sustainability

Article

Estimating Soil Carbon Sequestration Potential in Portuguese Agricultural Soils Through Land-Management and Land-Use Changes

Mariana Raposo [1,*], Paulo Canaveira [1,2] and Tiago Domingos [1]

[1] MARETEC—Marine, Environment and Technology Centre, LARSyS—Laboratory for Robotics and Engineering Systems, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal; paulo.canaveira@tecnico.ulisboa.pt (P.C.); tdomingos@tecnico.ulisboa.pt (T.D.)
[2] LEAF—Linking Landscape, Environment, Agriculture and Food, TERRA—Laboratório para a Sustentabilidade do Uso da Terra e dos Serviços dos Ecossistemas, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisbon, Portugal
* Correspondence: mariana.raposo@tecnico.ulisboa.pt

Abstract: Soil carbon sequestration (SCS) is a nature-based, low-cost climate mitigation strategy that also contributes to the climate adaptation of agricultural systems. Some land-use and land-management practices potentially lead to an enhancement of the soil organic carbon (SOC) sink, such as no-till, the use of cover crops, leaving residues on fields, improving the variety of legume species in grasslands and reducing grazing intensity. However, uncertainties remain both in estimating and measuring the impact of the application of certain practices, as these vary with the soil, climate and historic land use. IPCC (Intergovernmental Panel on Climate Change) guidelines are commonly used to estimate SOC and SOC sequestration potentials at different tiers. Here, the IPCC's tier 1 methodology was applied to estimate (1) the sequestration potential of nine mitigation practices and (2) the emission or sequestration potential of four current land-change trends for n = 7092 unique agricultural sites in mainland Portugal. The conversion of irrigated crops to improved grasslands resulted in the highest average unit sequestration (1.05 tC ha^{-1} yr^{-1}), while cropland conversion to poor degraded pasture (abandonment) resulted in the highest unit SOC loss (−0.08 tC ha^{-1} yr^{-1}). The abandonment of cropland results in a national SOC loss of up to 0.09 MtC yr^{-1}, while the improvement of poor degraded pastures has the highest national sequestration potential, equal to 0.6 MtC yr^{-1} (2.2 $MtCO_{2eq}$ yr^{-1}), about 4% of Portugal's emissions in 2021, if applied in all managed areas. The results enable a comparison between different practices and land uses; however, to enhance accuracy, a higher tier methodology tailored to the Portuguese context should be developed.

Keywords: soil organic carbon; IPCC guidelines; mitigation; cropland management; grassland management; natural climate solutions

Academic Editor: Anna De Marco

Received: 16 December 2024
Revised: 16 January 2025
Accepted: 23 January 2025
Published: 3 February 2025

Citation: Raposo, M.; Canaveira, P.; Domingos, T. Estimating Soil Carbon Sequestration Potential in Portuguese Agricultural Soils Through Land-Management and Land-Use Changes. *Sustainability* **2025**, *17*, 1223. https://doi.org/10.3390/su17031223

1. Introduction

Greenhouse gas (GHG) emissions from agriculture, forestry and other land use (AFOLU) represent 22% of total global emissions [1]. This considerable impact can be reduced with adequate changes in agricultural practices and land management [2,3] while improving soil resilience [4] and contributing to the adaptation of agricultural systems [5].

The loss of soil organic carbon (SOC) due to anthropogenic deforestation, biomass burning, intensive plowing and farming intensification [6] has directly contributed to increased atmospheric CO_2. This historic 12,000-year carbon debt of an estimated 133 GtC [7] represents an opportunity to restore carbon in soils by implementing strategies that counteract soil depleting processes, enhance SOC sinks and hence offset other emissions. Soil carbon sequestration (SCS) implies the enhancement of C inputs to and the reduction in C outputs from soils. It can be achieved with agricultural practices such as cover cropping, reduced tillage, rotational grazing, the use of organic manure and adequate land-use changes [2,6,8]. Its low costs and high applicability render SCS an appealing nature-based climate change mitigation strategy [9]. However, SCS potential varies greatly with historic land use and C loss and soil and climate variables, which are context and region specific. Hence, one of the key challenges lies in understanding how different land-use and land-management practices may benefit SCS in various regions and quantify their impact.

SOC stocks can be increased for both temporary and permanent crops by enhancing carbon inputs into the soil, e.g., leaving crop residues on the field, applying organic fertilizers and irrigating land [10–12], and by changing tillage practices, e.g., by practicing reduced or no tillage [13,14]. For the EU-15, the application of a combined set of measures, which include the introduction of conservation tillage and set-aside land, has an estimated sequestration potential of 50 MtC per year [15]. In the Mediterranean region, long-term experiments have reported a positive accumulation of C as a result of shifting from intensive tillage to no tillage and/or reduced tillage practices [16–19].

For grasslands, a set of practices that include rotational grazing, irrigation and improved grass species or varieties with the introduction of multiple species, including legumes, have been popularized as an effective measure toward SCS. Specifically in Portugal, grassland management with the introduction of legume-rich pastures, known as "sown biodiverse permanent pastures rich in legumes" (SBPPRLs), has shown potential for large scale carbon sequestration. These grasslands were used in the Terraprima project (https://www.terraprima.pt/ (accessed on 30 May 2023)), funded by the Portuguese Carbon Fund, to reward carbon sequestration by farmers who converted degraded pastures into SBPRL between 2009 and 2014, leading to an estimated sequestration of 1.54 Mt CO_2 [20,21].

Three main land-use conversion transitions have been promoted as efficient in increasing SOC stocks: the conversion of temporary crops to permanent (perennial) crops, of cropland to pasture and of cropland to forest [22]. The conversion of temporary crops to permanent crops has been estimated to lead to an average 20% SOC gain over a 20-year period [23] since perennials produce more residues than temporary crops, have larger roots and suffer less disturbance, which leads to greater C input into the soil. In the tropics, the conversion of cropland to pasture has also shown evidence of sequestering carbon (+26%), while a conversion of cropland to forest delivers the highest SOC enhancement (+33%) [24].

Nevertheless, the impact of land-use and land-management changes varies regionally with historic land-use and soil degradation status, climate and edaphic factors [6]. Hence, there is no "one-size fits all" solution toward SCS, and regional characteristics will play a determining role in the results. Furthermore, the amount of carbon that can be accumulated in the soils is finite—when alternative land-use or land-management practices are continuously applied, the soil will eventually reach a new equilibrium point. Beyond this point, no additional carbon will be sequestered [25]. Maintaining that SOC level depends on the continued application of the land-use or land-management practices that led to the SOC change. For example, a cropland previously managed with conventional tillage and transitioned to no-tillage practices will sequester carbon during the first 20 to 100 years of applying the no-tillage practice. During this period, SOC stocks increase until a new equilibrium is reached, after which no additional carbon will be stored [26]. However, the loss of carbon may occur if land-management or land-use changes occur that deplete SOC stocks.

The accurate determination of changes in SOC stocks is a prerequisite for better understanding the potential of soils to contribute to climate change mitigation and the development of strategies toward SCS to match different regional contexts [27,28]. Nevertheless, quantifying these changes is challenging due to the complex nature of the ecosystem processes involved and the lack of robust data, models or appropriate study designs and sampling protocols [29].

The IPCC (Intergovernmental Panel on Climate Change) provides guidelines to calculate GHG emission flows in the AFOLU sector to be used by the countries under the UNFCCC and the Paris Agreement in their yearly emissions reports. Estimating carbon stocks and stock changes can be achieved by following the IPCC's tier 1 approach, which relies on default emission factors; a tier 2 approach, which incorporates country- or region-specific emission factors; and a tier 3 approach, which integrates highly disaggregated land-use and management data (such as crop type) and detailed climate and soil characteristics into models such as RothC or Century, or in situ sampling.

Directly measuring SOC stocks and SOC changes through field measurements provides the most accurate onsite information, but it is also resource-consuming—in time, labor and cost [29]. This requires intricate protocols that involve sampling in large numbers and to up to 100 cm in soil depth [30] in order to guarantee accuracy, reduce sources of error and avoid biased results [31,32]. The LUCAS (Land Use/Cover Area Survey) is the greatest collective effort at a European level to develop a spatially referenced database, with in situ measurements of over 270,000 land points, following standardized sampling and analytical procedures and including information of different soil properties [33]. However, in Portugal, the LUCAS database has sampled soils at only 465 points [34]. Efforts have been made to develop the INFOSOLO database, a soil information system in Portugal that currently gathers information on 3461 soil profiles across Portugal resulting from sampling campaigns between 1966 and 2014. However, the diversity of sampling and analytical protocols, along with the geographical and temporal dispersion of the data, inhibit the use of this database for SOC monitoring.

Portugal does not yet have a systematic soil monitoring network with periodic and repeated soil sampling, which limits the application of higher-tiered methods. In this work, the IPCC's tier 1 methodology was followed, as described in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, to obtain soil carbon sequestration or emission estimates in Portuguese cropland and grassland soils for land-use and land-management changes, followed by a comparison between the obtained SOC stock estimates and in situ LUCAS measurements. This paper aims to (1) estimate current SOC stocks and how these relate to the different climate regions and soil types in mainland Portugal; (2) identify land-management and land-use strategies that are best suited to soil carbon sequestration in mainland Portugal; and (3) test the adequacy of the tier 1 methodology by comparing $SOC_{Initial}$ stocks with in situ LUCAS measurements. To our knowledge, this is the first work that applies the IPCC's tier 1 methodology to Portugal's agricultural land and estimates sequestration/emission potentials for selected land-use and land-management change scenarios.

2. Materials and Methods

This work relied on the use of publicly available datasets and the application of the tier 1 methodology, as described in the IPCC Guidelines for Greenhouse Gas Inventories. Figure 1 summarizes the steps taken in the collection and processing of data and calculation procedures, which are described in greater detail below.

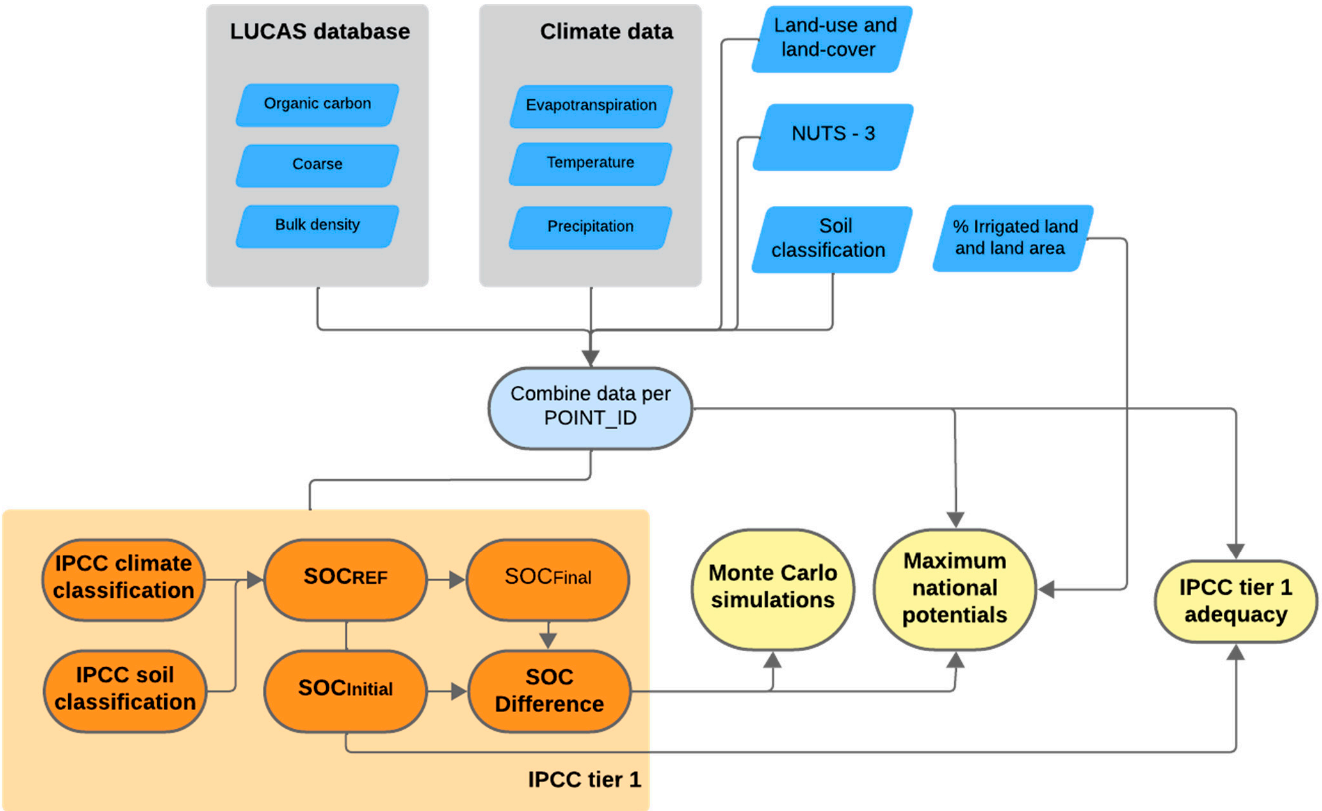

Figure 1. Data preparation workflow to be implemented in the application of the IPCC tier 1 methodology, Monte Carlo simulations, maximum national potentials and IPCC tier 1 adequacy. NUTS—Nomenclature of Territorial Units for Statistics.

