Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 03, March, 2025

Assessment of Organic Carbon Stocks at Landscape Levels Using the InVEST Software

Polina Drygval [1, 2, 3*], Anna Drygval [1, 2], Vladimir Tabunshchik [1, 2]

[1] *A.O. Kovalevsky Institute of Biology of the Southern Seas of RAS, Sevastopol, 299011, Russia.*

[2] *T.I. Vyazemsky Karadag Scientific Station – Nature Reserve of RAS – Branch of A.O. Kovalevsky Institute of Biology of the Southern Seas of RAS, Feodosia, Kurortnoye, 298188, Russia.*

[3] *FSE RTC RCSH, Moscow, 123182, Russia.*

Received 18 December 2024; Revised 12 February 2025; Accepted 21 February 2025; Published 01 March 2025

Abstract

This study aims to calculate and assess organic carbon levels at various landscape levels of the Crimean Peninsula using the Carbon Storage and Sequestration model of the InVEST software. It outlines the stages of working with this model and highlights limitations such as the quality of input data, temporal coverage, and spatial resolution, which can significantly influence the results. Assessment of organic carbon stocks in soils, aboveground and belowground biomass, and vegetation types revealed that the highest carbon concentration was in the low-altitude landscape level of the southern macroslope. From 2017 to 2023, an annual decrease in organic carbon stocks of 0.062 t/ha was recorded, which is likely linked to climate change and shifts in land use. This research provides the first calculations of organic carbon content within the landscape levels of the Crimean Peninsula. As carbon is a significant greenhouse gas, its accumulation or emissions directly affect climate change. Evaluating organic carbon stocks in ecosystems enhances our understanding of their role in mitigating climate change and informing carbon dioxide (CO_2) reduction strategies. These findings highlight the need to consider vegetation types and their changes when calculating organic carbon in landscapes and supporting regional environmental policy development.

Keywords: Organic Carbon Stocks; Aboveground Biomass; Soil Carbon; Belowground Biomass; Land Cover Types; Landscape Levels; Invest Software; The Crimean Peninsula.

1. Introduction

Many studies examining carbon accumulation in the environment focus primarily on carbon accumulation in soils, as seen in works [1-3], while also considering carbon accumulation in forest litter [4]. Less frequently, researchers have addressed the question of carbon accumulation in ecosystems and landscapes [5]. Soil is a key component of the global carbon cycle and accounts for approximately 80% of the organic carbon in the biosphere. It is estimated that Earth's soil cover contains three times more organic carbon than vegetation cover and twice as much organic carbon as the atmosphere [6]. According to another group of researchers [7], soil contains three times more organic carbon than the atmosphere does. However, soil carbon is present in both organic and inorganic forms [8]. Carbon serves as a source of nutrients for soil biomass, promoting the formation and accumulation of humus and microelements (Cu, Zn, B, Mn, Mo, and Co) in the soil. These elements form complexes with humic substances, making them easily absorbed by plants [9]. When carbon is deficient, microbial activity declines and nitrogen activity in the soil weakens [10].

* Corresponding author: pdrygval@yandex.ru

http://dx.doi.org/10.28991/CEJ-2025-011-03-018

In general, the question of the possibility of organic carbon storage by ecosystems or components of the natural environment is being considered in many world studies. Organic carbon stocks in the ecosystem, particularly in the soil, can significantly change due to anthropogenic activities (land use change), which, in turn, affects ecosystem services such as climate regulation. Many studies have shown that land-use change significantly influences organic carbon stocks; for example, a study conducted in Nepal revealed that they vary depending on land-use type, reaching the highest values in forests and the lowest in degraded lands [11].

Few studies have addressed the problem of carbon storage in ecosystems, particularly through model calculations. Recently, researchers have highlighted the connection between the slowdown of organic carbon accumulation in ecosystems and global warming processes. Despite increasing anthropogenic emissions, terrestrial ecosystems annually absorb approximately 30% of all anthropogenic emissions, particularly carbon dioxide (CO_2). In this process, absorbed carbon mainly accumulates in plant biomass or soil organic matter [12].

The potential decrease in carbon content in ecosystems might be related to the general trend of increasing average annual temperatures and warming climate trends overall. Previous studies [13, 14] have tested the hypothesis that ecosystems could accumulate more carbon dioxide (CO_2) in the future than they do now, as the intensity of photosynthesis increases with rising air temperatures. However, when exceeding a critical level of air warming, the photosynthesis process decreases, and the process of organic carbon accumulation by ecosystems is also suppressed. The authors established that the temperatures for peak photosynthetic activity were 18 and 28 °C for plants (with C3 and C4 types of photosynthesis, respectively), and after exceeding these threshold temperatures, the intensity of photosynthesis decreased. At a certain point, with critical levels of temperature and atmospheric concentrations of pollutants, conditions arise where terrestrial ecosystems can release more carbon than they can absorb. This can also be linked to changes in the overall land-use patterns (for example, an increase in built-up areas and a decrease in areas with vegetation cover).

Most of the research in this direction is limited to the assessment of carbon in soils and its relationship to the vegetation cover growing on them. Beillouin et al. [15] established that land conversion for agriculture leads to significant losses of soil organic carbon. Land use change also sometimes leads to radical changes in the vegetation cover of the territory, sometimes leading to deforestation (which accounts for approximately 12% of global anthropogenic greenhouse gas emissions). Some significant Initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) are aimed at addressing these issues, including actions to reduce emissions, conserving carbon in forests, and sustainably managing forest resources. However, effective national monitoring systems are necessary for the successful implementation of REDD+ [16].

Standardized protocols and methods are required to monitor soil carbon stocks effectively. However, there are no universally applicable protocols for measuring and monitoring carbon in diverse landscapes. Such methods need to integrate carbon measurements into broader observation schemes that consider land conditions, soil quality, and vegetation productivity [17].

The results of research on soil organic carbon stocks in various ecosystems and their spatial distribution are crucial for understanding the role of these ecosystems in the global carbon cycle. A study in Hakkari province, Turkey [18], showed that carbon stocks in wetlands (flooded vegetation) are significantly higher than those in other land types, with the highest values reaching 61.46 Mg C/ha. The accumulation of carbon dioxide (CO_2) in the atmosphere is promoted by the burning of fossil fuels and deforestation [19], which influences modern climate change processes. Therefore, the creation of a network of monitoring sites or carbon polygons to observe climate processes and carbon fluxes in ecosystems is an important task in climate science [20].

In the context of monitoring and assessing changes in ecosystems in terms of carbon content, methods utilizing remote sensing are increasingly being employed. In particular, the InVEST model can effectively calculate and visualize carbon storage in ecosystems based on organic carbon stock data. Currently, some scientific studies assessing organic carbon content and its accumulation characteristics use this model to identify the spatiotemporal characteristics of carbon accumulation in ecosystems. The nature of research in such studies generally focuses on evaluating various territories, including individual countries [21], cities [22-27], natural areas [23, 25], and watersheds [28-30].

After analyzing the carbon content using the InVEST model, it was noted that this model is not the only one that describes the potential spatiotemporal distribution of organic carbon in a territory; for example, the CASA model also effectively reflects carbon stocks in urban ecosystems [22]. Another study quantitatively assessed carbon absorption during the restoration of riparian zones in Ecuador. A comparison of six restoration scenarios using the InVEST model showed that wider corridors along waterways provide higher carbon absorption values [28]. A scenario-based approach for studying carbon accumulation in ecosystems using the InVEST model was conducted in Liaoning Province (China). Projections for 2050 indicated significant differences in carbon accumulation depending on the scenario (with the ecological restoration scenario demonstrating positive growth due to an increase in forested areas), and the authors of the study emphasized the need for strict policies to control the growth of urbanized lands [23]. The same findings have been reported in studies [25, 31], where the analysis of carbon accumulation in Kunming and Heilongjiang (China) indicated a decrease in carbon in the region from 2000 to 2020, which is associated with a reduction in forest land area. However, projections for 2030 suggest possible carbon accumulation, depending on the development scenario.

A study in the city of Abha (Saudi Arabia), related to the quantitative assessment of carbon accumulation potential under changing land use, using the InVEST model, showed that from 1990 to 2040, agriculture and vegetation will lose significant amounts of organic carbon [24]. In previous studies [26, 29] (the Beht watershed in Morocco and Uva Province, Sri Lanka), the main conclusion was related to the fact that the increase in carbon accumulation in ecosystems is associated with the spread of natural forests, highlighting the importance of forest ecosystems for carbon accumulation and the need for the development of environmental policies regarding them. Additionally, a study using the InVEST model conducted in northwestern Morocco showed an increase in the total carbon stock due to the conversion of unused lands into forests and agricultural lands, which further emphasizes the importance of managing these ecosystems [21].

A decrease in organic carbon levels when assessing its stocks using the InVEST model was noted in studies [27] in Noida Province (India) and within the Nour-rud watershed in Iran [30]. These studies emphasize that land use change could lead to irreparable losses of carbon stocks in ecosystems in the future, which, in turn, would affect its economic value. It should be noted that the modern approach to local monitoring of the absorption and release of greenhouse gases (including carbon dioxide (CO_2)) by ecosystems is the formation of carbon polygons, which are territories with vegetation, terrain, and soil characteristics of local ecosystems. Carbon polygons are aimed at conducting activities related to carbon balance control, accounting for the release and absorption of climate-active gases by ecosystems, and creating new methods for regulating the release and absorption of climate-active gases [32]. Carbon trusses perform slightly different tasks. They are used to capture carbon dioxide (CO_2) from the atmosphere through natural ecosystems and carbon farms. Carbon farms are plantations and plots of land where these technologies for absorbing greenhouse gases are directly applied [33].

Since February 2021, the Russian Federation has implemented a program to create carbon polygons as part of the national plan of measures for the first stage of adaptation to climate change. This program includes research aimed at assessing the integrated values of the carbon balance for different types of ecosystems, which will allow for the calculation of the carbon footprint for individual subjects of the Russian Federation and the country [34-36]. In this regard, Russia has started creating projects with carbon polygons, which are already operational in the Chechen Republic [37], Republic of Tatarstan [38], Kaluga Region [39], Krasnodar Territory, Kaliningrad Region, Moscow Region, Sverdlovsk Region, Tyumen Region, Novosibirsk Region, Sakhalin Region, Voronezh Region, Republic of Bashkortostan, Khanty-Mansi Autonomous Area, Kirov Region, Rostov Region, Volgograd Region, Samara Region, Primorsky Territory, Yamal-Nenets Autonomous Area, and Tomsk Region. There are 19 operational carbon polygons in Russia in total [40]. Overall, Russia is currently developing a system of carbon polygons with detailed and modern studies of greenhouse gas exchange (such as the global eddy covariance flux measurement systems Eddy Covariance, AmeriFlux, or EuroFlux [41]).

