP1 total	—	19	—	—	—	—
SP2	<i>Quercus pubescens</i> Willd.	12	10.5 $\pm$ 2.0	6.0 $\pm$ 1.4	23.9 $\pm$ 10.1	11.1 $\pm$ 4.7
SP2	<i>Pinus brutia</i> var. <i>pityusa</i> (Steven) Silba	1	29.0	15.2	307.5	145.4
SP2	<i>Carpinus orientalis</i> Mill.	10	7.3 $\pm$ 1.6	4.8 $\pm$ 0.8	12.0 $\pm$ 1.9	5.6 $\pm$ 3.2
SP2	<i>Paliurus spina-christi</i> Mill.	7	4.9 $\pm$ 0.8	3.7 $\pm$ 0.3	3.13 $\pm$ 0.7	1.36 $\pm$ 0.32
SP2 total	—	30	—	—	—	—

3.3. Ecosystem-Level Carbon Pools

Tree-layer estimates (Section 3.2) were combined with the herb–dwarf-shrub layer and forest floor to give total aboveground carbon for each plot, treating each component as a distinct pool for comparability with the soil pools of [11]. The two communities differ substantially in the amount and organization of their carbon pools (see Table 5).

Table 5. Aboveground carbon stocks in the major ecosystem pools of the study plots.

Carbon Pool	SP1: t C ha ⁻¹	SP1: %	SP2: t C ha ⁻¹	SP2: %
Aboveground woody biomass	54.5	85.0	8.6	53.4
Herb–dwarf shrub layer	1.1	1.7	1.9	11.8
Forest floor (litter)	8.5	13.3	5.6	34.8
Total	64.1	100	16.1	100

3.4. Distribution of Carbon Among Pools

The terraced oak–pine forest (SP1) stores substantially more carbon and is overwhelmingly dominated by woody biomass (about 85% of the aboveground pool), which is consistent with the maturity of the pine and oak trees and prolonged accumulation under a closed canopy. Its forest floor also makes a substantial contribution, consistent with the accumulation of slowly decomposing conifer–broadleaf litter. The natural shiblyak (SP2) has much lower total stocks and a more even distribution among pools. Although woody biomass still accounts for the largest share (53.4%), the non-woody fractions (forest floor: 34.8%; herb–dwarf shrub: 11.8%) are considerably more important, consistent with low-statured shrubs/coppice, reduced canopy closure, and limited long-term accumulation.

The aboveground carbon density of the ecosystem was 64.1 t C ha⁻¹ at SP1, which is in the lower-to-middle range reported for sub-Mediterranean forests, and 16.1 t C ha⁻¹ at SP2. This reflects the low stature of the woody and shrub vegetation and the faster turnover of organic matter (Figures 3 and 4).