2.1. Study Region

Portugal is located in southwest Europe, bordered by Spain to the east and north and by the Atlantic Ocean to the west and south, with coordinates that range from 36.98° N to 42.14° N in latitude and 6.19° W to 9.53° W in longitude. Its diverse geography includes the mountainous regions of the north and center and rolling plains in the southern areas. Located in the Mediterranean climate zone, Portugal is characterized by hot, dry summers and mild, wet winters, with variations influenced by altitude and proximity to the ocean. Portugal's soils are varied, ranging from granite and schist in the northern and central regions to sandy and limestone soils in the southern Algarve. This diversity fosters a wide range of agricultural and ecological systems.

2.2. Data

LUCAS database—The LUCAS database consists of a 2 km × 2 km georeferenced grid that covers 1,000,000 points in the EU-27 territory and is available for download on request at ESDAC (https://esdac.jrc.ec.europa.eu, accessed on 20 May 2023). A series of attributes such as coordinates, elevation and slope classify each point (POINT_ID). Mainland Portugal is covered by 22,139 points in this grid. The LUCAS database also provides information on coarse particle content and organic carbon concentration at a 20 cm depth (g/kg) for 220 cropland and grassland unique POINT_IDs sampled in the years 2010, 2015 and 2018 (a total of 578 samples in the three years).

Soil classification—Soil classification data for mainland Portugal were extracted from the Soil Atlas of Europe, which classifies European soils according to both the World Reference Base for Soil resources (WRB) and the FAO-85 classification systems and is available for downloading at ESDAC (https://esdac.jrc.ec.europa.eu/, accessed on 20 May 2023).

Climate—Data resulting from both observations and models from 1971–2000 were extracted from a downloadable raster file available at IPMA's "Portal do Clima" (http://portaldoclima.pt, accessed on 21 May 2023), with data for mainland Portugal's temperature (TAnMed), precipitation (PPAnoTot) and evapotranspiration (EV0).

Land-use and land-cover data—Land-use and land-cover data for 2018 were retrieved from COS_LULUCF, a raster file produced by the Portuguese DGT (Direção Nacional do Território), a simplified 20-class version of the COS (Carta de Ocupação de Solos), the land-use map. These contain six main land-use classes for mainland Portugal: cropland (CL), forest (FL), grassland (GL), settlements (ST), wetlands (WT) and other lands (OL). NUTS-3-subregions—The official limits of different Nomenclature of Territorial Units for Statistics (NUTS) levels (NUTS-1, NUTS-2 and NUTS-3) for Portugal, the 2013 version, in ESRI shapefile format, was downloaded from "Portal de dados abertos da Administração Pública" (https://dados.gov.pt, accessed on 24 May 2023).

Area of each land use and the percentage of irrigated land—The area per land-use category and the percentage of irrigated land in .xls file formats were downloaded from INE (National Statistics Office) (https://www.ine.pt/, accessed on 5 June 2023). Four datasets were downloaded: "Area of temporary crops (ha) by location (NUTS—2013), type (temporary crops) and area classes; ten-yearly (1) (2019)", "Area of permanent crops (ha) by location (NUTS-2013), type (permanent crops) and area classes; ten-yearly (1) (2019)", "Area of grasslands and permanent pastures (ha) by location (NUTS-2013) and type (grasslands and permanent pastures); ten-yearly (1) (2019)" and "Percentage (%) of irrigated land by location (NUTS 1, 2, 3—2013) (2019)".

2.3. Processing

The shapefiles were processed using QGIS 3.0 software, an open-source geographic information system application for geospatial data (https://www.qgis.org/ (accessed on 30 May 2023)). Using QGIS's processing tools, "Join Attributes by Location" and the "Extract Multi Values to Points tool", a shapefile was obtained from the original LUCAS 2 km $\times$ 2 km grid and a new set of fields for the compiled data for each POINT_ID. The resulting database is available in the Supplementary Material File S1.

2.4. IPCC Tier 1 Application

The IPCC (2019) defines twelve distinct climate types to be obtained following a classification decision tree based on mean annual temperature data (MAT), mean annual precipitation (MAP), potential evapotranspiration (PET) and days of frost per year. The database includes IPMA climate data for all unique points. For these, a climate classification was obtained using IPMA's corresponding data (Table 1) and following the IPCC's Climate Classification Scheme, as shown in Figure 2. The WRB soil map was converted to the IPCC soil classification using the correspondence table proposed by Batjes (2009) [35].

Table 1. IPMA variables and corresponding IPCC variables.

IPMA	IPCC Climate Classification Scheme
TAnMed	MAT (mean annual temperature)
PPAnoTot	MAP (mean annual precipitation)
EV0	PET (potential evapotranspiration)
TAnMinN < 0	Days of frost per year

A three-tiered approach for the estimation of SOC stocks and OC fluxes over a period of twenty years is provided by the IPCC [36]. In this work, tier 1—based on default emission factors—was applied. This approach follows the assumptions that (i) SOC is at equilibrium for a given set of soil and climate types and land-use and land-management conditions; and (ii) SOC changes linearly due to application of newland-use and/or land-management during a 20-year period, after which a new equilibrium is reached. Three concepts for different SOC states should be considered: (i) a SOC reference stock—the amount of carbon in soils in undisturbed conditions (SOC_{REF}), (ii) a SOC initial stock—the amount of carbon under initial land-use and land-management conditions ($SOC_{Initial}$) and (iii) a SOC final stock—the amount of carbon under final land-use and land-management conditions (SOC_{Final}). The SOC_{REF} values are provided by the IPCC and are climate- and soil-type dependent, and $SOC_{Initial}$ and SOC_{Final} are described as follows:

$$SOC = SOC_{REF_{c,s}} \times F_{LU_{c,i}} \times F_{MG_{c,i}} \times F_{I_{c,i}}, \quad (1)$$

where SOC is the amount of organic carbon in the soils at a 0–30 cm depth and at equilibrium in tC ha^{-1}, $SOC_{REF_{c,s}}$ is the amount of carbon in soils in undisturbed conditions in tC ha^{-1} and $F_{LU_{c,i}}$, $F_{MG_{c,i}}$ and$F_{I_{c,i}}$ are dimensionless stock change factors (SCFs) that represent, respectively, land-use type/level (cropland or grassland, with different land-use levels for each), tillage or grazing type, and input (low or medium, high with or without manure); "c", "s" and "i" represent climate, soil and the set of defining land-use/management conditions, respectively.

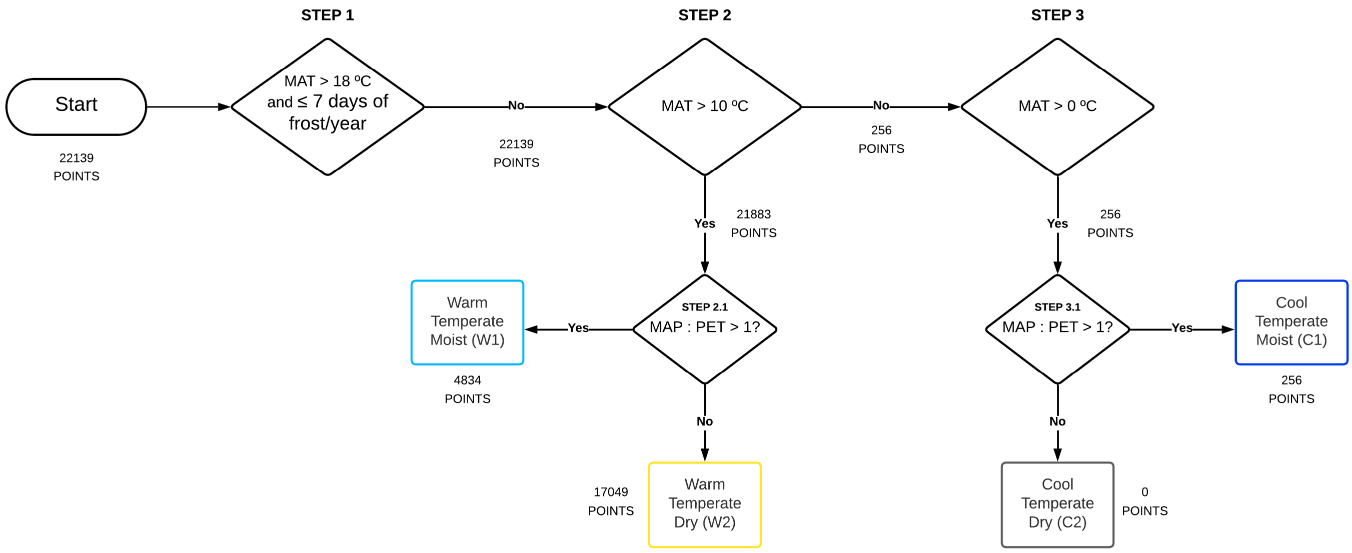

Figure 2. Application of the IPCC's Climate Classification Scheme to n = 22,139 points in mainland Portugal. The colors around each box are used to distinguish the different climate classifications and are coherent with the colors used in the climate classification map.

Average annual stock changes can then be calculated for a 20-year period with

$$\Delta C = \frac{SOC_{Final} - SOC_{Initial}}{D}, \quad (2)$$

where ΔC is the annual organic carbon stock change in tC ha^{-1} yr^{-1} at a 0–30 cm depth, and D corresponds to the period of application of the new land-use and/or land-management situation, taken as equal to 20 years. Following the IPCC 2019 convention for the LULUCF sector, positive values indicate soil carbon removals/sequestration (increase in SOC stocks), while negative values indicate soil carbon.

The "Initial" land use was set according to COS's land-use data from 2018, available for each POINT_ID in the database. In this work, specific land-management conditions were proposed to attempt to describe the most common management practices in Portugal since such data was not available at farm scale. These were then translated into the most appropriate descriptions, which then determined the default SCF values (F_{LU}, F_{MG} and F_I), as shown in Table 2. $SOC_{Initial}$ was then calculated for all managed cropland and grassland points following Equation (1).

Table 2. COS land uses (2018) and corresponding SCF descriptions for the initial land-use, land-management and input conditions, following IPCC Tables 5.5 (Ch. 5, Vol. 4) and 6.2 (Ch. 6, Vol. 4) of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [36].