The opening of new carbon polygons has been planned, including in the Republic of Crimea. Currently, some studies are being conducted in the territory of the Crimean Peninsula to assess the potential of the territory for a general contribution to carbon dioxide (CO_2) accumulation in ecosystems, as carbon polygons are expected to cover all representative ecosystems of Russia with the aim of accounting for their carbon balances. In general, the aforementioned studies highlight the importance of assessing the carbon sequestration capacity of ecosystems for the effective management of carbon resources. Given the relevance of conducting such research on the assessment of organic carbon stocks, we determined that the most convenient method for studying carbon stocks at the landscape level of the Crimean Peninsula will be the use of InVEST® software [42]. This research will take into account the experience of previous studies and endeavors, as well as form new and relevant data on the issue of organic carbon accumulation in the study area.

Overall, understanding and monitoring changes in soil carbon stocks are crucial for developing strategies to combat land degradation and climate change. Modern approaches to assessing organic carbon content, including remote sensing and improved mathematical models, can significantly improve our understanding of the carbon cycle and contribute to more effective management of ecosystem resources.

The remainder of this paper is organized as follows: Section 2 describes the study area and the methodology for calculating organic carbon stocks using the InVEST software, outlining the main steps involved. In addition, information is provided on the sources of the input layers and their key characteristics. Section 3 presents the results of the accumulated organic carbon calculations within the ecosystems of various landscape levels. Section 4 discusses the study of organic carbon accumulation in different environmental components as well as the advantages and disadvantages of the remote assessment method using InVEST software. Section 5 summarizes the study, highlighting the novelty of the research, theoretical contributions, practical significance, key limitations, and opportunities for further studies.

2. Material and Methods

The main aim of this study is to calculate and assess the amount of organic carbon within the landscape of the Crimean Peninsula to incorporate this information into ecological research in the area. The study design is illustrated in Figure 1.

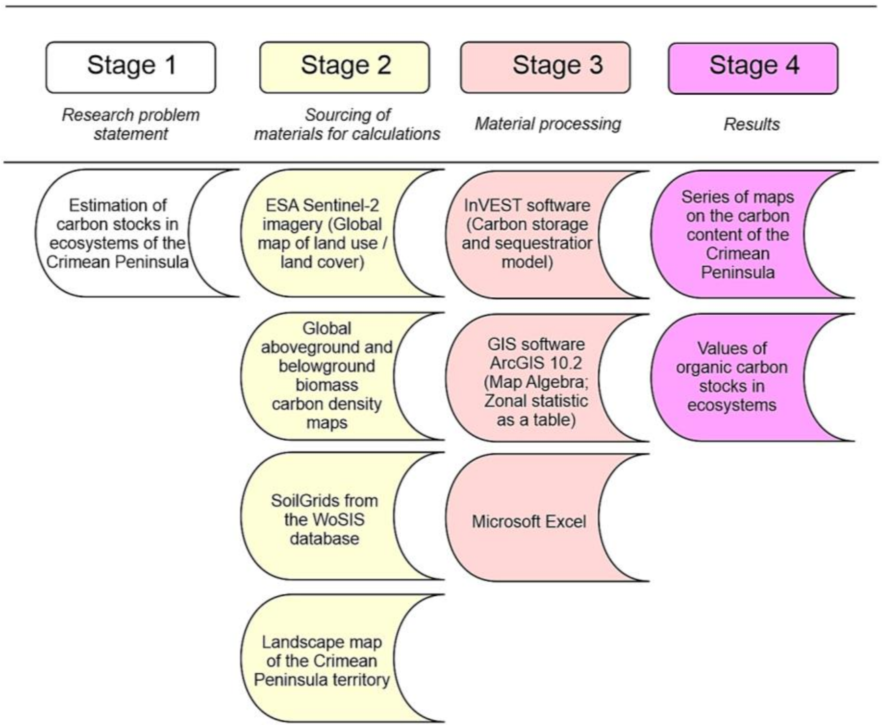

Figure 1. Flowchart of the research design

2.1. Study Area Characteristics

The Crimean Peninsula (Russia) is located almost equidistant from the equator and North Pole (44°23” – 46°15” N and 32°30” – 36°40” E) [43]. The peninsula is located south of the Eastern European Plain. The territory of the Crimean Peninsula is washed by the Black Sea and the Sea of Azov, which belong to the Atlantic Ocean basin (Figure 2).

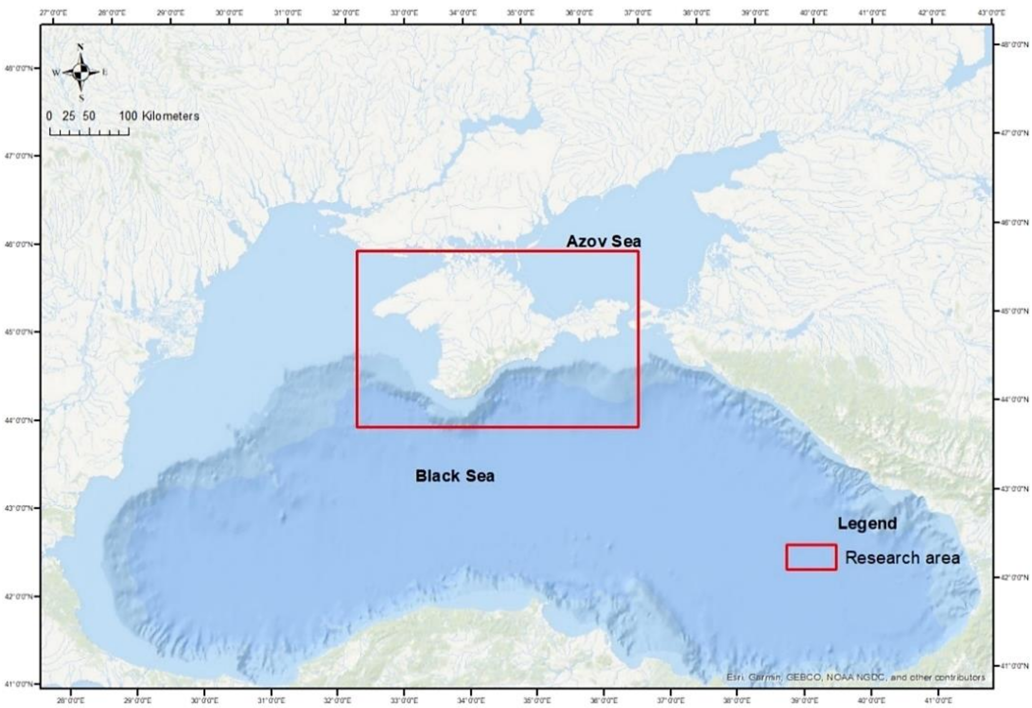

Figure 2. Territory of the Crimean Peninsula

The terrestrial ecosystems of the Crimean Peninsula are shaped by a diverse array of climatic, topographic, and soil factors. The climate of Crimea is predominantly considered temperate: a mild steppe climate characterizes the plain part of Crimea, whereas a mountain-broadleaf climate prevails in the mountainous region. However, the Southern Coast of Crimea is characterized by a sub-Mediterranean climate [43]. The average annual air temperature in the study area varies significantly, from +7.5 °C in mountainous areas to +11.5 °C in the steppe Crimea [44]. Overall, the climate of Crimea is arid.

Atmospheric circulation in Crimea is characterized by a predominance of westerly transport (75% of cases). Periodically, cold air from northern latitudes invades the peninsula (10% of cases) and warm moist air from the Mediterranean Sea (8% of cases). Dry air from Asia also influences this area. Unique local circulations developed in Crimea: breezes, foehn winds, bora winds, and mountain-valley winds [45]. Overall, the assessment of the spatial-temporal relationship and interannual dynamics of the productivity of Crimean ecosystems with hydro-thermal conditions was conducted in previous studies [46, 47], and the entry of biogenic elements into ecosystems with atmospheric precipitation has been shown in previous works [48, 49].

The bedrock (as the lithogenic basis for the development of terrestrial ecosystems) is diverse, both in origin and composition. Among the rock types, igneous, metamorphic, and sedimentary rocks were found. Surface deposits are represented by marine, lagoon-marine, and continental (eluvial, eluvial-deluvial, aeolian-eluvial-deluvial, and proluvial, alluvial, proluvial-alluvial, gravitational, and landslide deposits) deposits. The thickness of these deposits varies from fractions of a meter on the surface of the mountain ranges to tens of meters at their foot [43].

Soil processes on the Crimean Peninsula occur under conditions of a cool, prolonged, and dry spring; warm, dry summer; warm, long autumn; and short, mild (with thaws) winter. Under these conditions, the soil microbial activity continues throughout the year, with only a slight weakening during the cool season. As a result, the developing soils in Crimea contain less humus than the similar soils in other regions [43]. The following soil types are found within the Crimean Peninsula (soil classification according to Egorov et al. [50] and World Reference Base for Soil Resources [51] soil classifications): brown (Cambisols Chromic (CMcr)), mountain meadow (Leptosols Humic (LPhu)), meadow-steppe (Leptosols Mollic (LPmo)), mountain brown forest (Calcisols Haplic (CLha)), sod carbonate (Leptosols Rendzic (LPrz)), chestnut (Kastanozems Haplic (Ksha)), chernozem (Chernozems Chernic (CHch)), meadow-chernozem (Phaeozems Haplic (PHha)), meadow-chestnut (Phaeozems Haplic (PHha)), meadow (Gleysols Humic (GLhu)), meadow-bog (Gleysols Histic (GLhi)), and alluvial soils (Fluvisols Umbric (FLum) и Fluvisols Calcaric (FLcc)).

Based on botanical-geographical zoning, the Crimean territory belongs to the Euro-Asian steppe zone (Pontic province) and the Mediterranean mountain zone (Euxine province). In the Crimea steppe, the steppe type of vegetation (petrophytic, psammophytic, and semi-desert steppes) dominates, whereas meadow-type vegetation (halophytic and true meadows) is less common. It is also noted that the natural vegetation of the Crimean Steppe has been preserved only in certain areas, while the rest of the territory is occupied by agricultural crops. The distribution of vegetation cover in the mountainous part of Crimea follows an altitudinal zonation. In this study, forest steppes, oak forests, beech and beech-hornbeam forests, mountain steppes and meadows, juniper-oak forests, pine forests, and shrub thickets were studied [52].