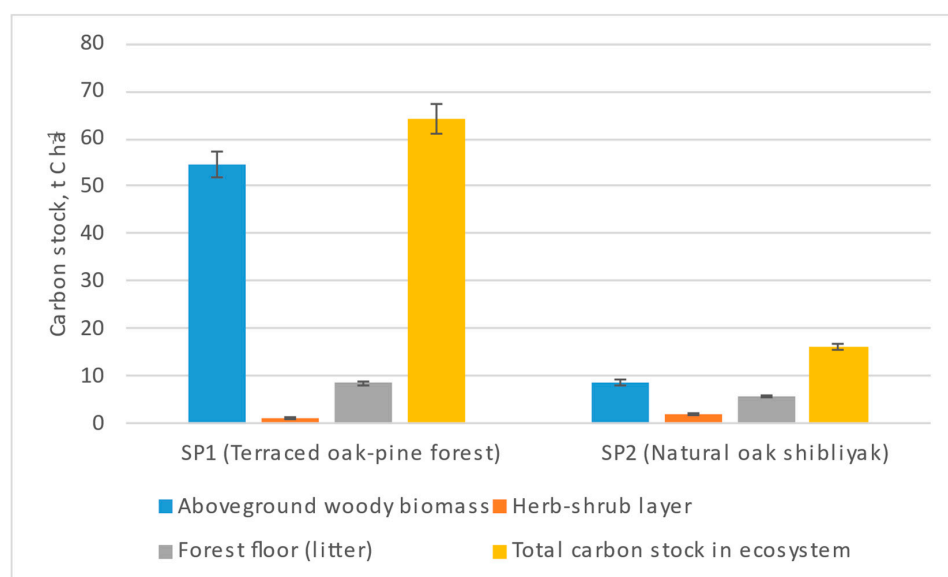


Figure 3. Aboveground carbon stocks in the measured ecosystem pools of sample plots SP1 (terraced oak–pine forest) and SP2 (natural oak shiblyak). Values are presented as mean $\pm$ SD.

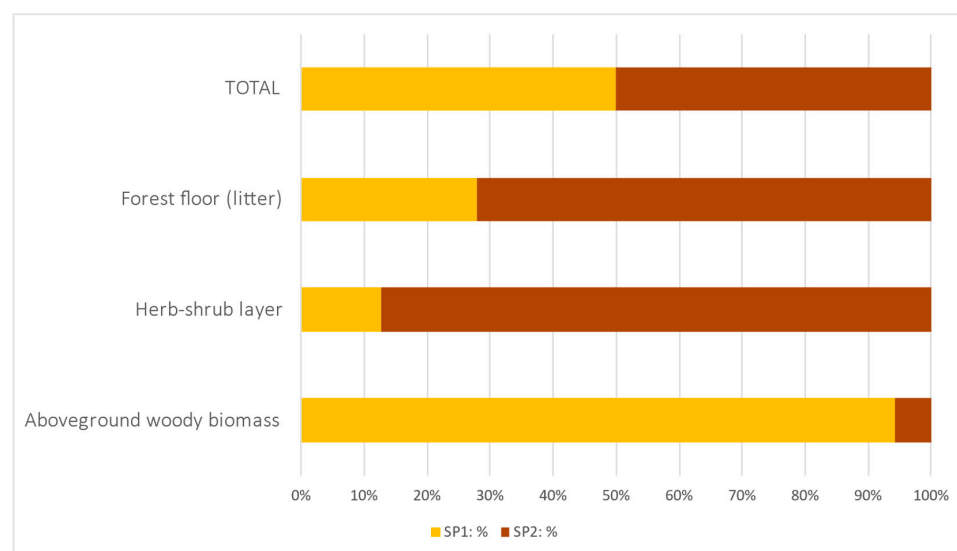


Figure 4. Relative contribution of the measured aboveground carbon pools to the total measured aboveground carbon stock of sample plots SP1 and SP2 (%).

For climate accounting comparison, carbon stocks are expressed as CO₂-equivalent ($\times 3.67$). The total aboveground stock for the 5.64-ha area was 225.7 t C, 79.8% of which was associated with the oak–pine forest (Table 6).

Table 6. Hypothetical extrapolation of the measured carbon plot, assuming homogeneous vegetation conditions and the corresponding CO₂-equivalent values for the studied plant communities.

Plant Community Type	C Stocks, t	Area, ha	Specific Stocks, t C ha ^{−1}	C Stocks as CO ₂ Equiv., t	Share, %
Oak–pine forest	180.1	2.81	64.1	661.0	79.8
Downy oak shiblyak	45.6	2.83	16.1	167.4	20.2
Supersite total	225.7	5.64	40.0	828.4	100

Note: Carbon stocks for vegetation areas were obtained by scaling plot-level measurements to the mapped area of each vegetation type. These estimates are illustrative only, assuming spatial homogeneity within each vegetation type. They should not be interpreted as direct measurements or regional carbon stock estimates.

3.5. C/N Ratios of Organic Matter

C/N ratios of the main organic fractions ranged from 11 to 100, indicating pronounced biochemical heterogeneity of inputs (Table 7, Figure 5). Herbaceous fractions had the lowest ratios (11–57), leaf litter of deciduous trees/shrubs had intermediate ratios (25–47), and branches/shoots of woody species had the highest (40–100); mixed forest-floor fractions ranged from 40 to 78.