COS_LULC	Initial LU Name	Land Use (F_{LU}) [2]	Management (F_{MG}) [2]	Inputs (F_I) [2]
Rainfed Annual Crops	Rainfed crop	Long-term cultivated	Full tillage	Medium
Irrigated Annual Crops	Irrigated crop	Long-term cultivated	Full tillage	HWOM
Vineyards	Permanent crops	Tree crop	Reduced tillage	Low
Olive Groves	Permanent crops	Tree crop	Reduced tillage	Medium
Other Permanent Crops	Permanent crops	Tree crop	Reduced tillage	Medium
Pastures [1]	Normal grassland	All	Non-degraded	-
Pastures [1]	Degraded grassland	All	Severely degraded	-

[1] COS does not differentiate between degraded, nominal management and improved grasslands. Initial maps show values for nominal management only. [2] The definitions linked to the descriptors used for the initial land-use, land-management and input conditions are shown in Table A1.

To apply the tier 1 methodology and estimate the carbon stock difference between two land-use and/or land-management practices following Equation (2), 13 transitions were set and the corresponding "Initial" and "Final" land-use and land-management conditions, as described in Table 3. The final land-use and land-management conditions represent a set of "aspirational" practices and land uses to be applied in alternative scenarios to the initial ones. SOC_{Final} was calculated in a similar manner to that described for $SOC_{Initial}$.

In this work, the following topics were explored: (i) the potential of "mitigation" transitions, i.e., land-use and land-management changes that lead to carbon sequestration, and (ii) whether "trend" transitions (which represent other tendencies observed in recent years) contribute to carbon sequestration.

Table 3. Initial and final land-use scenarios, corresponding transitions and descriptors to define SCFs according to the nomenclature proposed by IPCC Tables 5.5 (Ch. 5, Vol. 4) and 6.2 (Ch. 6, Vol. 4) of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [36].

Transition *		Scenario	Land-Use (F_{LU})	Management (F_{MG})	Inputs (F_I)
M1A [1]	I	Rainfed crop, full-till	Long-term cultivated	Full tillage	Medium
	F	Rainfed crop, no-till	Long-term cultivated	No tillage	Medium
M1B [1]	I	Irrigated crop, full-till	Long-term cultivated	Full tillage	HWOM [8]
	F	Irrigated crop, no-till	Long-term cultivated	No tillage	HWOM
M2 [2]	I	Rainfed crop, full-till	Long-term cultivated	Full tillage	Medium
	F	Irrigated crop, full-till	Long-term cultivated	Full tillage	HWOM
M3A [3]	I	Rainfed crop, full-till	Long-term cultivated	Full tillage	Medium
	F	Improved grassland	All	Improved	High
M3B [3]	I	Irrigated crop, full-till	Long-term cultivated	Full tillage	HWOM
	F	Improved grassland	All	Improved	High
M4A [4]	I	Rainfed crop, full-till	Long-term cultivated	Full tillage	Medium
	F	Set aside land	Set aside (<20 yr)	No tillage	Low
M4B [4]	I	Irrigated crop, full-till	Long-term cultivated	Full tillage	HWOM
	F	Set aside land	Set aside (<20 yr)	No tillage	Low
M5A [5]	I	Degraded grassland	All	Severely degraded	-
	F	Improved grassland	All	Improved	High
M5B [5]	I	Normal grassland	All	Non-degraded	-
	F	Improved grassland	All	Improved	High

Table 3. *Cont.*

Transition *		Scenario	Land-Use (F_{LU})	Management (F_{MG})	Inputs (F_I)
T1A [6]	I	Rainfed crop, full-till	Long-term cultivated	Full tillage	Medium
	F	Intensive permanent crop	Tree crop	Reduced tillage	HWOM
T1B [6]	I	Irrigated crop, full-till	Long-term cultivated	Full tillage	HWOM
	F	Intensive permanent crop	Tree crop	Reduced tillage	HWOM
T2A [7]	I	Rainfed crop, full-till	Long-term cultivated	Full tillage	Medium
	F	Degraded grassland	All	Severely degraded	-
T2B [7]	I	Intensive permanent crop	Tree crop	Reduced tillage	Medium
	F	Degraded grassland	All	Severely degraded	-

* "M" stands for "mitigation measure" and "T" stands for "observed trend". Testing the SOC change effect of [1] conversion from "full tillage" to "no tillage", [2] intensification by irrigation and increased inputs, [3] cropland conversion to grassland, [4] cropland conversion to set aside, [5] grassland improvement, [6] conversion from temporary cropland to intensive permanent crops, [7] cropland abandonment and [8] high input without manure. The definitions linked to the descriptors used for the initial and final land-use, land-management and input conditions are shown in Table A1.

2.5. Uncertainty of Estimates and Monte Carlo Simulations

The computation described in the previous section uses default values proposed by the IPCC, which resulted in average expected results for each transition. However, the IPCC also provides an uncertainty estimation associated with each default value. To represent the range of estimates, Monte Carlo (MC) simulations were performed using Python's "Numpy" and "Pandas" libraries. For each transition, 1000 different random values were generated for each $SOC_{REF_{c,s,i}}$ and each SCF ($F_{LU_{c,s,i}}$, $F_{MG_{c,s,i}}$, $F_{I_{c,s,i}}$) based on the assumption of normal distributions for each parameter and independence between parameters, where the average is the default IPCC value and the uncertainty is derived from the confidence intervals provided for each default value.

2.6. Determination of Maximum National Potentials

Having obtained annual SOC changes for all the listed transitions, a maximum theoretical national sequestration/emission potential for each transition was estimated by considering the application of the respective SOC change value to all areas available for each transition. For each transition, and per subregion (NUTS-3), a sequestration/emission potential was obtained by multiplying the average sequestration/emission factor by the area obtained from the INE datasets.

2.7. Testing the Adequacy of IPCC Tier 1

To understand the adequacy of the IPCC's tier 1 methodology in estimating SOC stocks, LUCAS in situ SOC values measured in the years 2009, 2015 and 2018 were compared with $SOC_{Initial}$ stocks obtained following the IPCC's method for cropland and grassland. However, OC values obtained through the IPCC and LUCAS values are not immediately comparable for two reasons: SOC values from the LUCAS database are expressed in gC kg^{-1} and were obtained for a layer of 20 cm, while the IPCC values are expressed in tC ha^{-1} for a 30 cm layer. To render these datasets comparable, LUCAS SOC data were converted to tC ha^{-1} at 30 cm using Equation (5) for n = 513 points.

OC at 0–30 cm was first estimated, following

$$OC_{0\text{–}30_i} = OC_{0\text{–}20_i} \times \frac{2 + \overline{r_{OC}}}{3}, \quad (3)$$

where $OC_{0\text{–}30_i}$ is the estimated OC at a 0–30 cm depth expressed in gC kg^{-1}, $OC_{0\text{–}20_i}$ is the measured OC at a 0–20 cm depth in point i expressed in gC kg^{-1} and $\overline{r_{OC}}$ is the average ratio between OC at 20–30 and at 0–20 cm of a selected number of samples (n = 65) available in the LUCAS database.

This was followed by an estimation of the bulk density:

$$\rho_{0\text{–}30_i} = -0.188 \times \ln\left(OC_{0\text{–}30_i}\right) + 1.6925, \quad (4)$$

where $\rho_{0\text{–}30_i}$ is the bulk density at a 0–30 cm depth for point i. This equation was derived from a linear-log regression between the bulk density and the natural log of organic carbon at 0–30 cm (n = 65), with the following performance coefficients: mean squared error (MSE): 0.0208, root mean squared error (RMSE): 0.1442 and r^2: 0.4523.

Finally, the determination of LUCAS SOC values in tC ha^{-1} was calculated using

$$T_{0\text{–}30_i} = \left(\rho_{0\text{–}30_i} \times OC_{0\text{–}30_i} \times D\right) \times (1 - S_i) \times 10, \quad (5)$$

where $T_{0\text{–}30_i}$ is the total amount of organic carbon over 30 cm deep in tC ha^{-1}, $\rho_{0\text{–}30_i}$ is the bulk density at point i in Mg m^{-3}, $\rho_{0\text{–}30_i}$ is the organic carbon at point i in gC kg^{-1}, D is a layer thickness of 0.3 m and S_i is the fraction of coarse elements.

A sensitivity analysis was performed to understand if the observed underestimations when compared to the LUCAS in situ data could be attributed to (i) the use of inaccurate factors to describe the initial land-use conditions and (ii) only certain soil types, climate types or land uses.

3. Results

3.1. IPCC Tier 1

A climate map was obtained for mainland Portugal, as shown in Figure 3a. "Warm temperate dry" (W2) is the climate with the most representation (77%), followed by "warm temperate moist" (W1) (22%). The climate type "cool temperate moist" (C1) is residual (1%) and limited to the areas with the highest altitudes. The resulting IPCC soil classification is represented in Figure 3b. High-activity clay (HAC) soils are the most prevalent (84%), followed by podzols (POD, 11%), low-activity clay soils (LAC, 4%) and sandy soils (SAN, 1%).

SOC stocks in undisturbed conditions were obtained and are represented in Figure 4a. SOC_{REF} stocks are exclusively dependent on the combination of climate and soil type. Eight climate- and soil-type combinations were obtained, leading to eight distinct SOC_{REF} values. The highest SOC_{REF} stock (143 tC ha^{-1}) was obtained for n = 3 points on podzol soils in warm temperate moist conditions. The second highest SOC_{REF} stock (81 tC ha^{-1}) was obtained in cold temperate moist climate regions with a high-activity clay soil (HAC) for n = 256 points, represented in light blue. A SOC_{REF} value of 24 tC ha^{-1} has the most representation (n = 13,531, 61%) and results from a combination of high-activity clay soils (HAC) and a warm temperate dry climate (W2). A total potential undisturbed SOC_{REF} stock of 320 MtC for mainland Portugal was estimated.

$SOC_{Initial}$ stocks were obtained for n = 7093 points, as represented in Figure 4b. Land-use conversion from reference conditions to agriculture (initial conversion to agriculture) has led to an estimated loss of 19 MtC for the represented cropland and grassland points. Excluding podzol soils, which have a very low representation, the highest $SOC_{Initial}$ stock (81 tC ha^{-1}) was obtained for pastures in high-activity clay soils and cold temperate moist climates (n = 48), followed by irrigated temporary cropland in high-activity clay soils and warm temperate moist climate conditions (49 tC ha^{-1}) (n = 394), permanent crops (48 tC ha^{-1}) (n = 160) and rainfed temporary cropland (44 tC ha^{-1}) (n = 349), also in high-activity clay soils and warm temperate moist climate conditions. In contrast, the lowest estimated $SOC_{Initial}$ stocks were obtained for permanent crops in sandy soils and warm temperate dry conditions (7 tC ha^{-1}).

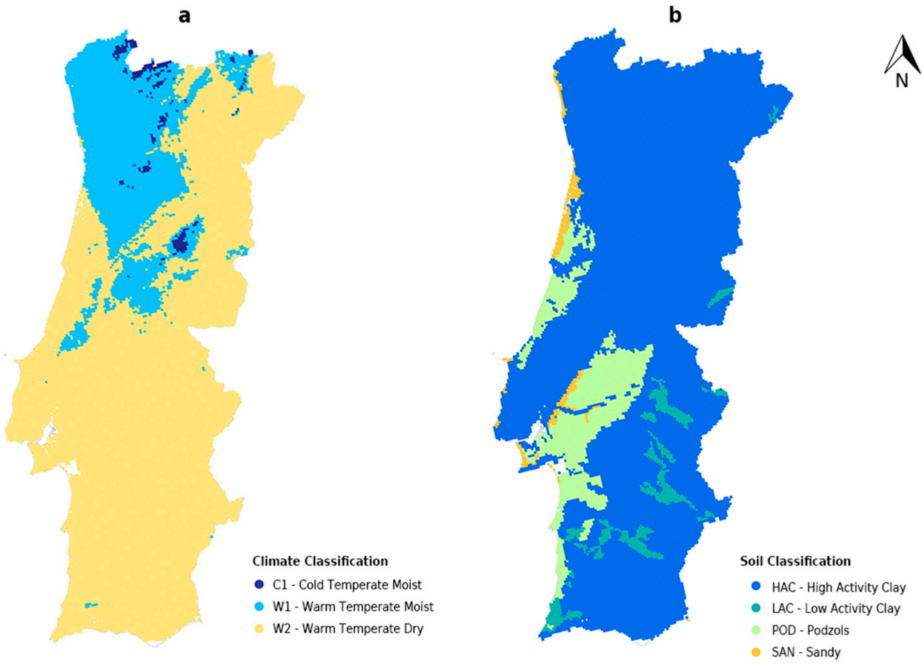

Figure 3. (**a**) Mainland Portugal IPCC climate classification; (**b**) mainland Portugal IPCC soil classification.