2.2. Using InVEST Software to Calculate Carbon Stocks

The Carbon Storage and Sequestration model of InVEST software [42] is user-friendly, as it is based on a simplified carbon cycle. It utilizes four carbon pools and a land cover data layer (LULC) for operation. Carbon storage in the study area depends on the volumes of the four carbon reservoirs: aboveground biomass, belowground biomass, soil, and dead organic matter (which can be ignored). Aboveground live biomass includes all living plants above the soil surface, such as the bark, stems, branches, and leaves. The belowground live biomass encompasses the root systems of these plants. Soil organic matter is a key component of the soil and represents the largest terrestrial carbon reservoir. Dead organic matter includes litter and dead wood (if available). The model integrates data on the carbon content in these pools according to land use maps (LULC) and estimates the total amount of carbon in the area. However, this model does not account for certain dynamic changes, such as tree growth, changes in soil chemical composition, or the impact of temperature and precipitation changes on carbon stocks over time [53].

Carbon stocks were calculated within landscape levels for the Crimean Peninsula using the Carbon Storage and Sequestration model of the InVEST software [42], ArcGIS 10.2, and MS Excel. The following input raster data were considered for using this model: (1) land use and land cover (LULC) raster layer, (2) soil organic carbon stock raster layer, (3) aboveground live biomass carbon stock raster layer, (4) belowground live biomass carbon stock raster layer, and (5) dead biomass carbon stock raster layer (if available).

The characteristics of the input layers used for the overall carbon stock calculations are presented in Table 1.

Table 1. Characteristics of input layers for carbon stock calculation

Land use and land cover raster layer			
Source	**Spatial Coverage (resolution)**	**Temporal Coverage**	**Types of land use**
Sentinel-2 10 m Land Use/Land Cover [54]	10 m × 10 m	2017-2023	Water, Trees, Flooded vegetation, Crops, Built area, Rangeland, Bare ground, Snow | Ice, Clouds
Soil organic carbon stock raster layer			
Source	**Spatial Coverage (resolution)**	**Thickness**	**Unit of measurement**
SoilGrids250 [55]	250 m × 250 m	0-30 cm	t/ha
Aboveground and belowground live biomass carbon stock raster layers			
Source	**Spatial Coverage (resolution)**	**Scale**	**Unit of measurement**
Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010 [56]	300 m × 300 m	×10	t/ha

All uncertainties in the data, such as the absence of the "*Dead biomass*" layer and different spatial resolutions of the data, affect the final calculation and assessment of organic carbon stocks within the landscape levels of the Crimean Peninsula. However, we accept the result with a certain degree of error, as the use of the model will provide new data on the total carbon stocks in the study area, allowing for more detailed research in the future.

In general, terms, the scheme for calculating carbon stocks in landscapes using the Carbon Storage and Sequestration model of the InVEST software within landscape contours is presented in Figure 3. There are several steps to be taken and some nuances in performing these steps are described below.

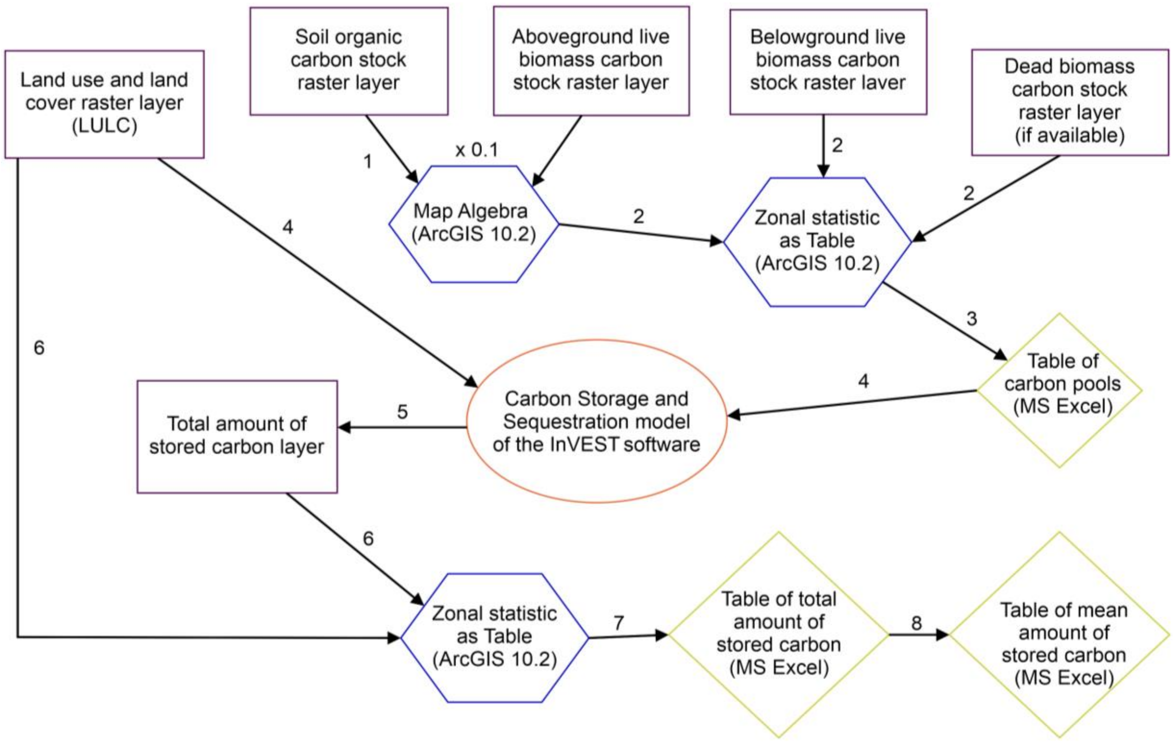

Figure 3. Basic steps for calculating organic carbon stocks using InVEST software [41]

2.2.1. Data Preparation

Land cover types and land use layers [54] use land cover types where stored carbon is present for calculations, such as trees, flooded vegetation, crops, and bare ground. This rasterized layer was directly loaded into the Carbon Storage and Sequestration model of InVEST software [42].

Data in above-ground and below-ground living biomass layers [56] need to be transformed using the Map Algebra tool in ArcGIS 10.2 - multiplied by 0.1, because the data in their original form are scaled by a factor of 10 to reduce the weight of the primary raster files. In addition, we neglected data on carbon stocks in dead biomass because the Carbon Storage and Sequestration model allows us to do so if they are not available for further calculations.

2.2.2. Calculating Carbon Pools

To calculate the amount of carbon for each land cover type, the "Zonal Statistic as a Table" tool in ArcGIS 10.2 is used to summarize the values of rasters within zones of another dataset. Using this tool, we obtained in attribute tables how much t/ha of carbon (average value) is contained in soil at 0-30 cm depth, aboveground biomass, and belowground biomass within each land cover type from 2017 to 2023.

The data were then copied from the attribute tables of the resulting new files into a general table of carbon pools in MS Excel. Further, for calculations, we needed data only on land cover type and "mean" values for each carbon pool. The resulting tables for the period from 2017 to 2023 MS Excel are saved with extension csv.

2.2.3. Using the Carbon Storage and Sequestration Model of the InVEST Software

Calculate carbon stocks within the Crimean Peninsula using the Carbon Storage and Sequestration model of the InVEST software [42]. For this purpose, raster layers of land cover types (LULC) from 2017 to 2023 and tables of carbon pools for the corresponding period were loaded into the model. The output from the model is layers with units of tons/pixel for the period 2017 to 2023.

Figure 4 shows, for example, the layer of carbon stocks within the Crimean Peninsula in 2023 obtained after processing the input data in the InVEST program [42].

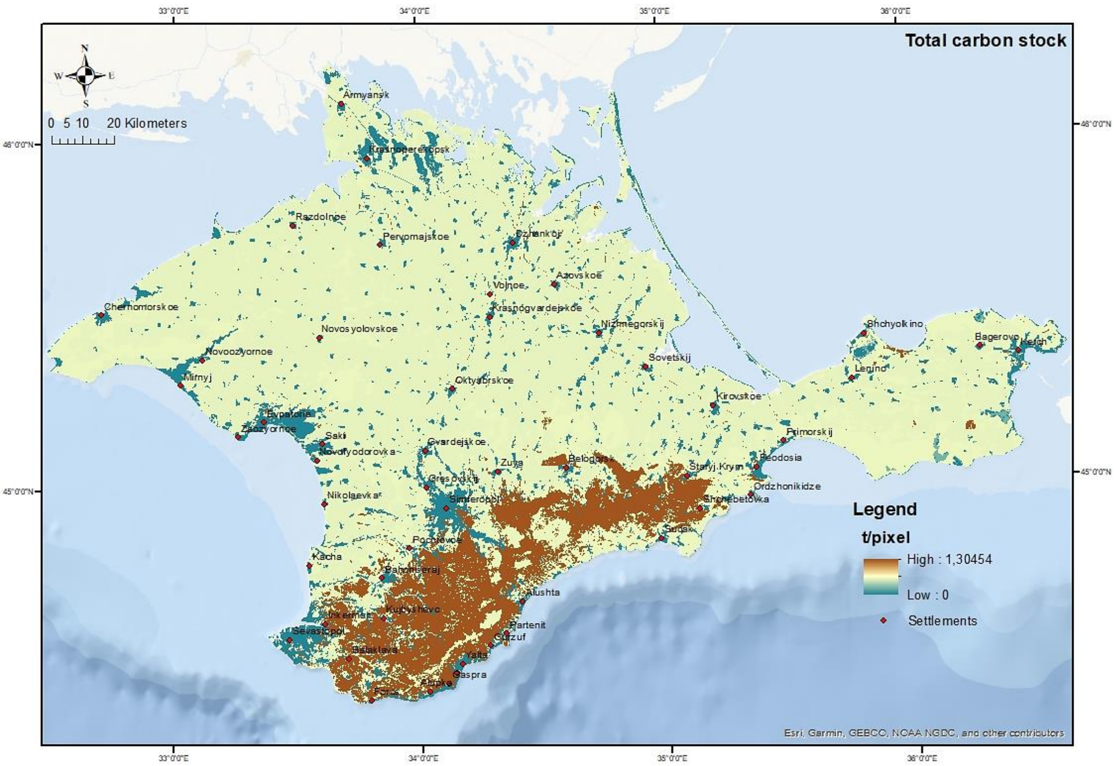

Figure 4. Total carbon stock within the Crimean Peninsula in 2023

2.2.4. Calculation of the Average Amount of Stored Carbon within Territorial Units

The next step was to calculate the total amount of stored carbon within the Crimean Peninsula from 2017 to 2023. Using the tool "Zonal statistics as a table" in the program ArcGIS 10.2, which summarizes the values of rasters within the zones of another data set, we find the total amount of stored carbon within the contour of the Crimean Peninsula, as well as within the individual landscape levels of the Crimean Peninsula (based on the landscape map by Pozachenyuk) [57], using shapefiles of these zones:

- hydromorphic landscape level (HLL);
- low-altitude landscape level of the southern macroslope (LLLSM);
- low-altitude landscape level of the northern macroslope (LLLNM);
- upland landscape level (ULL);
- mid-mountain landscape level (MLL).