Table 7. C/N ratios in the major functional groups of organic matter substrates.

Functional Group	Mean C, %	Mean N, %	C/N Range
Herbaceous plants (grasses, forbs)	43.6	1.5	11–57
Leaf litter from deciduous trees and shrubs	45.0	1.1	25–47
Branches and shoots of woody species	46.5	0.7	40–100
Forest floor and mixed fractions	37–45	0.6–0.8	40–78



Figure 5. Ranges of C/N values in the major functional groups of plant-derived organic matter at the sample plots of the carbon supersite (minimum and maximum values).

A visual breakdown comparing the relative spreads and ranges across these structural compartments can be seen in Figure 5, which shows the minimum and maximum values for each group.

The highest values recorded for branch and stem fractions (up to 100) characterize recalcitrant substrates that form a long-term stable pool of organic carbon [14,15].

3.6. Spatial Distribution of Carbon Stocks: Application of Two-Dimensional Heat Map Visualization

The carbon content of the tree layer within each plot was explored using RBF interpolation of per-tree stocks (see Figures 6 and 7 and Section 2.6 for caveats). In SP1, the pattern was highly heterogeneous. The highest values coincided with clusters of large-diameter *Pitsunda* pine near the center of the plot. Peripheral, more open, and shrubby areas showed the lowest values. Across the single 400 m² plot, the range spanned approximately two orders of magnitude, highlighting the influence of a few large trees. SP2 exhibited much lower absolute values and a more diffuse, mosaic pattern consistent with the absence of large-diameter trees.

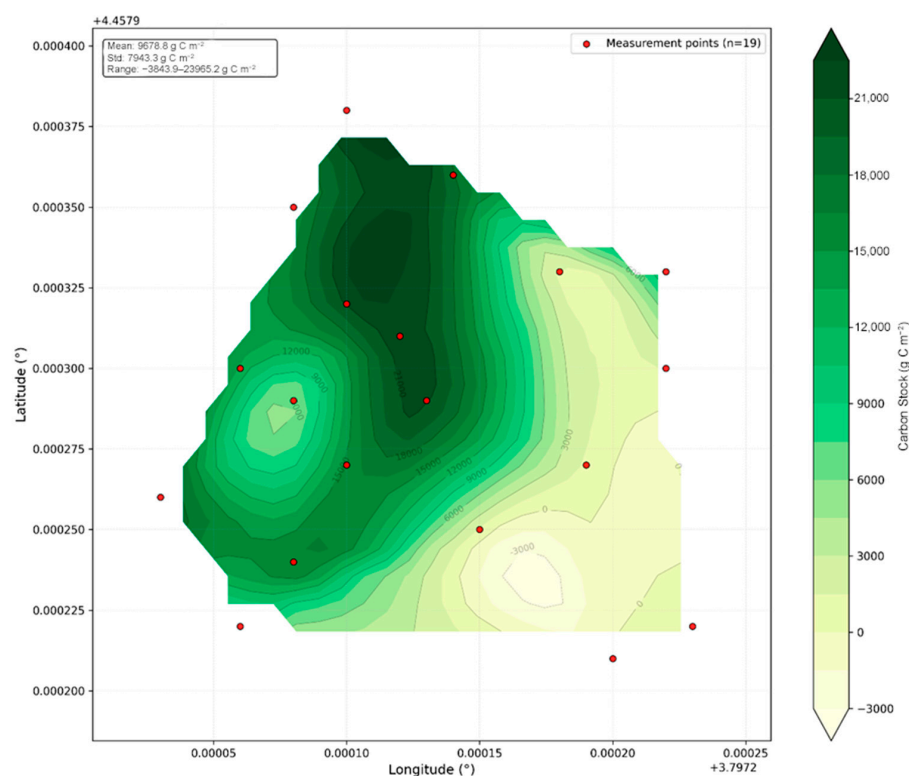


Figure 6. Spatial distribution map of aboveground biomass carbon stocks in the tree layer of SP1 (oak–pine forest, 20×20 m). The color gradient (viridis palette) reflects carbon density (g C m^{-2}); white dots denote individual tree positions; isolines show equidistant values. Interpolation by the RBF method (scipy.interpolate.Rbf), grid step 0.5 m. Negative interpolated values are artifacts of the interpolation procedure and have no physical meaning.