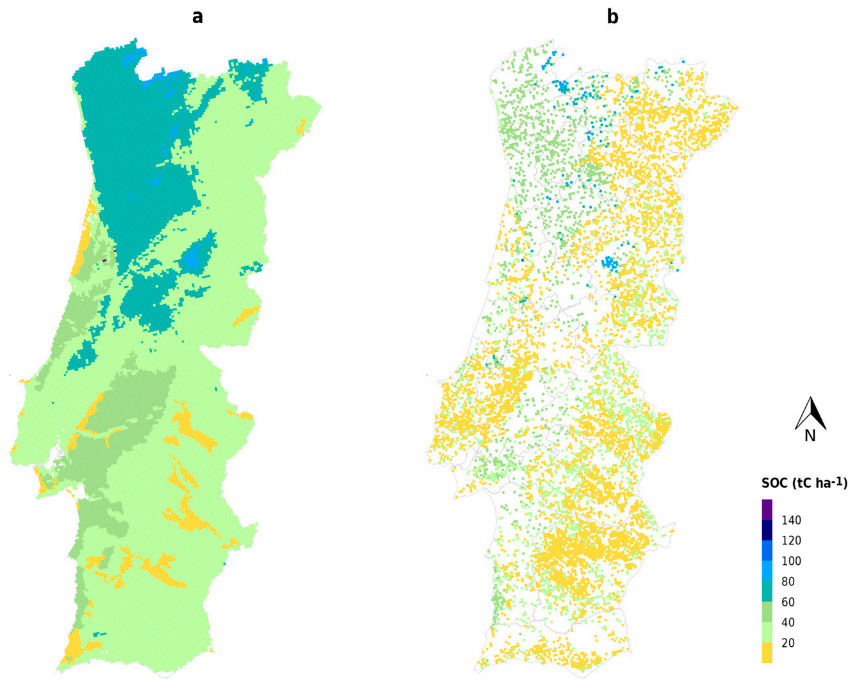

Figure 4. (**a**) SOC_{REF} (before land-use conversion for agriculture) and (**b**) $SOC_{Initial}$ (after land-use conversion for agriculture) for cropland and grassland LU in 2018 (tC ha^{-1}).

All the simulated "mitigation" transitions resulted in SOC sequestration. The conversion of irrigated crops to improved grasslands (M3B, Figure 5d) was estimated to lead to the highest average SOC sequestration potential (1.05 tC ha^{-1} yr^{-1}), with SOC accumulation all over Portugal (Table 4). The second highest average was obtained for the improvement of poor degraded pastures, resulting in a yearly average sequestration of 0.84 tC ha^{-1}. The ranges for these transitions were 0.24–3.57 tC ha^{-1} yr^{-1} and 0.28–4.05 tC ha^{-1} yr^{-1}, respectively. For both transitions, the potentials at the higher end were obtained for farm sites in podzol soils and warm temperate moist conditions, and the lowest for farm sites on sandy soils and in warm temperate dry conditions. The lowest SCS potentials were obtained for a change from "full" to "no tillage" in both rainfed and irrigated crops (M1A and M1B, Figure 5a,b), with yearly average sequestration potentials of 0.07 and 0.12 tC ha^{-1} and ranges equal to 0.02–0.49 and 0.02–0.55 tC ha^{-1} yr^{-1}, respectively, with farm sites on podzol soils and warm temperate moist conditions (POD/W2) at the highest end of the estimations.

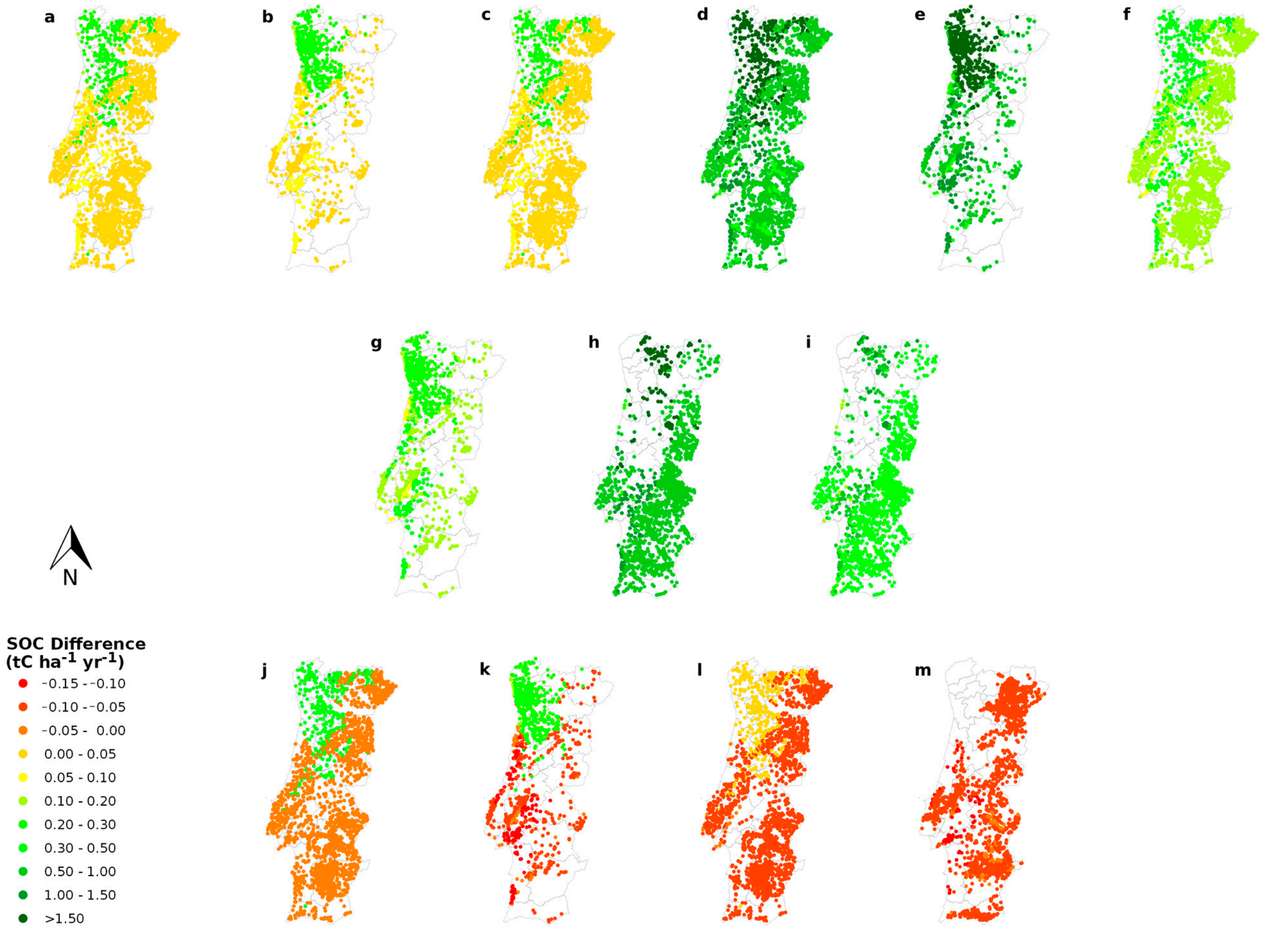

Figure 5. Yearly difference in SOC stocks since the onset of the activity and applicable for 20 years per transition in tC ha^{-1} yr^{-1}. (**a**) M1A—rainfed crop conversion from "full tillage" to "no tillage", (**b**) M1B—irrigated crop conversion from "full tillage" to "no tillage", (**c**) M2—intensification by irrigation, (**d**) M3A—rainfed crop conversion to grassland, (**e**) M3B—irrigated crop conversion to grassland, (**f**) M4A—rainfed crop to set aside, (**g**) M4B—irrigated crop to set aside, (**h**) M5A—improvement of poor degraded pastures, (**i**) M5B—improvement of normal pastures, (**j**) T1A—rainfed crop to intensive permanent crops, (**k**) T1B—irrigated crop to intensive permanent crops, (**l**) T2A—rainfed crop abandonment, (**m**) T2B—irrigated crop abandonment; positive values indicate carbon sequestration, and negative values indicate carbon emission.

Conversely, and for all the "trends" transitions, SOC loss is estimated to occur for most of Portugal's mainland territory, except sites in the north (T1A, T1B, T2A, T2B, Figure 5j–l,m). Interestingly, transitions T1A and T1B (Figure 5j,k) lead to contrasting results in mainland Portugal. On podzol soils and in warm temperate moist conditions (POD/W1), a conversion to intensive permanent crops is estimated to lead to a SOC sequestration of 1.07 tC ha^{-1} yr^{-1} and 0.52 tC ha^{-1} yr^{-1} for rainfed and irrigated temporary cropland, respectively. On the other hand, on podzol soils and in warm temperate dry conditions (POD/W2), cropland perennialization is estimated to lead to a SOC loss of 0.02 and 0.13 tC ha^{-1} yr $^{-1}$, respectively. Cropland abandonment leads to the highest SOC loss (T2A and T2B, Figure 5), with yearly average losses of 0.06 tC ha^{-1} and 0.08 tC ha^{-1}, respectively. Notably, the conversion of intensive permanent cropland to degraded poor grassland (land-abandonment scenario) is estimated to lead to a SOC loss for all sites and all climate/soil combinations in mainland Portugal (T2B, Figure 5m).

Table 4. SOC sequestration (+)/loss (−) average and range expressed in tC ha^{-1} yr^{-1} and average SOC variation (%) over a 20-year application of the new (final) land use.

Transition	$\overline{\text{dSOC}}$ (tC ha^{-1} yr^{-1})	[Range] (tC ha^{-1} yr^{-1})	Average SOC Increase (%) Over 20 Years
M1A	0.07	[0.02–0.49]	+5%
M1B	0.12	[0.02–0.55]	+6%
M2	0.07	[0.02–0.54]	+5%
M3A	0.82	[0.25–4.11]	+69%
M3B	1.05	[0.24–3.57]	+62%
M4A	0.24	[0.08–1.00]	+21%
M4B	0.20	[0.06–0.46]	+13%
M5A	0.84	[0.28–4.04]	+81%
M5B	0.39	[0.13–1.90]	+27%
T1A	0.05	[−0.02–1.07]	0%
T1B	0.05	[−0.13–0.52]	1%
T2A	−0.06	[−0.15–0.07]	−7%
T2B	−0.08	[−0.99–−0.02]	−8%

Results from the application of the tier 1 methodology in this study, by "POINT_ID", are available in the Supplementary Material File S1 for consultation and download.

3.2. Uncertainty of Estimates

The estimates obtained in the previous section result from the IPCC default factors (SOC_{REF}, F_{LU}, F_{MG}, F_I), which represent the means of normal distributions. In this section, the results with their associated variability are shown.