Figure 5 shows the distribution of landscape levels within the Crimean Peninsula (based on the landscape map by Pozachenyuk) [57].

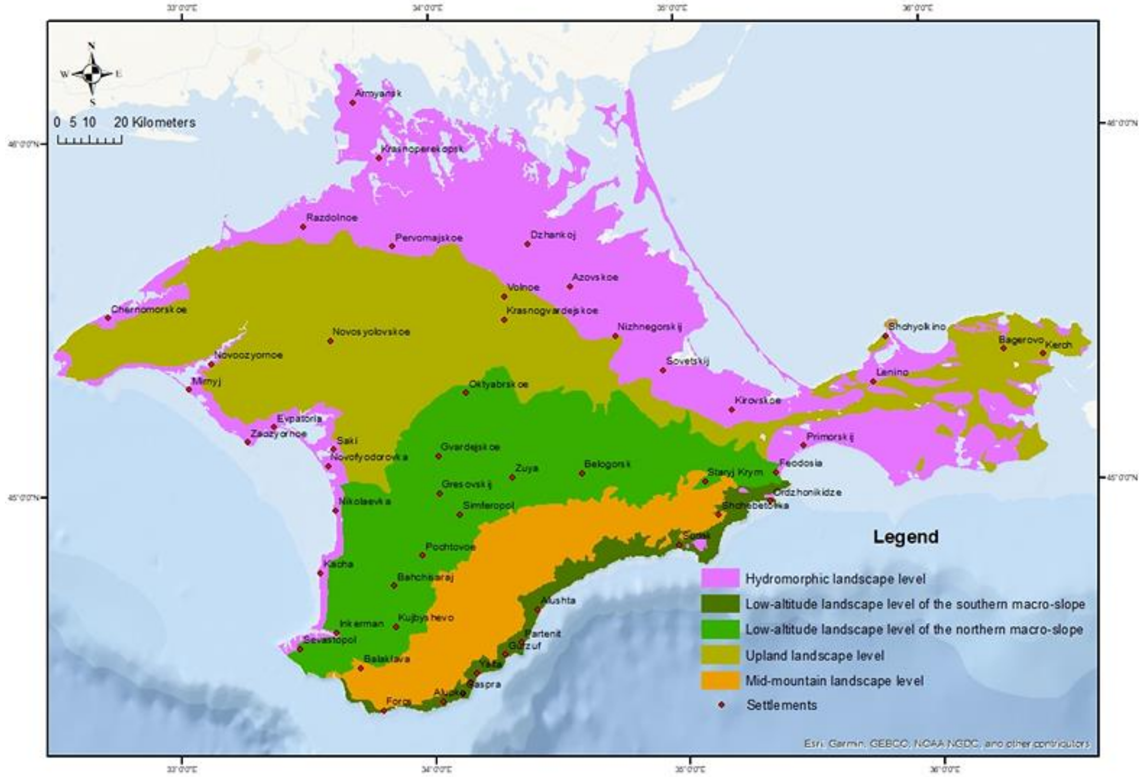

Figure 5. Landscape levels of the Crimean Peninsula according to the landscape map by Pozachenyuk [57]

Using the designated tool of the program ArcGIS 10.2, we obtained in the attribute tables the total amount of stored carbon within the entire Crimean Peninsula and separately within each landscape level from 2017 to 2023. However, knowing the total area of the territories of the Crimean Peninsula as a whole and landscape levels of the Crimean Peninsula in particular, we calculated the average amount of stored carbon within the given territorial units (Table 3) using MS Excel.

3. Results

The Crimean Peninsula, based on the land use and land cover (LULC) type distribution from SENTINEL-2 satellite data [54], encompasses the following land cover categories: water, trees, flooded vegetation, crops, rangeland, built area, bare areas devoid of vegetation, snow-covered areas and glaciers, and cloud-covered zones. Figure 6 depicts the land use and land cover layer for the Crimean Peninsula in 2023. Table 2 presents the percentages of the distribution of land cover types during the period 2017-2023.

Table 2. Distribution of land use and land cover types in the Crimean Peninsula during the period 2017-2023 based on SENTINEL-2 satellite data [54]

Land Use and Land Cover Type	Year						
	2017	2018	2019	2020	2021	2022	2023
Water, %	2.05	2.18	2.22	2.03	2.41	2.44	2.33
Trees, %	11.18	11.20	10.92	10.68	10.54	11.42	11.25
Flooded vegetation, %	0.09	0.12	0.11	0.11	0.22	0.24	0.22
Crops, %	56.25	58.47	57.64	58.65	60.73	60.32	59.41
Built area, %	5.75	5.89	5.99	6.08	6.16	6.26	6.27
Bare ground, %	0.68	0.47	0.42	0.52	0.19	0.25	0.36
Snow/Ice, %	$6*10^{-5}$	$9*10^{-5}$	$1.1*10^{-4}$	$1.6*10^{-4}$	$3*10^{-5}$	$1.1*10^{-4}$	$5*10^{-5}$
Clouds, %	$5*10^{-5}$	$8*10^{-5}$	$4.7*10^{-4}$	$2.2*10^{-4}$	$2.7*10^{-4}$	$4.8*10^{-4}$	$3.3*10^{-4}$
Rangeland, %	23.99	21.66	22.69	21.92	19.74	19.06	20.15

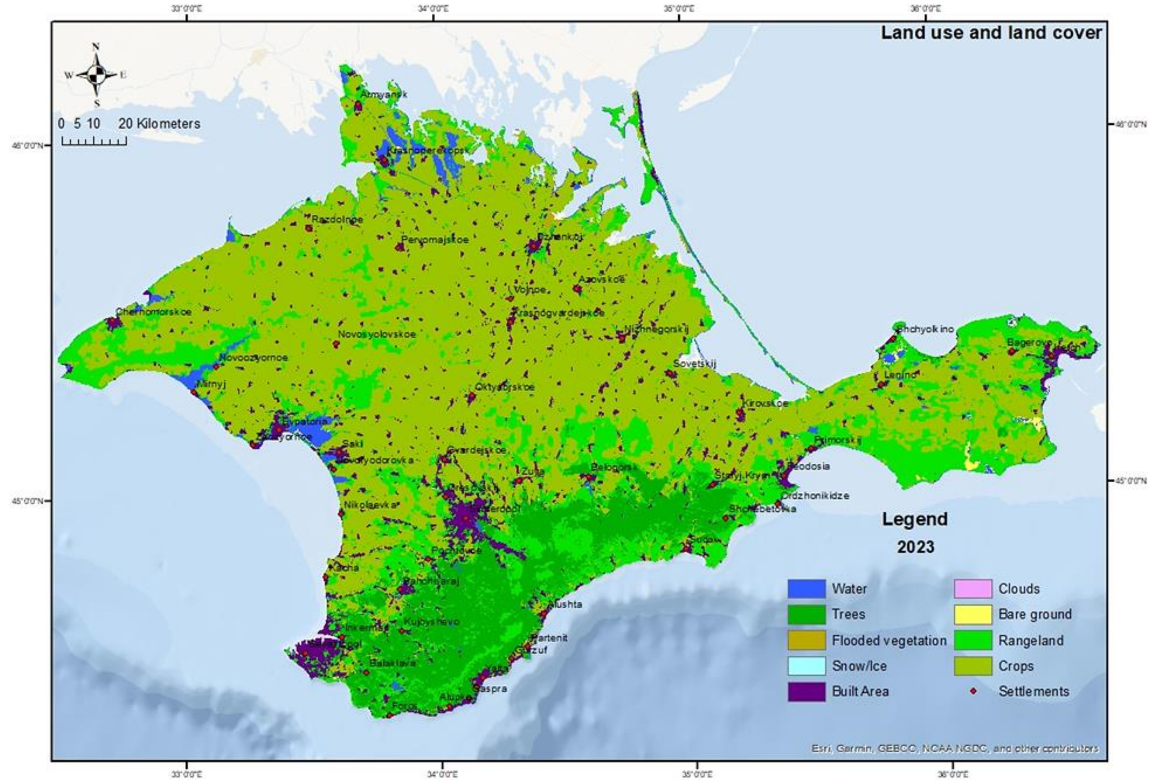

Figure 6. Land use and land cover types in 2023 on the Crimean Peninsula (based on Sentinel-2 [54])

According to Table 2, it is noteworthy that crops (around 60%) dominate a significant part of the Crimean Peninsula, particularly in the steppe region and Kerch Peninsula. Additionally, approximately 19-23% of the territory, varying from year to year, is characterized by areas with rangeland, particularly on the Southern Coast of Crimea, the yaylas (mountain plateaus), within the steppe part of Crimea, and on the Kerch Peninsula. Trees cover a substantial part of Crimea (approximately 10-11%), especially in mountainous regions. Built areas account for approximately 5-6% of the total area of Crimea. The remaining land cover and land use types were present in smaller proportions, constituting less than 2.5% of the total area of the Crimean Peninsula.

Considering the distribution of land use and cover types (Figure 6) within the study area is essential for subsequent calculations to utilize zones where carbon is stored. These zones encompass the following land-use and land-cover types: trees, flooded vegetation, crops, rangeland, and bare ground. This represents approximately 91-92% of the total area, which is further utilized in calculating carbon content within landscape levels using the Carbon Storage and Sequestration model of the InVEST software [42].

Figure 7 presents a map of soil organic carbon stocks within the Crimean Peninsula, constructed based on materials from soil organic carbon stocks [55]. Soil organic carbon stocks are presented for the upper part of the soil profile up to a depth of 30 cm (Figure 7). Carbon content was estimated in t/ha. The highest amount of soil organic carbon accumulated within the yaylas (mountain plateaus), particularly the Babugan-yayla and Karabi-yayla, where the highest carbon stocks (over 85 t/ha) were observed. Similarly, high soil carbon content was noted in the eastern end of the Crimean Mountains (between the town of Stary Krym and the village of Shchebetovka). This indicated that the highest amount of soil carbon accumulated in mountainous but relatively flat areas. The reason for the highest accumulation of organic carbon in mountainous areas, especially in the yaylas, is that the yaylas represent plateau-like and flat surfaces within the mountains. Under such conditions, accumulative conditions prevail, without the transportation of accumulated material down the slopes owing to gravitational forces. Additionally, as seen in Figure 6, the following types of land cover (LULC) dominate these areas: trees and rangeland, which in turn contain a significant amount of carbon compared to other types of land cover. Slightly lower but above average (from 60 t/ha) soil organic carbon accumulation occurs in the Crimean Mountains, where forests are widespread, as well as in the steppe part of Crimea, where rangeland areas are common, and in certain crop areas (particularly in the Krasnogvardeysky, Dzhankoy, Krasnoperekopsk, Nizhnegorodsky, and Razdolny districts). In the rest of Crimea, the amount of soil organic carbon stored fell within the average range – 40-60 t/ha. Lower values are associated with areas that fall under the built areas.