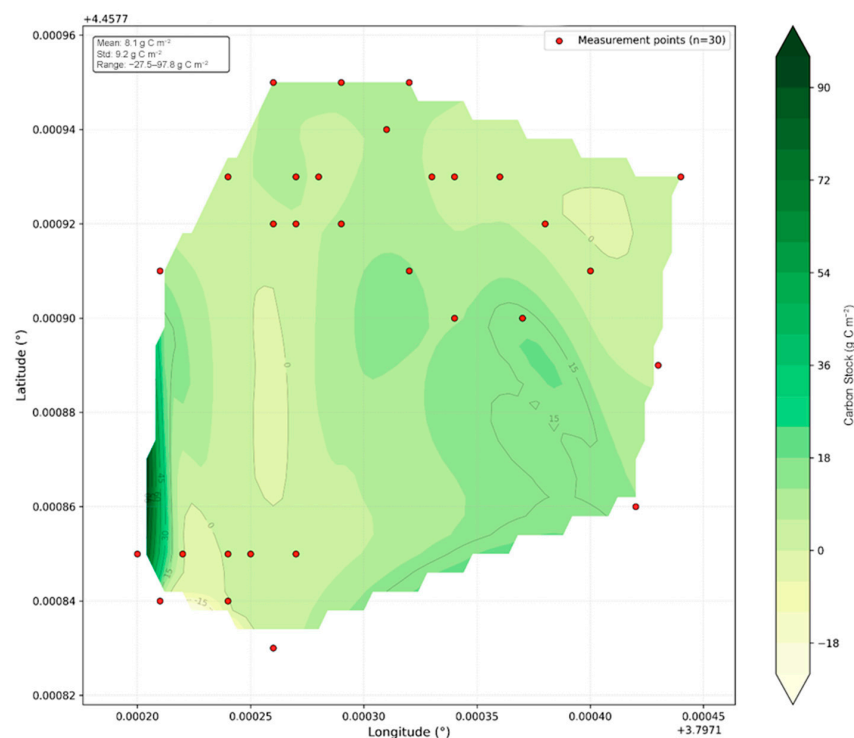


Figure 7. Spatial distribution map of aboveground biomass carbon stocks in the tree layer of SP2 (downy oak shiblyak, 20×20 m). The legend is the same as in Figure 6. Low absolute carbon values correspond to the predominance of small-diameter woody and shrub life forms. Negative interpolated values are artifacts of the interpolation procedure and have no physical meaning.

The produced maps are interpolative, indicating spatial patterns rather than quantitative extrapolation. The selection of the optimal interpolation method (RBF vs. geostatistical approaches such as kriging) and the incorporation of topography require further methodological evaluation. Since each community is represented by a single plot with limited point density, these maps are used for exploratory diagnostics only and are not employed to support quantitative conclusions at the ecosystem or landscape scale.

Nevertheless, the two-dimensional heat map approach was informative as a preliminary spatial diagnostic tool for carbon pools in structurally heterogeneous forest plant communities. Pronounced within-plot heterogeneity was identified in both plant communities (see Figures 6 and 7). This underscores the importance of spatially explicit approaches for scaling ecosystem carbon assessments at the landscape level.

4. Discussion

The aboveground carbon data are best interpreted together with previously published soil carbon and greenhouse gas flux data for the same plots [11], giving an integrated view of carbon storage in sub-Mediterranean carbonate ecosystems that spans aboveground biomass, soil organic and inorganic carbon, and soil–atmosphere CO₂/CH₄ exchange. These results constitute a preliminary, site-specific case study of two representative plots at the Gelendzhik supersite. Due to the design comprising only one 400 m² plot per community and the plots differing in stand origin, terracing, slope position, and composition, the observed contrasts cannot be attributed to any single driver. They are presented as ecosystem-specific patterns requiring verification through replication, not as generalizable statistical relationships for the sub-Mediterranean Black Sea coast as a whole.