When variability is introduced for some transitions, emissions may occur. For example, the transition from rainfed to irrigated crops results in an estimated dSOC average of 0.07tC ha^{-1} yr^{-1} and positive ranges (M2, Table 4). However, when uncertainty is considered, all climate/soil combinations have negative dSOC values (M2, Figure 6c), with the lowest dSOC value obtained for POD/W2 of −0.17 tC ha $^{-1}$ yr $^{-1}$ (excluding outliers). The transitions of rainfed and irrigated crops to set aside land have positive dSOC averages and ranges in the previous section (M2, Table 4); however, negative values are obtained for all climate/soil-type combinations, with the highest emission values of 0.3 (W2/POD) and 0.47 (W1/POD) (for M4A, M4B, respectively, Figure 6f,g). For transitions that resulted in negative averages or negative ranges in the previous section (T2A, T2B, respectively, Table 4), when considering uncertainty, sequestration may occur, with maximum sequestration values of 0.49 (C1/HAC) and 0.46 (W1/POD), excluding outliers (for T2A and T2B, respectively, Figure 6a,m).

Uncertainty—represented in the ranges of values—is higher or lower according to climate- and soil-type combination for each transition, as shown in Table A2.

When occurring, the W1/POD climate/soil combination leads to the highest variability in the results, followed by the C1/HAC climate/soil combination.

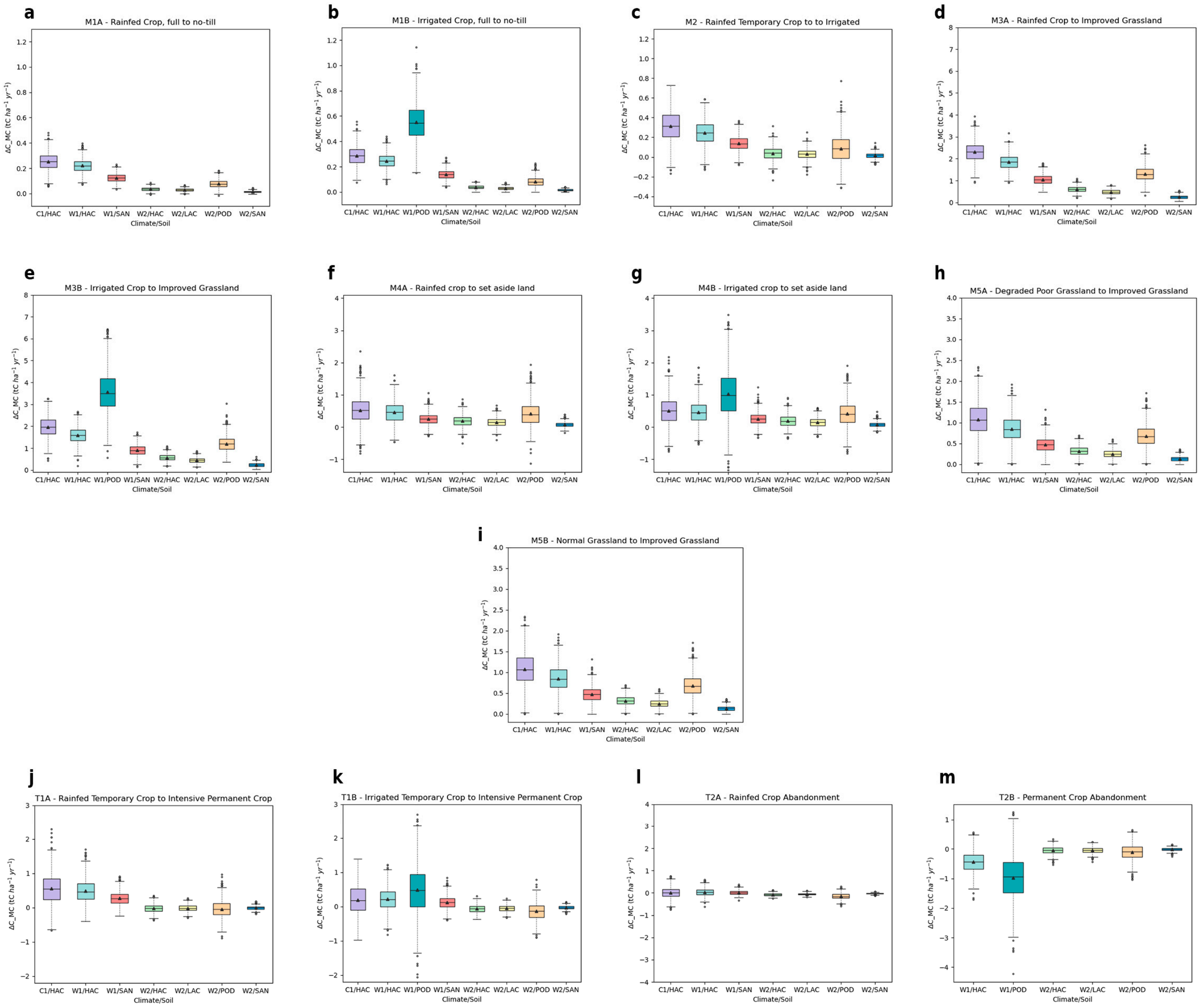

Figure 6. MC distribution of dSOC in tC ha^{-1} yr^{-1} per transition and climate/soil-type combination. (**a**) M1A—rainfed crop conversion from "full tillage" to "no tillage", (**b**) M1B—irrigated crop conversion from "full tillage" to "no tillage", (**c**) M2—intensification by irrigation, (**d**) M3A—rainfed crop conversion to grassland, (**e**) M3B—irrigated crop conversion to grassland, (**f**) M4A—rainfed crop to set aside, (**g**) M4B—irrigated crop to set aside, (**h**) M5A—improvement of poor degraded pastures, (**i**) M5B—improvement of normal pastures, (**j**) T1A—rainfed crop to intensive permanent crops, (**k**) T1B—irrigated crop to intensive permanent crops, (**l**) T2A—rainfed crop abandonment, (**m**) T2B—irrigated crop abandonment; positive values indicate carbon sequestration, and negative values indicate carbon emission. For each boxplot in the figure, (**a**) the box represents the interquartile range and includes values within the 25th and 75th percentiles, (**b**) a triangle represents the mean and the horizontal line the median, (**c**) the minimum and maximum values are shown at the ends of the plot (upper and lower bounds of the 2.5th and 97.5th percentiles) and (**d**) the dots are outliers.

3.3. Maximum National Potentials

The improvement of poor degraded grasslands in the region of Baixo Alentejo (M5A, Figure 7h) results in the highest maximum estimated sequestration potential, equal to 84.5 tC yr^{-1} if applied in all the managed grasslands of the region. Although Baixo Alentejo is not the region with the highest estimated average yearly SOC sequestration (0.7, vs. 2.1 tC ha^{-1} yr^{-1}, obtained for Alto do Minho region), its managed pasture area (150,974 ha)—the highest in the whole territory—leads to this result. This same type of land management would result to in the highest maximum national SOC sequestration potential, 0.6 MtC yr^{-1}, if applied in all the managed pastures in mainland Portugal. Alto do Tâmega is the region with the second highest SOC sequestration potential, obtained also for the improvement of degraded pastures (83.6 tC yr^{-1}).

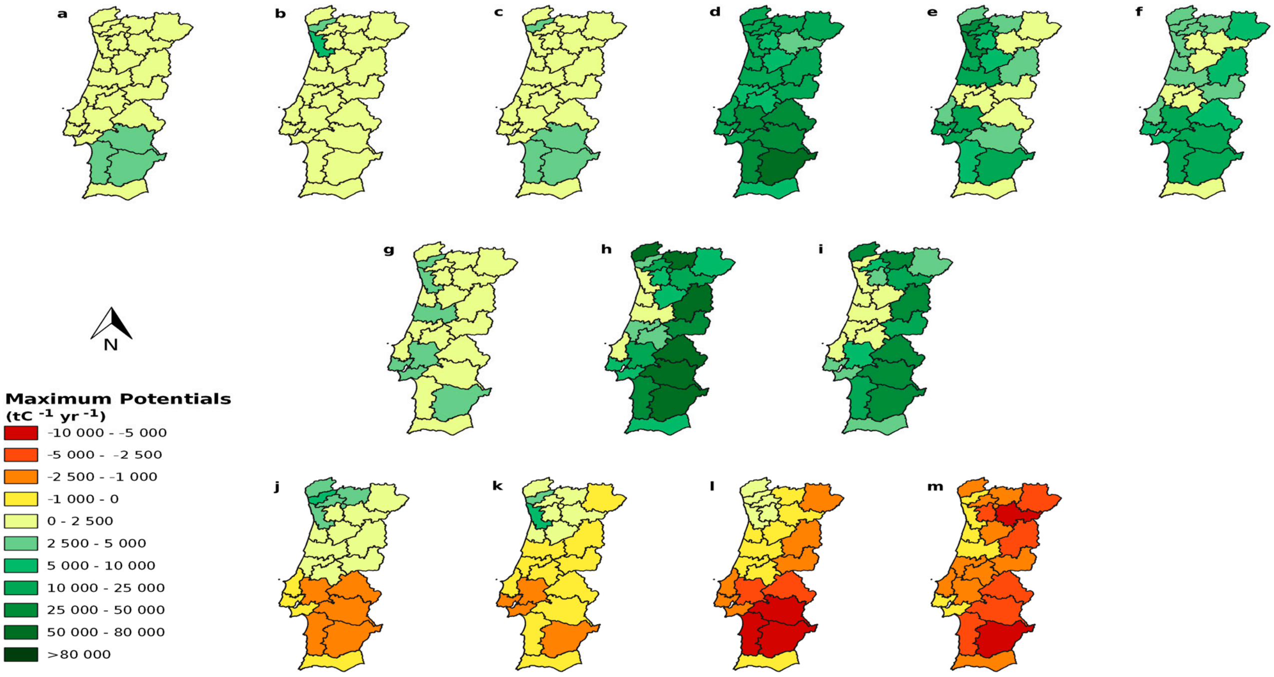

Figure 7. Maximum potentials in tC^{-1} yr^{-1} per NUTS-III (2022) per transition applied for 20 years since the onset of the activity: (**a**) M1A—rainfed crop conversion from "full tillage" to "no tillage", (**b**) M1B—irrigated crop conversion from "full tillage" to "no tillage", (**c**) M2—intensification by irrigation, (**d**) M3A—rainfed crop conversion to grassland, (**e**) M3B—irrigated crop conversion to grassland, (**f**) M4A—rainfed crop to set aside, (**g**) M4B—irrigated crop to set aside, (**h**) M5A—improvement of poor degraded pastures, (**i**) M5B—improvement of normal pastures, (**j**) T1A—rainfed crop to intensive permanent crops, (**k**) T1B—irrigated crop to intensive permanent crops, (**l**) T2A—rainfed crop abandonment, (**m**) T2B—irrigated crop abandonment; positive values indicate carbon sequestration, and negative values indicate carbon emission.

The abandonment of permanent crops (T2B, Figure 7m) in the Douro region leads to a SOC loss of up to 89.7 tC yr^{-1}, the highest C loss of all transitions and regions when applied in all the managed land in the region. The abandonment of temporary and permanent crops (T2A and T2B, Figure 7l,m) has an overall negative effect on SOC stocks, with a combined estimated loss of -0.09 MtC yr^{-1} if applied at a national level for both permanent and temporary cropland. Although the conversion of temporary crops to intensive permanent crops (T1A, T1B, Figure 7j,k) can cause notable SOC losses in the regions of Baixo Alentejo and Alentejo Litoral, the overall SOC change for this land-use conversion, if applied in all the managed rainfed and irrigated temporary cropland nationally, is estimated to be 0.03 MtC yr^{-1}, a scenario of SOC sequestration.

3.4. IPCC Tier 1 Adequacy

The results show that the IPCC's tier 1 methodology tends to underestimate $SOC_{Initial}$ stocks when compared to LUCAS in situ sampled OC in the years 2009, 2015 and 2018 (n = 578), as shown in Figure 8. The two distinct bands of values—one in the upper range and one in the lower range—correspond to points in warm temperate moist conditions (W1) and points in warm temperate dry conditions (W2), respectively.