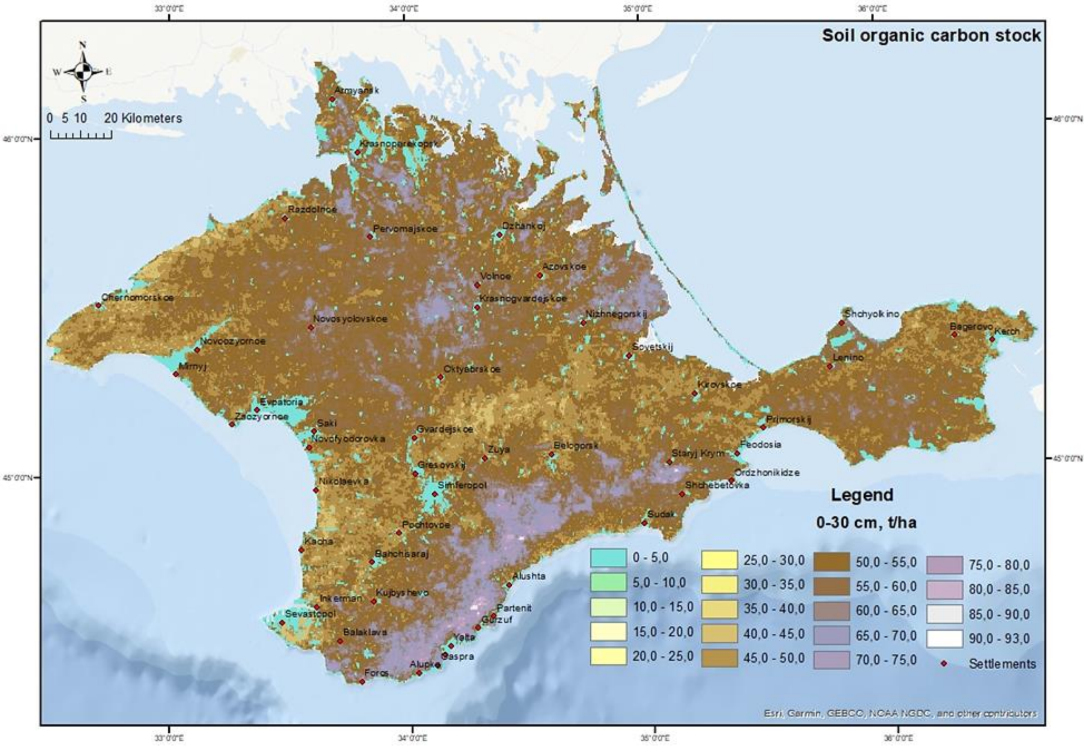

Figure 7. Soil organic carbon stock within the Crimean Peninsula (based on [55])

Furthermore, the organic carbon stock in aboveground and belowground living biomass within the Crimean Peninsula was considered. Aboveground biomass encompasses parts of woody, shrub, and herbaceous vegetation growing above the soil surface. The belowground living biomass represents the underground parts of these plants (roots). It is important to note that the data on carbon stocks in dead biomass (fallen dead plant parts) were disregarded in this study. This is because the Carbon Storage and Sequestration model of the InVEST software [42] allows for calculations, even if this information is unavailable.

Figures 8 and 9 illustrate maps of carbon stocks in aboveground and belowground living biomass, respectively, within the Crimean Peninsula.

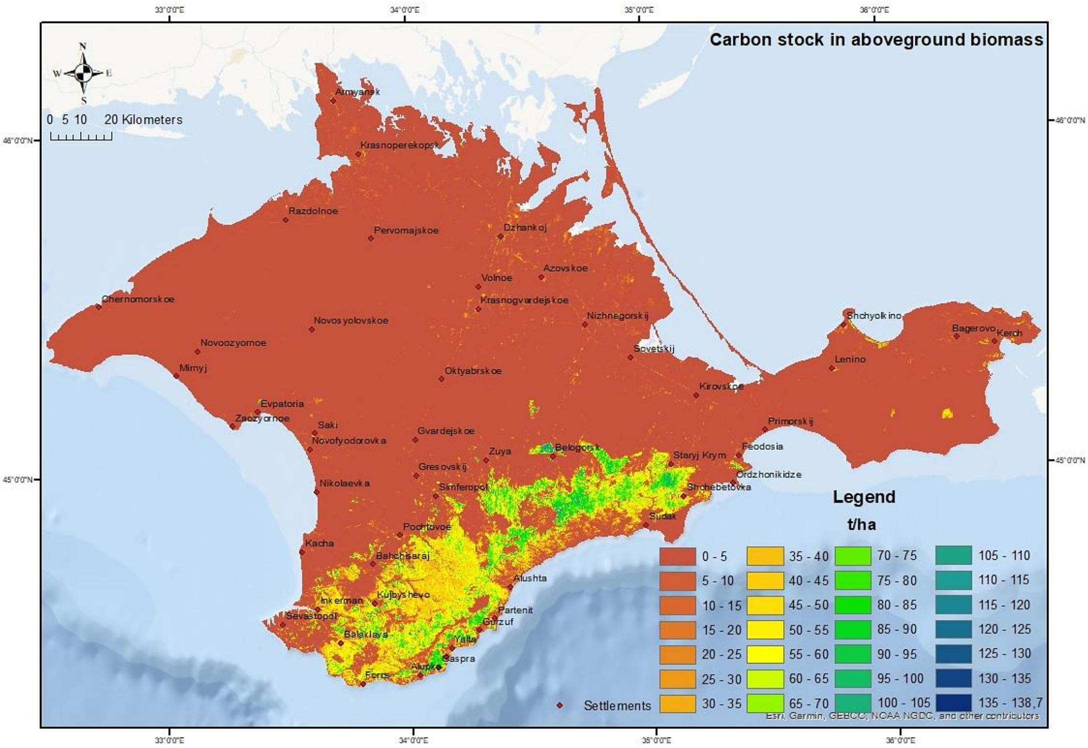

Figure 8. Aboveground living biomass within the Crimean Peninsula (based on [56])

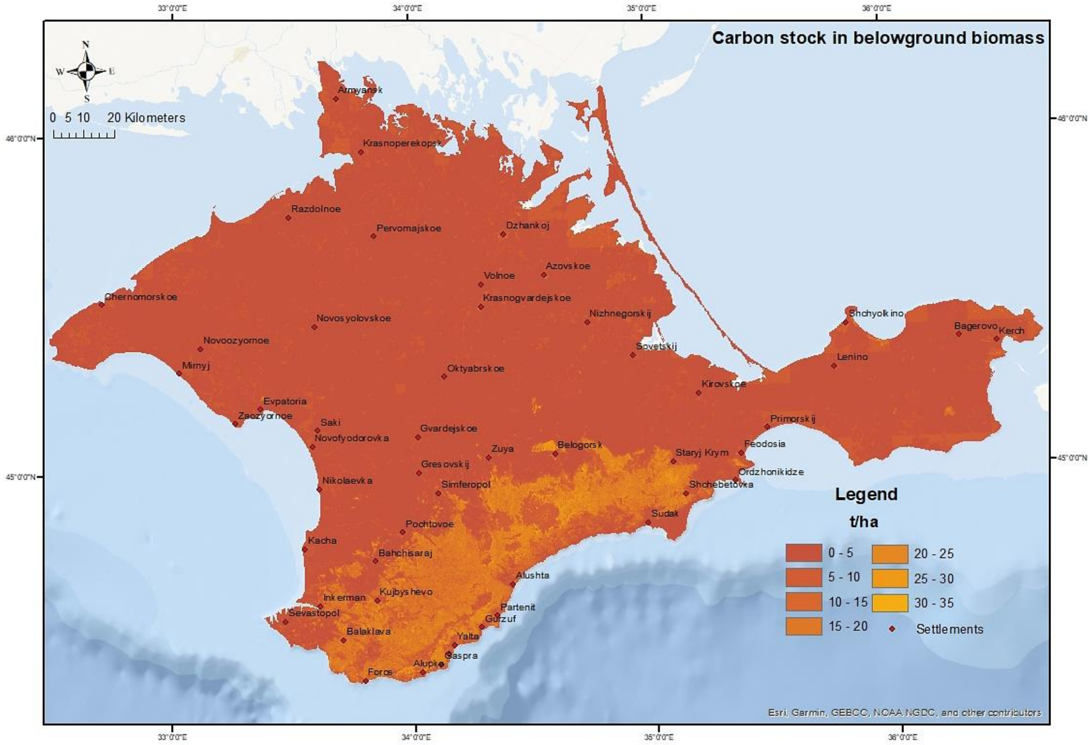

Figure 9. Belowground living biomass within the Crimean Peninsula (based on [56])

According to figures 8 and 9, carbon stocks were concentrated within the Crimean Mountains, where forests are widespread, revealing the highest amounts of aboveground and belowground carbon stocks (over 30 t/ha and 15 t/ha, respectively). The highest accumulation of carbon in living plant biomass is associated with the White Rock (Belogorsky district) zone, the eastern end of the Crimean Mountains (between the town of Stary Krym and the village of Shchebetovka), and the east of the Karabi-yayla. Here, the aboveground and belowground biomass carbon stocks exceeded 100 t/ha and 35 t/ha, respectively. Similar high values were observed within certain sections of the Crimean Mountains.

The average amount of stored organic carbon within the entire Crimean Peninsula and separately within each landscape level from 2017 to 2023, as calculated using the Carbon Storage and Sequestration model of the InVEST software [42], is presented in Table 3.