4.1. Aboveground Versus Soil Carbon Pools

At SP1, the aboveground carbon stock (64.1 t C ha^{−1}) was substantially lower than the reported soil organic carbon (SOC) stocks for terraced Skeletic Rendzic Leptosols (120–170 t C ha^{−1}) [11]. Consequently, the soil carbon pool was approximately 1.9–2.7 times larger than the aboveground carbon pool, consistent with temperate and sub-Mediterranean forests, where soils typically store the majority (approximately 60%) of ecosystem carbon [25]. Buried humic horizons are important (up to 7.41% TOC at 0–10 cm in Pit 1) and largely absent from natural rendzinas [11]. At SP2, the aboveground density (16.1 t C ha^{−1}) is roughly 4× lower, and the soil is dominated by inorganic (carbonate) carbon (IC 15–28 kg m^{−2}; TOC only 6–7 kg m^{−2} = 60–70 t C ha^{−1}) [11], so carbon storage is controlled more by carbonate than by organic accumulation. Reported MBC (mean 411 µg C g^{−1}, top 40 cm) tracks TOC (r = 0.8) and declines with depth [11].

The extrapolated carbon stocks presented for the mapped vegetation units are illustrative estimates derived from plot-level measurements. Since only one plot was sampled per vegetation type, these values are not intended to provide a statistically robust estimate of total ecosystem carbon stocks across the entire carbon supersite.

4.2. Role of Anthropogenic Terracing in the Carbon Sequestration System

Terracing at SP1 (~70 years ago) is associated with two co-occurring mechanisms that may enhance sequestration: in the soil, redistribution and partial burial of organically enriched horizons created additional TOC accumulation zones, with Ca-mediated organo-mineral stabilization under alkaline carbonate conditions (indirectly supported by lower qCO₂ in Pit 1) [11,16]; aboveground, the plantation accumulated 64.1 t C ha^{−1}, ~4× the natural shiblyak. Similar terracing effects on SOC are reported for Mediterranean Turkey, Spain, and the Apennines [26–28]. Terracing may also influence soil depth, water retention, and the redistribution of fine soil material, thereby affecting vegetation establishment and

long-term carbon accumulation. However, because the SP1–SP2 contrast is confounded (Section 2.1), the relative roles of terracing per se versus stand origin, species, slope position, terrace age, and hydrology cannot be separated here; isotopic work ($\delta^{13}\text{C}$, ^{14}C) is needed to apportion these factors, as emphasized in [11]. Therefore, the observed co-occurrence of high aboveground biomass and previously reported high SOC at SP1 should be interpreted as a site-specific observation rather than evidence of a causal terracing effect.

4.3. Litter C/N Ratios and Soil Microbial Activity

Here the C/N results (Section 3.5) are interpreted mechanistically. The high C/N of coniferous litter and woody pine fractions at SP1 is consistent with slow decomposition, low bioavailability, and the formation of comparatively stable carbon pools—in line with the lower qCO_2 recorded in Pit 1–2 soils [11]. At SP2, downy oak deciduous litter (C/N 25–47) decomposes faster, generating a larger labile pool, consistent with elevated microbial activity in Pit 4–5 soils [11]; this accelerates cycling and respiration but reduces long-term stabilization. These patterns suggest that floristic composition may influence soil carbon dynamics primarily through differences in litter quality (C/N), thereby potentially affecting the balance between mineralization and carbon accumulation [14,28]. The highest C/N values (branch/stem fractions, up to ~100) characterize recalcitrant substrates that may contribute to a longer-lived carbon pool [14,15].