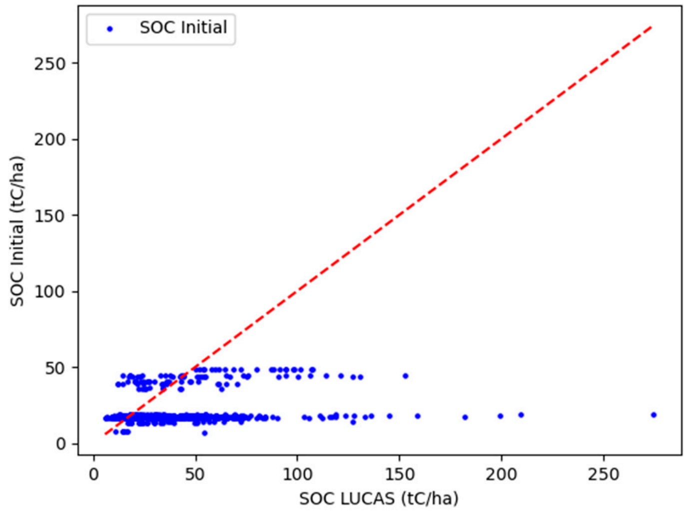

Figure 8. Initial soil organic carbon stocks ($SOC_{Initial}$) as obtained with the IPCC's tier 1 vs. LUCAS in situ soil organic carbon measurements (SOC_{LUCAS}) from 2009, 2015 and 2018 (n = 578).

It was concluded that (i) when changing the initial set of conditions (and thereby changing the SCFs that define the SOC stocks) to a more "optimistic scenario", the pattern of underestimation still prevails (60%, n = 344); and (ii) there is no specific emerging pattern (of underestimation or overestimation) for land-use, climate or soil type.

4. Discussion

4.1. Comparison with the Literature

The results obtained in this study and the figures reported in the literature (from long-term experiments, models or applications of tier 1) show different levels of agreement depending on the transition (Table 5).

For a management change of full- to no-till in cropland (M1A, M1B), long-term field experiments in the Mediterranean have reported yearly sequestration averages of 0.40 tC ha^{-1} and 0.46 tC ha^{-1} [37,38]. In this work, the same land-management change resulted in yearly sequestration averages of 0.07 and 0.12 tC ha^{-1}, considerably lower values when compared to the literature.

As for the conversion of cropland to grassland (M3A, M3B), a long-term experiment in Italy reported yearly sequestration rates of 0.54 tC ha^{-1} [39]. Results for the conversion of rainfed and irrigated crops to improved grassland were higher: 0.82 tC ha^{-1} yr^{-1} and 1.05 tC ha^{-1} yr^{-1}, respectively.

The literature reviewed on the conversion of temporary to perennial cropland (T1A, T1B) also shows contrasting results for different regions. A global meta-analysis concluded the conversion from annual to perennial crops led to a 20% increase in SOC [23]; although based on estimated C input and mineralization rates from a detailed global modeling of SOC stocks [12], an average yearly decrease in SOC stocks of 0.50 tC ha^{-1} yr^{-1} and 0.73 tC ha^{-1} yr^{-1} was calculated for Portugal.

For cropland abandonment (T2A, T2B), a yearly SOC loss of up to 0.08 tC ha^{-1} was estimated. Novara et al. (2017) estimated cropland abandonment in the Sicily region to lead to an average yearly increase of 0.45 tC ha^{-1} yr^{-1}, following a method adapted from the IPCC tier 1 [40]. Such contrasting results may be attributed to the choice of SCFs. While in this work the F_{MG} and F_I chosen to represent an abandoned scenario were, respectively, 0.7 and 1, in Novara et al. (2017), F_{MG} and F_I were set to 1, ultimately leading to higher stocks for the abandonment scenario.

Despite the lack of a consistent pattern in the figures obtained in this work and the comparison with the literature, it is important to note that the Monte Carlo ranges (Range MC) include the values found in the literature for the majority of the transitions.

Table 5. Average SOC change ($\overline{dSOC}$), SOC range after Monte Carlo simulations (Range MC) and the literature figures expressed in tC ha^{-1} yr^{-1}.

Transition	$\overline{dSOC}$ (tC ha^{-1} yr^{-1})	Range MC [a] (tC ha^{-1} yr^{-1})	Literature (tC ha^{-1} yr^{-1})	Reference
M1A	0.07	[0.00–0.40]	0.14, 0.40, 0.46, 0.45	[41] [1], [37] [2], [38] [3], [42] [4]
M1B	0.12	[0.00–0.88]	0.40, 0.46, 0.45	[37] [2], [38] [3], [42] [4]
M2	0.07	[−0.17–0.62]	0.18, +5.9%	[12] [5], [43] [6]
M3A	0.82	[0.11–3.23]	0.54	[39] [7]
M3B	1.05	[0.10–5.85]	0.54	
M4A	0.24	[−0.31–1.33]	<0.38	[15]
M4B	0.20	[−0.47–2.61]		
M5A	0.84	[0.03–1.95]	1.78	[44] [8]
M5B	0.39	[0.35–3.14]	0.71	
T1A	0.05	[−0.59–1.49]	+16.6%, +20%, 0.56, −0.50	[45] [9], [23] [10], [39] [11], [12] [5]
T1B,	0.05	[−0.67–2.01]	+16.6%, +20%, −0.73	[12,23,45]
T2A	−0.06	[−0.47–0.49]	0.45	[40] [12]
T2B	−0.08	[−2.9–0.46]		

[a] [2.5 percentile–97.5 percentile]. [1] Spain, results from eight studies under rainfed agriculture; [2] Italy, Mediterranean, 29-year sampling experiment, 0–30 cm; [3] Spain, Mediterranean, 16-year sampling experiment, 0–30 cm; [4] USA, literature review of long-term sampling experiments in southeast USA, 11-years, 0–20 cm; [5] calculated from modeled estimates for Portugal, 86 years, 0–30 cm; [6] global systematic literature review (n = 42), 2–47 years, 0–30 cm; [7] Italy, average calculated from the resulting database of a global literature review, 30-year sampling experiment, 0–30 cm; [8] Portugal, calibrated model from 5-year sampling experiment, 10 years, 0–10 cm; [9] global systematic review (n = 51) of long-term experiments, value for monoculture, 0–30 cm; [10] modeled estimates from a harmonized global dataset, 20-year period, 0–30 cm; [11] Spain, average calculated from the resulting database of a global literature review, 20–55 year sampling experiments; [12] Sicily, calculated through and adaptation of the IPCC methodology, 0–30 cm depth, 20-year period.

The literature reports that the application of no-till instead of conventional tillage in cropland [46,47], the conversion of cropland to grassland [22], the use of set aside land [48] and the improvement of grasslands [44] generally lead to SOC accumulation in Mediterranean systems. These results are similar to the conclusions obtained in this work.

As for rainfed versus irrigated crops, the literature reports contrasting scenarios—from a C accumulation [49] to a C loss [50] and even no change [51]. This is reflected in the results, where a low yearly C accumulation average and MC estimates that vary from negative values (C emission) to positive values (C sequestration) were obtained.

For the conversion of cropland to degraded pasture in the Mediterranean region, studies report contrasting results after abandonment, from negligible SOC gains to substantial SOC increases [52,53]; this is due to the fact that natural re-vegetation after land-abandonment varies from site to site [54]. In this work, however, cropland abandonment was found to decline C stocks. The choice of factors to characterize "degraded pasture" as the land-use to apply in all croplands to represent the land-abandonment scenario (T2A, T2B) may not fully represent the variability of the reality of land-abandonment conditions and may also not be comparable with the abandonment scenarios described in the literature.

The majority of studies report that conversion from temporary to permanent crops delivers beneficial C accumulation results [23,45]. In this study, a small positive yearly C accumulation for mainland Portugal was obtained. In the north of Portugal, where colder and more humid climates prevail, this conversion is especially beneficial. However, C loss is likely to occur in the south of the territory, where dry climates prevail. This is an important conclusion, as it reveals that this land-use conversion may not be adequate for the dry climate regions of Portugal.

Overall, the results obtained in this study add to the ongoing debate on the true potential of agricultural soils to sequester carbon, as uncertainties still prevail regarding the capacity of certain land-management practices and land-use conversion strategies to sequester carbon. These results also highlight the need for the development of regional and site-level SOC sequestration emission factors, as the IPCC's tier 1 emission factors may not be the most adequate to represent local variability due to their generalized nature.

4.2. Assumptions and Limitations

Temporal patterns of SOC changes—The IPCC tier 1 methodology is based on the key assumptions that SOC stocks change linearly after land-use conversion and/or land-management change, that they start with an equilibrium SOC stock and that the transition period invariably lasts for 20 years, after which a new equilibrium is reached. These assumptions greatly simplify the temporal dynamics of SOC stocks and changes. In fact, SOC accumulation or loss does not happen linearly and may fluctuate over time, with different patterns of accumulation/losses for different land-use and management changes [55,56]. For example, a logarithmic increase has been reported following farmland abandonment [57] and cropland conversion to grassland [26], while for a conversion from annual crops to perennial grasses, an initial SOC gain was followed by a marked SOC loss, followed by SOC gain [23]. Furthermore, the duration of the transition period also varies. This may limit the comparability of this paper's results, and the values obtained in the literature, since the reviewed articles show varying periods from 5 to 86 years.

Soil depth of 0–30 cm—The estimation of soil SOC changes and stocks over a 30 cm depth may not be sufficient to describe the overall C accumulation or loss dynamics, as deeper layers also show differences in SOC concentrations that may not follow the same tendency as layers below 30 cm [31]. This, however, does not affect the comparisons made with the literature, as most studies mentioned in this work consider the same layer depth.

The IPCC's methodology to derive the default emission factors—The application of the IPCC tier 1 methodology is based on climate- and soil-dependent default factors for SOC_{REF} and land-use- and climate-dependent default SCFs (FLU, FMG, FI) derived from a global dataset of experimental results for tillage, input, set aside and land use. The IPCC derived its references for "cropland" from a total of 497 articles and for "grassland" from a total of 35 articles. The IPCC mentions the use of "semi-parametric mixed effect models" to estimate the emissions factors but does not provide a full, comprehensive description of the methods used to compile the data and derive the default factors. This limits the understanding of the adequacy (or lack thereof) of the default factors in the Portuguese context.

Podzol/W2—No default emission factors were provided for podzols in W2 climate conditions, as the IPCC does not consider this a common soil/climate combination. This combination does occur in Portugal, even if it is limited in representation (11% of Portugal). This value was gap-filled using the relationship between SOC_{REF} in climates W2/W1 and in soil types LAC and HAC. However, due to the limited territorial expression of this soil/climate combination, it is unlikely that this has affected the results in a significant manner.

Generalist representation of land use and agricultural management practices—Although disaggregated data on actual farmland-management practices in Portugal are lacking, the application of the tier 1 methodology and its highly generalist default SCFs to define management and input characteristics would not allow for an accurate and detailed representation of the different crop types and management techniques. The "F_{LU}" factor only considers two major LUs—"cropland" and "grassland"—differentiating between temporary and perennial cropland and set aside land, with no crop-type specific LU. Furthermore, the same input factor, "FI", may represent a great variety of input management characteristics. For example, in this work, "FI = high w/o manure" was chosen to represent "irrigated" cropland. However, this same FI may also be used to represent the use of cover crops or green manure in temporary cropland. Hence, it is shown here that the IPCC considers the use of irrigation to have the same impact on C dynamics as the use of cover crops in temporary cropland, which is a generalist assumption.