Table 3. Average amount (t/ha) of stored carbon within the landscape levels of the Crimean Peninsula landscapes in the period from 2017 to 2023

Years	Crimean Peninsula	HLL	LLLSM	LLLNM	ULL	MLL
2017	60.62	76.89	192.61	65.68	55.52	109.23
2018	60.52	76.63	192.98	65.68	55.43	109.20
2019	60.48	76.57	191.33	65.68	55.55	108.36
2020	60.45	76.63	189.50	65.47	55.52	108.63
2021	60.35	76.38	188.03	65.30	55.69	107.57
2022	60.26	76.24	190.74	65.35	55.31	109.43
2023	60.25	76,12	190.69	65.36	55.37	108.58

Notation: HLL − hydromorphic landscape level; LLLSM − low-altitude landscape level of the southern macroslope; LLLNM − low-altitude landscape level of the northern macroslope; ULL − upland landscape level; MLL − mid-mountain landscape level.

According to the data in Table 3, the highest amount of organic carbon in ecosystems was found in the low-altitude landscape level of the southern macroslope (in some places more than 384 t/ha, and on average up to 193 t/ha). Next, in decreasing order of organic carbon content within landscape levels is the mid-mountain landscape level (on average more than 107-109 t/ha in different years). Within these landscape levels, there are different types of land cover and environmental conditions that allow tree vegetation to grow and accumulate carbon in ecosystems. Next, the decreasing order of carbon content in ecosystems is the hydromorphic landscape level (over 76 t/ha), the low-altitude landscape level of the northern macroslope (over 65 t/ha), and the upland landscape level (over 55 t/ha).

Despite the interannual variability of the amount of organic carbon from year to year, overall, we can speak of a small reduction in carbon stocks on the territory of the Crimean Peninsula and separately within landscape levels for the period from 2017 to 2023 by the following orders: (1) Crimean Peninsula – 0.062 t/ha per year; (2) hydromorphic landscape level – 0.128 t/ha per year; (3) low-altitude landscape level of the southern macroslope – 0.32 t/ha per year; (4) low-altitude landscape level of the northern macroslope – 0.053 t/ha per year; (5) upland landscape level – 0.025 t/ha per year; (6) mid-mountain landscape level – 0.108 t/ha per year.

In some years, within all landscape levels, there was a partial increase in the amount of stored organic carbon, that is, accumulation in ecosystems within landscape levels: the hydromorphic landscape level in 2020, the low-altitude landscape level of the southern macroslope in 2018 and 2022, the low-altitude landscape level of the northern macroslope in 2022 and 2023, the upland landscape level in 2019, 2021, and 2023, and the mid-mountain landscape level in 2020 and 2022.

The minimum values of stored carbon content within the ecosystems of the Crimean Peninsula are associated with built-up areas of surface – urbanized zones. The decrease in organic carbon content in ecosystems may also be related to changes in land use and land cover types of the territory over the seven years considered.

The patterns of organic carbon accumulation in the landscapes of the Crimean Peninsula identified in this study allow the inclusion of these data in modeling different scenarios of land use and climatic changes in the territory of the Crimean Peninsula.

4. Discussion

Currently, there are some ways to calculate and estimate the organic carbon content of the environment, mostly in soils. Organic carbon assessment methodologies in ecosystems have been conducted using various models, including those that consider strategies to combat land degradation and climate change. A study conducted in western Canada compared three methods for assessing soil carbon and found that modeling using the Canadian Forest Sector Carbon Budget Model (CBM-CFS2) showed higher soil carbon values compared to field data but also revealed similar patterns in carbon distribution [58]. Another study in Northumberland (England) [59] demonstrated that using a combination of soil types, land use types, and other factors, such as elevation and pH, can significantly improve the accuracy of predicting soil organic carbon content. The inclusion of data on farmland use practices also increased the explanatory power of the model, indicating a significant influence of this factor on carbon content [59, 60]. This also confirms the importance of ecosystem carbon content as an indicator of ecosystem services [61]. Nussbaum et al. [62] described a new method for accurately assessing soil organic carbon stocks, allowing for more reliable data on average carbon stocks in forests. Modeling showed that the top layer of soil stores approximately 64% of carbon stocks (up to a depth of 100 cm), in contrast to Quijano et al. [63], who showed that in eroded arable soils, carbon accumulation occurred in the lower soil layers, and that carbon accumulation in soil can reach a plateau, depending on a variety of factors [64]. This indicates the need for more accurate estimates that have been previously underestimated.

Tayebi et al. [65] and Georgiou et al. [66] using machine learning algorithms have established that factors such as soil properties, geological conditions of the territory, and land-use history are major factors controlling soil carbon stocks. Beillouin et al. [15] noted that changes in abiotic factors, such as temperature, can affect biogeochemical cycles, and consequently, soil organic carbon stocks and biodiversity. In addition, using machine learning and satellite data from studies in South Africa [67] and the Tibetan Plateau [68], carbon stock maps were compiled, providing high-spatial-resolution data that can be used to track carbon changes over time. Xu et al. [69] in Ireland combined existing soil databases to improve the assessment of soil organic carbon stocks at the national level. The results showed that the coastal areas of Ireland have a higher carbon density, which is related to the distribution of peatlands. These studies highlight the importance of studying the spatial distribution of soil carbon to understand the carbon balance of ecosystems [70]. It is important to note that these methods for assessing organic carbon stocks can be subject to significant distortions. For example, in soils with a high stone fragment content, stocks can be overestimated by more than 100%. This underlines the need to improve assessment methodologies for more accurate determination of carbon stocks in soils [71, 72].

In this study, the Carbon Storage and Sequestration model of the InVEST software [42] was used within the landscape levels of the Crimean Peninsula, which also has a number of limitations for calculating organic carbon in ecosystems. The main problem of using the model is that it requires high-quality spatial data on soil and vegetation cover with regular surface coverage. Insufficient or poor-quality data can lead to inaccurate calculations. It is also necessary to consider the complex structure of the ecosystems at different sites. These are quite diverse, and the model may not account for all the factors affecting carbon stocks, such as interactions between species, changes in land use, and anthropogenic impacts on individual sites.

Although the model used simplifies the carbon cycle to allow it to work with a relatively small amount of information, rigor in the use of model parameters is noted, as choosing the wrong parameters in the model can significantly affect the ecosystem carbon results. For example, as a simplification of the carbon cycle, it is noted that the model assumes that none of the land cover types (LULC) accumulate, store, or lose carbon over time, instead assuming that all LULC land cover types are at a fixed level. In addition, the model does not account for the organic carbon that moves from one biomass category to another. For example, if trees die due to disease, much of the carbon stored in aboveground living biomass is transferred to carbon stored in dead biomass, which is not accounted for permanently in the model [53].

In addition, there are technical limitations in the use of the model, as it uses a number of additional auxiliary programs for the computational steps of working with the model (ArcGIS, MS Excel), which can be a problem for users with limited technical capabilities. The limitations of this study include the use of data limited by the pixel size. The study used data with a spatial resolution of up to 300 m/pixel in the organic carbon stock layers of aboveground and belowground living biomass [56]. Thus, the model may not account for small-scale changes that can have a significant impact on carbon stocks in landscapes. Another important limitation of this study is the time frame for using this methodology to calculate the amount of stored carbon in ecosystems, as the Sentinel-2 layer data used (land cover types (LULC) [54] are available from 2017.

5. Conclusions

5.1. Scientific Novelty

For the first time, calculations and estimations of the organic carbon content in the ecosystems of the Crimean Peninsula were carried out. Based on data on carbon stocks in Crimean soils, living plant biomass (belowground and aboveground parts), and land cover types, the average organic carbon stocks within the landscape levels of the Crimean Peninsula were calculated using the InVEST software from 2017 to 2023.

5.2. Theoretical Contributions

The following established spatial and temporal patterns in the study area were noted: the most organic carbon in soils accumulated within the yaylas (over 85 t/ha): within Babugan-yayla and Karabi-yayla, as well as within the eastern end of the Crimean Mountains (between the city of Stary Krym and the village of Shchebetovka) at the mid-mountain landscape level. The main organic carbon stocks in the aboveground and underground parts of vegetation are distributed within the mountainous Crimea, where forests are widespread (over 30 t/ha and 15 t/ha for the aboveground and underground parts of biomass, respectively) at the mid-mountain landscape level and low-altitude landscape level of the northern macroslope. The highest values of carbon accumulation in living plant biomass were associated with the White Rock zone (Belogorsky district), within the eastern end of the Crimean Mountains (between the city of Stary Krym and the village of Shchebetovka), and east of Karabi-yayla (over 100 t/ha and 35 t/ha, respectively) – mid-mountain landscape level and low-altitude landscape level of the northern macroslope.

Organic carbon stocks in the territory of the Crimean Peninsula for the period 2017-2023 averaged from 193 t/ha (low-altitude landscape level of the southern macroslope) to 55 t/ha (upland landscape level), which is largely related to the different conditions of the distribution of land use and land cover (LULC) in the territory of the Crimean Peninsula.

5.3. Practical Implications

Overall, it can be concluded that there was an annual decrease in organic carbon stocks within the Crimean Peninsula from 2017 to 2023 of 0.062 t/ha per year, and separately within the landscape levels, ranging from 0.025 t/ha per year (upland landscape level) to 0.32 t/ha per year (low-altitude landscape level of the southern macroslope), which may be associated with trends in climate change in Crimea and changes in land cover types (active development of the territory, etc.).

5.4. Research Limitations

A number of technical limitations for the use of this method for calculating organic carbon in natural ecosystems have been noted, such as data quality, temporal coverage of data for calculations, spatial resolution of calculation results, and technical peculiarities of computational resources.

5.5. Future Research Directions

In general, future research needs to take into account the carbon cycle and its role in the global climate, as well as to establish, to a greater extent, the peculiarities of organic carbon dynamics in ecosystems. It is also important to consider the uncertainty that the input parameters (layers) are introduced into the overall calculation of organic carbon stocks. The development of more accurate models for predicting changes in carbon content in different types of terrestrial and aquatic ecosystems, taking into account the anthropogenic impact on these ecosystems, will allow us to come to the right mechanisms for monitoring and predicting. These directions of future research are relevant in connection with the modern socioeconomic and environmental aspects of natural resource use.

6. Declarations

6.1. Author Contributions

Conceptualization, P.D. and A.D.; methodology, A.D., P.D., and V.T.; software, P.D., A.D., and V.T.; validation, A.D. and P.D.; formal analysis, A.D. and P.D.; investigation, P.D. and A.D.; resources, V.T., A.D., and P.D; data curation, P.D. and A.D.; writing—original draft preparation, A.D. and P.D; writing—review and editing, P.D., A.D., and V.T.; visualization, A.D. and P.D.; supervision, A.D. and P.D.; project administration, A.D. and P.D.; funding acquisition, A.D., P.D., and V.T. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

This work was conducted within the framework of the state assignment of the T.I. Vyazemsky Karadag Scientific Station – Nature Reserve of RAS – Branch of A.O. Kovalevsky Institute of Biology of the Southern Seas of RAS, on the topic “Monitoring of climate-active substances in land ecosystems of the Republic of Crimea under the conditions of climate change and anthropogenic impact using remote sensing methods” (state registration number 124052000057-0).