4.4. Greenhouse Gas Fluxes and Carbon Sequestration Patterns

The chamber data in [11] show pronounced seasonal CO_2 dynamics and persistent CH_4 uptake at both plots (SP1: $0.54\text{--}3.51\ \mu\text{mol m}^{-2}\text{ s}^{-1}$; SP2: higher, with spring–summer peaks). The higher soil CO_2 emissions observed at SP2, together with its smaller aboveground carbon pool ($16.1\ \text{t C ha}^{-1}$), indicate differences in carbon cycling between the two investigated communities. However, because only soil greenhouse gas fluxes were measured, these observations should not be interpreted as evidence of differences in net ecosystem carbon sequestration or carbon source–sink behavior. The larger aboveground carbon pool at SP1 ($64.1\ \text{t C ha}^{-1}$) therefore reflects greater accumulated biomass rather than a directly measured carbon sequestration rate. The stable CH_4 uptake at both sites (-0.2 to $-0.95\ \text{nmol m}^{-2}\text{ s}^{-1}$) reflects methanotrophy in the aerobic carbonate horizons [11]. The SP1 forest floor stabilizes moisture and aeration. CO_2 emissions correlate positively with soil temperature ($r = 0.65$) and negatively with moisture ($r = -0.25$) [11], implying that soil respiration is sensitive to climatic conditions. These relationships suggest that soil carbon fluxes may respond differently to future climatic changes at the two sites, although confirmation would require long-term ecosystem-scale measurements.

4.5. Inorganic Carbon and Its Interaction with Aboveground Pools

Gorbov et al. [11] quantified IC separately. At SP2, IC in undisturbed rendzinas reached $28.7\ \text{kg m}^{-2}$, exceeding the corresponding TOC stock and substantially exceeding the aboveground carbon pool at SP1 ($\sim 6.4\ \text{kg m}^{-2}$). These values illustrate the importance of inorganic carbon as a major component of the soil carbon pool in carbonate sub-Mediterranean ecosystems, where it represents a relatively stable carbon reservoir. Rhizosphere organic acids (including those associated with conifer roots) may promote carbonate dissolution and contribute to soil CO_2 production under alkaline, well-aerated conditions (pH 8.1–8.9) [11].

The present study did not include field measurements of inorganic carbon or isotopic ($\delta^{13}\text{C}$, ^{14}C) analyses to evaluate vegetation–carbonate interactions, such as rhizospheric carbonate dissolution or its contribution to soil CO_2 efflux. Consequently, the discussion of inorganic carbon dynamics is based on previously published data [11] and should be

regarded as an interpretation requiring further verification through isotopic and process-based investigations (see Section 4.7).

4.6. Comparison with Other Mediterranean and Sub-Mediterranean Regions

The SP1 density (64.1 t C ha^{-1}) is toward the lower end of the reported range of $50\text{--}250 \text{ t C ha}^{-1}$ for temperate and sub-Mediterranean forests [5,6]. This is consistent with a young-to-mid-aged plantation on a skeletal carbonate substrate. The SP2 density (16.1 t C ha^{-1}), however, falls below this range, as expected for open, xerophytic shrubland. Similar differences in aboveground carbon storage have been documented between forest and shrub-dominated ecosystems across Mediterranean regions, including the Iberian Peninsula, the Apennines, and Anatolia. In these regions, forest management and stand development are recognized as key drivers of ecosystem carbon accumulation [28–30]. However, comparable studies from the Caucasian Black Sea coast are limited, leaving this region underrepresented in Mediterranean carbon stock literature. Comparing our plots to these ranges provides descriptive context for the investigated communities rather than establishing a quantitative regional benchmark, and the present observations should not be interpreted as representative of the broader region because they are based on two unreplicated study plots.

4.7. Limitations and Future Directions

This study is limited to two 400 m^2 permanent plots (one per vegetation community) and previously published soil carbon and greenhouse gas data obtained from five soil pits [11]. The study design is unreplicated and includes several confounding environmental factors, precluding statistical generalization and formal evaluation of aboveground–soil relationships.