Maximum national sequestration potentials—To estimate a sequestration potential per NUTS-3 region and per transition, an average dSOC was obtained, per region and per transition (tC yr^{-1} ha^{-1}), and then multiplied by the relevant managed agricultural area to obtain a dSOC per NUTS-3 in tC yr^{-1}. An alternative, more accurate way to produce these results would have been to multiply the estimates obtained for each site (POINT_ID) by the managed area associated with the farm where the site is located. However, these data are not available. Furthermore, the national sequestration potential obtained represents maximum potentials for SOC sequestration, i.e., theoretical potentials assuming the application of the practice to all the available managed area. The actual figures will likely be much smaller, as (1) not all farmers will apply these management changes, and (2) some management changes compete for the same area (e.g., M1A—rainfed crop conversion from "full tillage" to "no tillage" and T1A—rainfed crop to intensive permanent crops), and so their impact cannot be added. The values obtained are therefore theoretical and serve mostly to inform and compare the impacts of the application of different management strategies and not as forecasts of future impacts.

Method used to render LUCAS SOC comparable with the IPCC—The function used to estimate the bulk density, $\rho_{0\text{–}30_i}$, was derived from a linear-log regression between the bulk density and organic carbon for n = 65 points from the LUCAS database. This function showed performance coefficients R^2: 0.4523 and RMSE: 0.1442, values well within the ranges reported in a literature review of 48 published pedotransfer functions by Abdelbaki (2018) [58]. Nevertheless, this is a source of error in the determination of the organic carbon values of the LUCAS points since the estimated bulk density values were used to convert organic carbon values expressed in g kg^{-1} to tC ha^{-1}. However, it is unlikely that this factor alone could explain the differences between the IPCC and LUCAS estimates of SOC.

4.3. Potential Extensions of This Work and Future Work

This work offers valuable insights into national and regional policy directions toward soil carbon sequestration. By mapping potentials for SOC accumulation or loss for certain recommended mitigation practices (M1A to M5B) and land-change trends (T1A to T2B) for Portuguese agricultural soils, it is now possible to realize the potential impacts of these practices on a farm and at national levels. It is also possible to compare measures, not only in terms of their impact per hectare but also in terms of the impact at regional and national scales, which also depends on the land available for application.

However, this work also shows that the IPCC's tier 1 methodology and its default emission factors may not adequately quantify SOC content in the Portuguese context. It is therefore important that a higher tier method is developed, such as a tier 2 equivalent method with regional default factors, to more accurately represent region-specific conditions at a crop-specific level [59,60]. Developing such a method will require efforts to enhance in situ measurements and improve the standardization of sampling methods. Additionally, estimating the opportunity costs of the mitigation options discussed in this study would enhance the understanding of their technical and economic feasibility while providing valuable insights to inform policymakers and farmers.

5. Conclusions

This study highlights the significant potential for soil organic carbon (SOC) sequestration in Portuguese agricultural soils, providing valuable insights into the impact of various land-use and land-management practices. A comprehensive estimation of SOC stocks in mainland Portugal was conducted, showing significant variation due to climate-and soil-type combinations. For example, SOC stocks were found to be higher in cool temperate moist climates and high-activity clay soils compared to warm temperate dry climates. These findings underscore the importance of soil- and climate-specific factors.

Among the evaluated mitigation and trend strategies, the improvement of poor degraded pastures showed the highest national sequestration potential, achieving up to 0.6 MtC yr^{-1} (or 2.2 $MtCO_{2eq}$, about 4% of Portugal's emissions in 2021 [61]), if applied to all the managed pastures in mainland Portugal.

While the tier 1 approach provides a practical framework for comparing the relative effects of various practices, its generalized assumptions and reliance on global default factors limit its ability to fully reflect the Portuguese conditions at regional and crop-specific levels. This underscores the urgent need for a systematic soil monitoring network and the development of a tier 2 or tier 3 methodology tailored to regional contexts.

By identifying practices with high sequestration potential, such as improving degraded grasslands and converting croplands to grasslands, this research offers insights for stakeholders aiming to enhance SOC stocks as part of Portugal's climate mitigation strategy.

Future research should prioritize the integration of more local data and the refinement of emission factors to improve the accuracy of SOC sequestration estimates, particularly in Mediterranean agricultural systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17031223/s1, File S1: Database.

Author Contributions: Conceptualization, M.R., P.C. and T.D.; methodology, M.R., P.C. and T.D.; software, M.R.; formal analysis, M.R.; data curation, M.R. and P.C.; writing—original draft preparation, M.R.; writing—review and editing, P.C. and T.D.; visualization, M.R.; supervision, P.C. and T.D.; funding acquisition, P.C. and T.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by NºAgroClima projects (1 April 2022 to 30 June 2025), which are funded by the PRR (Plano de Recuperação e Resiliência) and "GreenBeef: Towards carbon neutral Angus beef production in Portugal" (PO-CI-01-0247-FEDER-047050), led by Terraprima—Serviços Ambientais and "BLOCKCHAIN.PT—Descentralizar Portugal com Blockchain" (Contract n.º 51), funded by IAPMEI/PRR (Agendas Mobilizadoras para a Inovação Empresarial). This work was also supported by FCT/MCTES (PIDDAC) through projects UIDB/50009/2025, UIDP/50009/2025 and LA/P/0083/2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets presented in this study are included in the Supplementary Material.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Definitions for each SCF description for cropland and grassland land uses, adapted from Tables 5.5 (Ch. 5, Vol. 4) and 6.2 (Ch. 6, Vol. 4) of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [36].

Cropland								
Land Use (F_{LU})			**Tillage (F_{MG})**			**Input (F_I)**		
Long-Term Cultivated	**Perennial**	**Set Aside (<20 yrs)**	**Full**	**Reduced**	**No-Till**	**Low**	**Medium**	**HWOM**
Area that has been converted from native conditions and continuously managed for predominantly annual crops for over 50 yrs.	Long-term perennial tree crops such as fruit and nut trees, coffee and cacao.	Represents temporary set aside of annual cropland (e.g., conservation reserves).	Substantial soil disturbance with full inversion and/or frequent (within a year) tillage operations.	Primary and/or secondary tillage but with reduced soil disturbance.	Direct seeding without primary tillage, with only minimal soil disturbance in the seeding zone.	Low residue return occurs when there is removal of residues and frequent bare fallowing.	Representative of annual cropping with cereals where all crop residues are returned to the field.	Represents significantly greater crop residue inputs due to additional practices, such as the production of high residue yielding crops and the use of green manures, cover crops, improved vegetated fallows and irrigation.
Pastures								
Land use (F_{LU})	**Management (F_{MG})**							**Input (F_I)**
All	**Non-degraded**	**Severely degraded**			**Improved grassland**			**High**
All permanent grassland is assigned a land-use factor of 1.	Represents non-degraded and sustainably managed grassland but without significant management.	Implies major long-term loss of productivity and vegetation cover due to severe mechanical damage to the vegetation and/or severe soil erosion.			Represents grassland that is sustainably managed with moderate grazing pressure and that receives at least one improvement (e.g., fertilization, species improvement, irrigation).			Applies to improved grassland where one or more additional management inputs/improvements has been used.

Table A2. dSOC in tC ha^{-1} yr^{-1} and Range $_{MC}$ per climate/soil-type combination and per transition.

Transition		C1/HAC	W1/HAC	W1/POD	W1/SAN	W2/HAC	W2/LAC	W2/POD	W2/SAN
M1A	**dSOC**	0.26	0.22	-	0.13	0.04	0.03	0.08	0.02
	Range $_{MC}$	[0.12–0.39]	[0.13–0.32]	-	[0.06–0.19]	[0.01–0.06]	[0.01–0.05]	[0.01–0.15]	[0.00–0.03]
M1B	**dSOC**	0.285	0.245	0.55	0.14	0.04	0.03	0.08	0.02
	Range $_{MC}$	[0.14–0.45]	[0.14–0.37]	[0.28–0.88]	[0.07–0.21]	[0.01–0.07]	[0.12–0.39]	[0.12–0.39]	[0.12–0.39]
M2	**dSOC**	0.31	0.25	-	0.14	0.035	0.03	0.08	0.02
	Range $_{MC}$	[−0.17–0.73]	[−0.13–0.59]	-	[−0.08–0.37]	[0.23–0.23]	[−0.18–0.25]	[−0.57–0.77]	[−0.08–0.14]
M3A	**dSOC**	2.29	1.84	-	1.035	0.605	0.48	1.30	0.26
	Range $_{MC}$	[1.43–3.22]	[1.20–2.56]	-	[0.64–1.50]	[0.37–0.86]	[0.28–0.71]	[0.68–2.01]	[0.12–0.43]
M3B	**dSOC**	1.98	1.6	3.57	0.9	0.57	0.45	1.225	0.24
	Range $_{MC}$	[1.04–2.92]	[0.88–2.32]	[1.72–5.76]	[0.46–1.37]	[0.28–0.85]	[0.23–0.70]	[0.57–2.00]	[0.09–0.43]
M4A	**dSOC**	0.50	0.45	-	0.25	0.19	0.15	0.41	0.08
	Range $_{MC}$	[−0.32–1.41]	[−0.20–1.09]	-	[−0.11–0.64]	[−0.13–0.53]	[−0.10–0.43]	[−0.27–1.22]	[−0.06–0.25]
M4B	**dSOC**	0.50	0.45	1.00	0.25	0.19	0.15	0.41	0.08
	Range $_{MC}$	[−0.30–1.39]	[−0.21–1.18]	[−0.46–2.76]	[−0.12–0.69]	[−0.14–0.54]	[−0.11–0.43]	[−0.27–1.19]	[−0.06–0.25]
M5A	**dSOC**	1.07	0.85	-	0.48	0.32	0.25	0.68	0.13
	Range $_{MC}$	[0.33–1.86]	[0.26–1.47]		[0.15–0.83]	[0.10–0.54]	[0.08–0.45]	[0.21–1.26]	[0.04–0.27]
M5B	**dSOC**	2.29	1.81	-	1.02	0.68	0.54	1.46	0.29
	Range $_{MC}$	[1.52–3.07]	[1.21–2.46]	-	[0.60–1.47]	[0.45–0.92]	[0.34–0.75]	[0.87–2.24]	[0.13–0.47]
T1A	**dSOC**	0.53	0.48	-	0.27	−0.02	−0.02	−0.05	−0.01
	Range $_{MC}$	[−0.24–1.46]	[−0.17–1.23]	-	[−0.10–0.70]	[−0.23–0.21]	[−0.18–0.17]	[−0.51–0.45]	[−0.11–0.10]
T1B	**dSOC**	0.22	0.24	0.53	0.13	−0.06	−0.05	−0.13	−0.03
	Range $_{MC}$	[−0.63–1.06]	[−0.41–0.92]	[−1.00–2.13]	[−0.24–0.53]	[−0.28–0.15]	[−0.22–0.12]	[−0.62–0.34]	[−0.13–0.07]
T2A	**dSOC**	0	0.03	-	0.02	−0.07	−0.06	−0.16	−0.03
	Range $_{MC}$	[−0.47–0.51]	[−0.29–0.37]	-	[−0.16–0.22]	[−0.18–0.05]	[−0.14–0.04]	[−0.42–0.10]	[−0.08–0.02]
T2B	**dSOC**	-	−0.45	−1.00	-	−0.05	−0.04	−0.11	−0.02
	Range $_{MC}$	-	[−1.11–0.20]	[−2.55–0.45]	-	[−0.29–0.17]	[−0.22–0.15]	[−0.62–0.38]	[−0.12–0.08]