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Kostenko, I. V. (2017). The Relationship of Humus Status Indicators of Forest and Meadow Soils with Terrain Altitude on the Main Ridge of the Crimean Mountains. Pochvovedenie, 5(5), 532–543. doi:10.7868/80032180x17050082. (In Russian).

[2] Aleksandrova, L., Gordeev, A. S., Babichuk, V. R., Kuryntseva, P. A., & Selivanovskaya, S. Yu. (2023). Assessment of Carbon Stocks in Soils on the Territory of the Carbon Polygon "Carbon - Volga Region". Russian Journal of Applied Ecology, 4, 12–21. doi:10.24852/2411-7374.2023.4.12.21. (In Russian).

[3] Fedotova, A.V. (2024). Assessment of Soil Carbon Reserves in the South of the European Part of Russia Arid Conditions. Scientific Agronomy Journal, 4(4(123)), 105–110. doi:10.34736/fnc.2023.123.4.016.105-110.

[4] Likhanova, I. A., Deneva, S. V., Kholopov, Y. V., Rud, E. A., Skrebenkov, E. A., & Lapteva, E. M. (2024). Litter features in different forest types in the middle taiga subzone. Theoretical and Applied Ecology, 2, 72–81. doi:10.25750/1995-4301-2024-2-072-081.

[5] Vlasenko, O. (2015). Organic matter carbon content and stocks in agrocenoses of perennial grasses in the Krasnoyarsk forest-steppe region. Proceedings of the Problems of Modern Agrarian Science, 6–9.

[6] Peri, P. L., Gaitán, J., Mastrangelo, M., Nosetto, M., Villagra, P. E., Balducci, E., Pinazo, M., Eclesia, R. P., Von Wallis, A., Villarino, S., Alaggia, F., Polo, M. G., Manrique, S., Meglioli, P. A., Rodríguez-Souilla, J., Mónaco, M., Chaves, J. E., Medina, A., Gasparri, I., … Pastur, G. M. (2024). Soil organic carbon stocks in native forest of Argentina: a useful surrogate for mitigation and conservation planning under climate variability. Ecological Processes, 13(1), 1-22. doi:10.1186/s13717-023-00474-5.

[7] Chappell, A., Baldock, J., & Sanderman, J. (2016). The global significance of omitting soil erosion from soil organic carbon cycling schemes. Nature Climate Change, 6(2), 187–191. doi:10.1038/nclimate2829.

[8] Chimitdorzhieva, E. O. (2017). Carbon reserves in postagrogenic dry steppe soils of Western Transbaikalia. Arid Ecosystems, 7(3), 178–183. doi:10.1134/s2079096117030027.

[9] Larionov, Y. (2019). Role of Carbon Circulation as a Basis for Improvement of the Soil Fertility Monitoring System. Interexpo GEO-Siberia, 4(2), 124–134. doi:10.33764/2618-981x-2019-4-2-124-134.

[10] Semenov V., S., & Lebedeva, T. (2015). The Carbon Problem in Sustainable Agriculture: Agrochemical Aspects. Agrochemistry, 11, 3–12.

[11] Ghimire, P., Bhatta, B., Pokhrel, B., Kafle, G., & Paudel, P. (2019). Soil organic carbon stocks under different land uses in Chure region of Makawanpur district, Nepal. SAARC Journal of Agriculture, 16(2), 13–23. doi:10.3329/sja.v16i2.40255.

[12] Sambuu, A. (2024). Carbon pools in the steppes of the Republic of Tyva (Russia). E3S Web of Conferences, 510, 3037. doi:10.1051/e3sconf/202451003037.

[13] Randers, J., & Goluke, U. (2020). An earth system model shows self-sustained melting of permafrost even if all man-made GHG emissions stop in 2020. Scientific Reports, 10(1), 18456. doi:10.1038/s41598-020-75481-z.

[14] Duffy, K. A., Schwalm, C. R., Arcus, V. L., Koch, G. W., Liang, L. L., & Schipper, L. A. (2021). How close are we to the temperature tipping point of the terrestrial biosphere? Science Advances, 7(3), 1-8. doi:10.1126/sciadv.aay1052.

[15] Beillouin, D., Corbeels, M., Demenois, J., Berre, D., Boyer, A., Fallot, A., Feder, F., & Cardinael, R. (2023). A global meta-analysis of soil organic carbon in the Anthropocene. Nature Communications, 14(1), 3700. doi:10.1038/s41467-023-39338-z.

[16] Nabiollahi, K., Eskandari, S., Taghizadeh-Mehrjardi, R., Kerry, R., & Triantafilis, J. (2019). Assessing soil organic carbon stocks under land-use change scenarios using random forest models. Carbon Management, 10(1), 63–77. doi:10.1080/17583004.2018.1553434.

[17] Aynekulu, E., Vagen, T-G., Shepherd, K., Winowiecki, L. (2011). A Protocol for measurement and monitoring soil carbon stocks in agricultural landscapes. Version 1.1. World Agroforestry Centre, Nairobi.

[18] Budak, M., Günal, E., Kılıç, M., Çelik, İ., Sırrı, M., & Acir, N. (2023). Improvement of spatial estimation for soil organic carbon stocks in Yuksekova plain using Sentinel 2 imagery and gradient descent–boosted regression tree. Environmental Science and Pollution Research, 30(18), 53253–53274. doi:10.1007/s11356-023-26064-8.

[19] The World Bank. (2021). Soil Organic Carbon MRV Sourcebook for Agricultural Landscapes. The World Bank, Washington, United States. Available online: https://documents1.worldbank.org/curated/en/948041625049766862/pdf/Soil-Organic-Carbon-MRV-Sourcebook-for-Agricultural-Landscapes.pdf (accessed on February 2025).

[20] Polyakov, V., Abakumov, E., Nizamutdinov, T., Shevchenko, E., & Makarova, M. (2023). Estimation of Carbon Stocks and Stabilization Rates of Organic Matter in Soils of the "Ladoga" Carbon Monitoring Site. Agronomy, 13(3), 807. doi:10.3390/agronomy13030807.

[21] Maanan, M., Maanan, M., Karim, M., Ait Kacem, H., Ajrhough, S., Rueff, H., Snoussi, M., & Rhinane, H. (2019). Modelling the potential impacts of land use/cover change on terrestrial carbon stocks in north-west Morocco. International Journal of Sustainable Development and World Ecology, 26(6), 560–570. doi:10.1080/13504509.2019.1633706.

[22] Wang, R. Y., Mo, X., Ji, H., Zhu, Z., Wang, Y. S., Bao, Z., & Li, T. (2024). Comparison of the CASA and InVEST models' effects for estimating spatiotemporal differences in carbon storage of green spaces in megacities. Scientific Reports, 14(1), 5456. doi:10.1038/s41598-024-55858-0.

[23] Li, P., Chen, J., Li, Y., & Wu, W. (2023). Using the InVEST-PLUS Model to Predict and Analyze the Pattern of Ecosystem Carbon storage in Liaoning Province, China. Remote Sensing, 15(16), 4050. doi:10.3390/rs15164050.

[24] Mallick, J., Almesfer, M. K., Alsubih, M., Ahmed, M., & Ben Kahla, N. (2022). Estimating Carbon Stocks and Sequestration with Their Valuation under a Changing Land Use Scenario: A Multi-Temporal Research in Abha City, Saudi Arabia. Frontiers in Ecology and Evolution, 10, 905799. doi:10.3389/fevo.2022.905799.

[25] Li, Y., Yang, X., Wu, B., Zhao, J., Jiang, W., Feng, X., & Li, Y. (2023). Spatio-temporal evolution and prediction of carbon storage in Kunming based on PLUS and InVEST models. PeerJ, 11, 15285. doi:10.7717/PEERJ.15285.

[26] Piyathilake, I. D. U. H., Udayakumara, E. P. N., Ranaweera, L. V., & Gunatilake, S. K. (2022). Modeling predictive assessment of carbon storage using InVEST model in UVA province, Sri Lanka. Modeling Earth Systems and Environment, 8(2), 2213–2223. doi:10.1007/s40808-021-01207-3.

[27] Sharma, R., Pradhan, L., Kumari, M., Bhattacharya, P., Mishra, V. N., & Kumar, D. (2024). Spatio-Temporal Assessment of Urban Carbon Storage and Its Dynamics Using InVEST Model. Land, 13(9), 1387. doi:10.3390/land13091387.

[28] Carvalho de Castro, P. (2021). Quantifying carbon sequestration for riparian-zone restoration in Ecuador. Ph.D. Thesis, University of Northern Iowa, Cedar Falls, United States.

[29] Ismaili Alaoui, H., Chemchaoui, A., El Asri, B., Ghazi, S., Brhadda, N., & Ziri, R. (2023). Modeling predictive changes of carbon storage using invest model in the Beht watershed (Morocco). Modeling Earth Systems and Environment, 9(4), 4313–4322. doi:10.1007/s40808-023-01697-3.

[30] Kohestani, N., Rastgar, S., Heydari, G., Jouibary, S. S., & Amirnejad, H. (2024). Spatiotemporal modeling of the value of carbon sequestration under changing land use/land cover using InVEST model: a case study of Nour-rud Watershed, Northern Iran. Environment, Development and Sustainability, 26(6), 14477–14505. doi:10.1007/s10668-023-03203-2.

[31] Li, X., Huang, C., Jin, H., Han, Y., Kang, S., Liu, J., Cai, H., Hu, T., Yang, G., Yu, H., & Sun, L. (2022). Spatio-Temporal Patterns of Carbon Storage Derived Using the InVEST Model in Heilongjiang Province, Northeast China. Frontiers in Earth Science, 10, 846456. doi:10.3389/feart.2022.846456.

[32] Mungalova, V. (2024). Carbon polygons in Russia: contribution to achieving carbon neutrality. Bulletin of Science, 1, 632–635.

[33] Dochkina, D. D., & Filimonova, I. V. (2022). Socio-economic impact of the development of carbon farms in the regions. Interexpo GEO-Siberia, 2(4), 218–226. doi:10.33764/2618-981x-2022-2-4-218-226.

[34] Ivanov, A. L., Savin, I. Yu., Stolbovoy, V. S., Dukhanin, Yu. A., & Kozlov, D. N. (2021). Methodological approaches to the formation of a unified national system of monitoring and accounting of carbon balance and greenhouse gas emissions on lands of the agricultural fund of the Russian Federation. Dokuchaev Soil Bulletin, 108, 175–218. doi:10.19047/0136-1694-2021-108-175-218.