Aboveground biomass was estimated using the generalized allometric model of Chave et al. [12], as species-specific equations are currently unavailable for several Mediterranean woody species occurring in the study area. Applying a single allometric framework also ensured methodological consistency across all sampled trees.

The available greenhouse gas measurements represent only the 2024–2025 observation period. The RBF interpolation maps are exploratory and were not subjected to geostatistical uncertainty analysis; therefore, they should be interpreted as visualizations of local spatial patterns rather than predictive maps. Additional sampling would be required to reduce interpolation uncertainty and improve spatial prediction.

Future research should expand replication across the $\sim 5.6 \text{ ha}$ supersite and include repeated biomass measurements to quantify annual vegetation carbon sequestration rates. Additional priorities include $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ isotopic analyses to distinguish biogenic and carbonate-derived CO_2 , verification of rhizospheric carbonate feedbacks, automated chamber measurements to capture diurnal greenhouse gas dynamics, measurements of net ecosystem exchange (NEE), and comparison of the RBF approach with cross-validated geostatistical interpolation incorporating topographic covariates.

5. Conclusions

This descriptive case study quantified aboveground biomass carbon in two contrasting plant communities of the Gelendzhik carbon-monitoring supersite and interpreted these observations together with previously published soil carbon and greenhouse gas data [11].

The terraced oak–pine plantation (SP1) stored $\sim 64.1 \text{ t C ha}^{-1}$, approximately four times more aboveground carbon than the natural downy oak shiblyak (SP2, $\sim 16.1 \text{ t C ha}^{-1}$). Woody biomass was the dominant carbon pool in both communities, whereas litter and herbaceous vegetation contributed proportionally more in the shiblyak. Both communi-

ties belong to the *Quercion pubescenti–petraeae* and *Paliuro–Quercion pubescentis* alliances, characteristic of the northeastern Black Sea region.

C/N ratios (11–100) indicate strong substrate heterogeneity. High C/N values in coniferous and woody fractions may be associated with slower decomposition and greater carbon stabilization, whereas lower C/N values in deciduous and herbaceous material may be associated with faster mineralization. These observations provide a potential ecological explanation for the soil microbial patterns previously reported in [11].

At the terraced site, previously published high soil organic carbon stocks (up to $\sim 17 \text{ kg m}^{-2}$ TOC) co-occurred with a large aboveground woody carbon pool. This spatial pattern may reflect the combined influence of vegetation, historical terracing, and soil-forming processes, although the present study does not allow these factors to be distinguished. Because the SP1–SP2 comparison is based on two contrasting, unreplicated study plots, this interpretation should be regarded as a site-specific hypothesis requiring validation through replicated investigations, including isotopic and process-based analyses, rather than as evidence of a causal terracing effect.

RBF interpolation revealed pronounced within-plot heterogeneity, illustrating the value of spatially explicit sampling. These maps are intended exclusively for exploratory visualization and require independent geostatistical validation before quantitative extrapolation.

Although this work is based on only two permanent study plots, it provides one of the first integrated descriptions of aboveground biomass carbon, together with previously published soil carbon and greenhouse gas data, for contrasting sub-Mediterranean vegetation on the northeastern Black Sea coast. These results establish a baseline for future replicated, spatially explicit investigations of ecosystem carbon dynamics and long-term carbon monitoring in this understudied region. Future studies based on replicated field experiments should further evaluate the relative roles of vegetation composition, historical terracing, and soil properties in shaping ecosystem carbon storage. The observations presented here are site-specific and should not be extrapolated beyond the two investigated plots.

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Abbreviations

The following abbreviations are used in this manuscript:

AGB	aboveground biomass
BR	basal respiration
C/N	carbon-to-nitrogen ratio

DBH	diameter at breast height
IC	inorganic carbon
MBC	microbial biomass carbon
NEE	net ecosystem CO ₂ exchange
qCO ₂	metabolic quotient
RBF	radial basis function
SBIO RAS	Southern Branch of the P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences
SOC	soil organic carbon
SP	sample plot
TOC	total organic carbon

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