[35] Agafonov, V. B. (2023). Environmental and Legal Support for the Implementation of a Pilot Project for the Creation of Carbon Landfills and Carbon Farms. Courier of Kutafin Moscow State Law University (MSAL), 3, 17–27. doi:10.17803/2311-5998.2023.103.3.017-027.

[36] Veselova, D. N. (2023). Russia’s Policy in the Field of Climate Change Mitigation. Discourse-P, 20(2), 86–105. doi:10.17506/18179568_2023_20_2_86.

[37] Gunya, A. N., Gairabekov, U. T., Makhmudova, L. Sh., & Alakhverdiev, F. D. (2021). An integrated approach to assessing land use changes and their impact on carbon dynamics in mountain landscapes of the Chechen Republic. News of the Dagestan State Pedagogical University. Natural and Exact Sciences, 15(4), 39-52. doi:10.31161/1995-0675-2021-15-4-39-52. (In Russian).

[38] Nurgaliev, D. K., Selivanovskaya, S. Y., Kozhevnikova, M. V., & Galitskaya, P. Y. (2021). Some challenges and opportunities for Russia and regions in terms of the global decarbonization trend. Georesursy, 23(3), 8–16. doi:10.18599/grs.2021.3.2.

[39] Kurganova, I. N., Lopes de Gerenyu, V. O., Ipp, S. L., Kaganov, V. V., Khoroshaev, D. A., Rukhovich, D. I., Sumin, Y. V., Durmanov, N. D., & Kuzyakov, Y. V. (2022). Pilot carbon polygon in Russia: analysis of carbon stocks in soils and vegetation. Soils and Environment, 5(2), 169. doi:10.31251/pos.v5i2.169. (In Russian).

[40] Ministry of Education and Science of Russia (2025). Carbon Supersites of the Russian Federation, Moscow, Russia. (2024). Available online: https://carbon-polygons.ru/en/ (accessed on February 2025).

[41] Zamolodchikov, Dmitry. (2021). The Carbon Cycle and Climate Change. Journal of Environmental Earth and Energy Study (JEEES). doi:10.1017/9781108924849.005. (In Russian).

[42] InVEST Software (2025). NatCap at Stanford: Stanford University. Stanford, United States. Available online: https://naturalcapitalproject.stanford.edu/software/invest (accessed on February 2025).

[43] Dragan, N. A. (2004). Soil resources of Crimea. Dolya, Simferopol, Ukraine. (In Russian).

[44] METEO (2025). Hydrometcenter of Russia, Crimean Department of Hydrometeorology and Environmental Monitoring, Moscow, Russia. Available online: https://meteo.crimea.ru (accessed on February 2025). (In Russian).

[45] Kosarev, A. N., Arkhipkin, V. S., & Surkova, G. V. (2008). Hydrometeorological conditions. The Black Sea Environment, 135-158. doi:10.1007/698_5_086.

[46] Gorbunov, R. V. (2021). Relationship of Regional Ecosystems Productivity with the Dynamics of Hydrothermal Conditions on the Territory Ofthe Crimean Peninsula. Bulletin of the State Nikitsky Botanical Gardens, 1(138), 17–25. doi:10.36305/0513-1634-2021-138-17-25.

[47] Gorbunov, R. (2023). Functioning and dynamics of regional geo-ecosystems under climate change (on the example of the Crimean Peninsula). KMK Publisher, Moscow, Russia. (In Russian).

[48] Pham, C. N., Gorbunov, R., Lapchenko, V., Gorbunova, T., & Tabunshchik, V. (2023). Biogenic Elements of Atmospheric Fallout and Impact of Sub-Mediterranean Forest Communities of Downy Oaks on Changes in the Chemical Composition of Atmospheric Precipitation. Forests, 14(2), 294. doi:10.3390/f14020294.

[49] Pham, C. N., Gorbunov, R., Lapchenko, V., Gorbunova, T., & Tabunshchik, V. (2024). Macro- and Microelements and the Impact of Sub-Mediterranean Downy Oak Forest Communities on Their Composition in Rainwater. Forests, 15(4), 612. doi:10.3390/f15040612.

[50] Egorov, V. V., Fridland, V. M., Ivanova, E. N., Rozov, N. N., Nosin, V. A., & Friev, T. A. (1987). Classification and diagnostics of soils of the USSR. A.A. Balkema, Rotterdam, Netherlands.

[51] FAO. (2014). World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. Food and Agriculture Organization (FAO), Rome, Italy.

[52] Didukh, Y., Kontar, I., & Boratynski, A. (2018). Phytoindicating comparison of vegetation of the Polish Tatras, the Ukrainian Carpathians, and the Mountain Crimea. Geographical Changes in Vegetation and Plant Functional Types, 185-210. doi:10.1007/978-3-319-68738-4_9.

[53] InVEST User Guide. (2025). NatCap at Stanford: Stanford University. Stanford, United States. Available online: https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/index.html (accessed on January 2025).

[54] ArcGIS (2025). Sentinel-2. 10M Land Use/Land cover. ArcGIS, Southwest Harbor, United States. Available online: https://livingatlas.arcgis.com/landcoverexplorer/#mapCenter=92.21745,26.42377,11&mode=swipe&timeExtent=2017,2023&downloadMode=true (accessed on February 2025).

[55] Soilgrids (2025). Soil organic carbon stock, SOILGRIDS, Tallinn, Estonia. Available online: https://soilgrids.org/ (accessed on February 2025).

[56] Spawn, S. A., & Gibbs, H. K. (2020). Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010. Ornl Daac, 2–6. doi:10.3334/ornldaac/1763.

[57] Pozachenyuk, E. (2009). Modern landscapes of Crimea and adjacent water areas. Business-Inform, Simferopol, Ukraine. (In Russian)

[58] Bhatti, J. S., Apps, M. J., & Tarnocai, C. (2002). Estimates of soil organic carbon stocks in central Canada using three different approaches. Canadian Journal of Forest Research, 32(5), 805–812. doi:10.1139/x01-122.

[59] Bell, M. J., & Worrall, F. (2009). Estimating a region's soil organic carbon baseline: The undervalued role of land-management. Geoderma, 152(1–2), 74–84. doi:10.1016/j.geoderma.2009.05.020.

[60] Smeaton, C., Ladd, C. J. T., Miller, L. C., McMahon, L., Garrett, E., Barlow, N. L. M., Gehrels, W. R., Skov, M. W., & Austin, W. E. N. (2023). Organic carbon stocks of Great British saltmarshes. Frontiers in Marine Science, 10. doi:10.3389/fmars.2023.1229486.

[61] Nel, L., Boeni, A. F., Prohászka, V. J., Szilágyi, A., Tormáné Kovács, E., Pásztor, L., & Centeri, C. (2022). InVEST Soil Carbon Stock Modelling of Agricultural Landscapes as an Ecosystem Service Indicator. Sustainability (Switzerland), 14(16), 9808. doi:10.3390/su14169808.

[62] Nussbaum, M., Papritz, A., Baltensweiler, A., & Walthert, L. (2014). Estimating soil organic carbon stocks of Swiss forest soils by robust external-drift kriging. Geoscientific Model Development, 7(3), 1197–1210. doi:10.5194/gmd-7-1197-2014.

[63] Quijano, L., Aldana-Jague, E., Heckrath, G., & Van Oost, K. (2021). Estimating temporal and spatial changes in soil organic carbon stocks and its controlling factors in moraine landscapes in Denmark. Catena, 206, 105502. doi:10.1016/j.catena.2021.105502.

[64] British Society of Soil Sciences. (2023). Guidance Note for Land Managers. Soil Carbon: What are carbon stocks and how can they be measured?. British Society of Soil Sciences, Cranfield University campus, Milton Keynes, United Kingdom. Available online: https://soils.org.uk/wp-content/uploads/2023/06/BSSS_Science-Note_June-23_Soil-Carbon-Stocks_FINAL-DIGITAL_300623.pdf (accessed on February 2025).

[65] Tayebi, M., Rosas, J. T. F., Mendes, W. de S., Poppiel, R. R., Ostovari, Y., Ruiz, L. F. C., Dos Santos, N. V., Cerri, C. E. P., Silva, S. H. G., Curi, N., Silvero, N. E. Q., & Demattê, J. A. M. (2021). Drivers of organic carbon stocks in different LULC history and along soil depth for a 30 years image time series. Remote Sensing, 13(11), 2223. doi:10.3390/rs13112223.

[66] Georgiou, K., Jackson, R. B., Vindušková, O., Abramoff, R. Z., Ahlström, A., Feng, W., Harden, J. W., Pellegrini, A. F. A., Polley, H. W., Soong, J. L., Riley, W. J., & Torn, M. S. (2022). Global stocks and capacity of mineral-associated soil organic carbon. Nature Communications, 13(1), 3797. doi:10.1038/s41467-022-31540-9.

[67] Venter, Z. S., Hawkins, H. J., Cramer, M. D., & Mills, A. J. (2021). Mapping soil organic carbon stocks and trends with satellite-driven high resolution maps over South Africa. Science of the Total Environment, 771, 145384. doi:10.1016/j.scitotenv.2021.145384.

[68] Yang, R. M., Zhang, G. L., Yang, F., Zhi, J. J., Yang, F., Liu, F., Zhao, Y. G., & Li, D. C. (2016). Precise estimation of soil organic carbon stocks in the northeast Tibetan Plateau. Scientific Reports, 6(1). doi:10.1038/srep21842.

[69] Xu, X., Liu, W., Zhang, C., & Kiely, G. (2011). Estimation of soil organic carbon stock and its spatial distribution in the Republic of Ireland. Soil Use and Management, 27(2), 156–162. doi:10.1111/j.1475-2743.2011.00342.x.

[70] Yussupov, K., Aben, E., Myrzakhmetov, S., Akhmetkanov, D., & Sarybayev, N. (2024). Increasing the Efficiency of Underground Block Leaching of Metal. Civil Engineering Journal (Iran), 10(10), 3339–3349. doi:10.28991/CEJ-2024-010-10-014.

[71] Poeplau, C., Vos, C., & Don, A. (2017). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. Soil, 3(1), 61–66. doi:10.5194/soil-3-61-2017.

[72] Shipilova, K., Radkevich, M., Tsoy, V., Shoergashova, S., Vildanova, L., & Gapirov, A. (2020). Land use by transport infrastructure in Tashkent City. IOP Conference Series: Materials Science and Engineering, 883(1), 12067. doi:10.1088/1757-899X/883/1/012067.