References

1. Romero, J.; Lee, H. Summary for Policymakers. In *Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2023; pp. 1–34.
2. Smith, P.; Martino, D.; Cai, Z.; Gwary, D.; Janzen, H.; Kumar, P.; McCarl, B.; Ogle, S.; O'Mara, F.; Rice, C.; et al. Greenhouse Gas Mitigation in Agriculture. *Philos. Trans. R. Soc. B Biol. Sci.* **2008**, *363*, 789–813. [CrossRef] [PubMed]
3. Lal, R. Carbon Sequestration. *Philos. Trans. R. Soc. B Biol. Sci.* **2008**, *363*, 815–830. [CrossRef]
4. Paustian, K.; Lehmann, J.; Ogle, S.; Reay, D.; Robertson, G.P.; Smith, P. Climate-Smart Soils. *Nature* **2016**, *532*, 49–57. [CrossRef]
5. Verchot, L.V.; Van Noordwijk, M.; Kandji, S.; Tomich, T.; Ong, C.; Albrecht, A.; Mackensen, J.; Bantilan, C.; Anupama, K.V.; Palm, C. Climate Change: Linking Adaptation and Mitigation through Agroforestry. *Mitig. Adapt. Strateg. Glob. Chang.* **2007**, *12*, 901–918. [CrossRef]
6. Lal, R. Agricultural Activities and the Global Carbon Cycle. *Nutr. Cycl. Agroecosyst.* **2004**, *70*, 103–116. [CrossRef]
7. Sanderman, J.; Hengl, T.; Fiske, G.J. Soil Carbon Debt of 12,000 Years of Human Land Use. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9575–9580. [CrossRef] [PubMed]
8. Lal, R. Soil Carbon Sequestration to Mitigate Climate Change. *Geoderma* **2004**, *123*, 1–22. [CrossRef]
9. Fuss, S.; Lamb, W.F.; Callaghan, M.W.; Hilaire, J.; Creutzig, F.; Amann, T.; Beringer, T.; De Oliveira Garcia, W.; Hartmann, J.; Khanna, T.; et al. Negative Emissions—Part 2: Costs, Potentials and Side Effects. *Environ. Res. Lett.* **2018**, *13*, 063002. [CrossRef]
10. Trost, B.; Prochnow, A.; Drastig, K.; Meyer-Aurich, A.; Ellmer, F.; Baumecker, M. Irrigation, Soil Organic Carbon and N_2O Emissions. A Review. *Agron. Sustain. Dev.* **2013**, *33*, 733–749. [CrossRef]
11. Sainju, U.M.; Jabro, J.D.; Stevens, W.B. Soil Carbon Dioxide Emission and Carbon Content as Affected by Irrigation, Tillage, Cropping System, and Nitrogen Fertilization. *J. Environ. Qual.* **2008**, *37*, 98–106. [CrossRef]
12. Morais, T.G.; Teixeira, R.F.M.; Domingos, T. Detailed Global Modelling of Soil Organic Carbon in Cropland, Grassland and Forest Soils. *PLoS ONE* **2019**, *14*, e0222604. [CrossRef]
13. Paustian, K.; Collier, S.; Baldock, J.; Burgess, R.; Creque, J.; DeLonge, M.; Dungait, J.; Ellert, B.; Frank, S.; Goddard, T.; et al. Quantifying Carbon for Agricultural Soil Management: From the Current Status toward a Global Soil Information System. *Carbon Manag.* **2019**, *10*, 567–587. [CrossRef]
14. West, T.O.; Post, W.M. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1930–1946. [CrossRef]
15. Smith, P. Carbon Sequestration in Croplands: The Potential in Europe and the Global Context. *Eur. J. Agron.* **2004**, *20*, 229–236. [CrossRef]
16. Álvaro-Fuentes, J.; López, M.V.; Arrúe, J.L.; Moret, D.; Paustian, K. Tillage and Cropping Effects on Soil Organic Carbon in Mediterranean Semiarid Agroecosystems: Testing the Century Model. *Agric. Ecosyst. Environ.* **2009**, *134*, 211–217. [CrossRef]
17. Ordóñez Fernández, R.; González Fernández, P.; Giráldez Cervera, J.V.; Perea Torres, F. Soil Properties and Crop Yields after 21 Years of Direct Drilling Trials in Southern Spain. *Soil Tillage Res.* **2007**, *94*, 47–54. [CrossRef]
18. Forte, A.; Fiorentino, N.; Fagnano, M.; Fierro, A. Mitigation Impact of Minimum Tillage on CO_2 and N_2O Emissions from a Mediterranean Maize Cropped Soil under Low-Water Input Management. *Soil Tillage Res.* **2017**, *166*, 167–178. [CrossRef]
19. Carvalho, M.; Basch, G.; Calado, J.M.G.; Barros, J.F.C. Long Term Effect of Tillage System and Crop Residue Management on Soil Carbon Content of a Luvisol under Rainfed Mediterranean Conditions. *Agrocienc. Urug.* **2012**, *16*, 183–187. [CrossRef]
20. Teixeira, R.F.M.; Proença, V.; Crespo, D.; Valada, T.; Domingos, T. A Conceptual Framework for the Analysis of Engineered Biodiverse Pastures. *Ecol. Eng.* **2015**, *77*, 85–97. [CrossRef]
21. Ravaioli, G.; Domingos, T.; Teixeira, R.F.M. Data-Driven Agent-Based Modelling of Incentives for Carbon Sequestration: The Case of Sown Biodiverse Pastures in Portugal. *J. Environ. Manag.* **2023**, *338*, 117834. [CrossRef] [PubMed]
22. Guo, L.B.; Gifford, R.M. Soil Carbon Stocks and Land Use Change: A Meta Analysis: Soil Carbon Stocks and Land Use Change. *Glob. Change Biol.* **2002**, *8*, 345–360. [CrossRef]
23. Ledo, A.; Smith, P.; Zerihun, A.; Whitaker, J.; Vicente-Vicente, J.L.; Qin, Z.; McNamara, N.P.; Zinn, Y.L.; Llorente, M.; Liebig, M.; et al. Changes in Soil Organic Carbon under Perennial Crops. *Glob. Change Biol.* **2020**, *26*, 4158–4168. [CrossRef] [PubMed]
24. Don, A.; Schumacher, J.; Freibauer, A. Impact of Tropical Land-Use Change on Soil Organic Carbon Stocks—A Meta-Analysis. *Glob. Change Biol.* **2011**, *17*, 1658–1670. [CrossRef]
25. Powlson, D.S.; Whitmore, A.P.; Goulding, K.W.T. Soil Carbon Sequestration to Mitigate Climate Change: A Critical Re-Examination to Identify the True and the False. *Eur. J. Soil Sci.* **2011**, *62*, 42–55. [CrossRef]
26. Freibauer, A.; Rounsevell, M.D.A.; Smith, P.; Verhagen, J. Carbon Sequestration in the Agricultural Soils of Europe. *Geoderma* **2004**, *122*, 1–23. [CrossRef]
27. Schrumpf, M.; Schulze, E.D.; Kaiser, K.; Schumacher, J. How Accurately Can Soil Organic Carbon Stocks and Stock Changes Be Quantified by Soil Inventories? *Biogeosciences* **2011**, *8*, 1193–1212. [CrossRef]

28. Scharlemann, J.P.; Tanner, E.V.; Hiederer, R.; Kapos, V. Global Soil Carbon: Understanding and Managing the Largest Terrestrial Carbon Pool. *Carbon Manag.* **2014**, *5*, 81–91. [CrossRef]
29. Kuhnert, M.; Vetter, S.; Smith, P. Measuring and Monitoring Soil Carbon Sequestration. In *Burleigh Dodds Series in Agricultural Science*; Rumpel, C., Ed.; Burleigh Dodds Science Publishing: Cambridge, UK, 2022; pp. 305–322. ISBN 978-1-78676-969-5.
30. FAO. *Measuring and Modelling Soil Carbon Stocks and Stock Changes in Livestock Production Systems: Guidelines for Assessment (Version 1)*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2019.
31. Baker, J.M.; Ochsner, T.E.; Venterea, R.T.; Griffis, T.J. Tillage and Soil Carbon Sequestration—What Do We Really Know? *Agric. Ecosyst. Environ.* **2007**, *118*, 1–5. [CrossRef]
32. Luo, Z.; Wang, E.; Sun, O.J. Can No-Tillage Stimulate Carbon Sequestration in Agricultural Soils? A Meta-Analysis of Paired Experiments. *Agric. Ecosyst. Environ.* **2010**, *139*, 224–231. [CrossRef]
33. Orgiazzi, A.; Ballabio, C.; Panagos, P.; Jones, A.; Fernández-Ugalde, O. LUCAS Soil, the Largest Expandable Soil Dataset for Europe: A Review. *Eur. J. Soil Sci.* **2018**, *69*, 140–153. [CrossRef]
34. Ramos, T.B.; Horta, A.; Gonçalves, M.C.; Pires, F.P.; Duffy, D.; Martins, J.C. The INFOSOLO Database as a First Step towards the Development of a Soil Information System in Portugal. *Catena* **2017**, *158*, 390–412. [CrossRef]
35. Batjes, N.H. *IPCC Default Soil Classes Derived from the Harmonized World Soil Data Base*; ISRIC—World Soil Information: Wageningen, The Netherlands, 2009.
36. IPCC. *IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2019; Volume 4.
37. Mazzoncini, M.; Antichi, D.; Di Bene, C.; Risaliti, R.; Petri, M.; Bonari, E. Soil Carbon and Nitrogen Changes after 28 Years of No-Tillage Management under Mediterranean Conditions. *Eur. J. Agron.* **2016**, *77*, 156–165. [CrossRef]
38. Álvaro-Fuentes, J.; Plaza-Bonilla, D.; Arrúe, J.L.; Lampurlanés, J.; Cantero-Martínez, C. Soil Organic Carbon Storage in a No-Tillage Chronosequence under Mediterranean Conditions. *Plant Soil* **2014**, *376*, 31–41. [CrossRef]
39. Chen, S.; Shuai, Q.; Arrouays, D.; Chen, Z.; Dai, L.; Hong, Y.; Hu, B.; Huang, Y.; Ji, W.; Li, S.; et al. GSOCS-LULCC: The Global Soil Organic Carbon Stock Dataset after Land Use and Land Cover Change. *Earth Syst. Sci. Data Discuss.* **2024**, preprint. [CrossRef]
40. Novara, A.; Gristina, L.; Sala, G.; Galati, A.; Crescimanno, M.; Cerdà, A.; Badalamenti, E.; La Mantia, T. Agricultural Land Abandonment in Mediterranean Environment Provides Ecosystem Services via Soil Carbon Sequestration. *Sci. Total Environ.* **2017**, *576*, 420–429. [CrossRef] [PubMed]
41. Alvaro-Fuentes, J.; Cantero-Martinez, C. Short communication. Potential to mitigate anthropogenic CO_2 emissions by tillage reduction in dryland soils of Spain. *Span. J. Agric. Res.* **2010**, *8*, 1271–1276. [CrossRef]
42. Franzluebbers, A.J. Achieving Soil Organic Carbon Sequestration with Conservation Agricultural Systems in the Southeastern United States. *Soil Sci. Soc. Am. J.* **2010**, *74*, 347–357. [CrossRef]
43. Emde, D.; Hannam, K.D.; Most, I.; Nelson, L.M.; Jones, M.D. Soil Organic Carbon in Irrigated Agricultural Systems: A Meta-Analysis. *Glob. Change Biol.* **2021**, *27*, 3898–3910. [CrossRef] [PubMed]
44. Teixeira, R.F.M.; Domingos, T.; Costa, A.P.S.V.; Oliveira, R.; Farropas, L.; Calouro, F.; Barradas, A.M.; Carneiro, J.P.B.G. Soil Organic Matter Dynamics in Portuguese Natural and Sown Rainfed Grasslands. *Ecol. Model.* **2011**, *222*, 993–1001. [CrossRef]
45. Siddique, I.A.; Grados, D.; Chen, J.; Lærke, P.E.; Jørgensen, U. Soil Organic Carbon Stock Change Following Perennialization: A Meta-Analysis. *Agron. Sustain. Dev.* **2023**, *43*, 58. [CrossRef]
46. Baiamonte, G.; Gristina, L.; Orlando, S.; Palermo, S.S.; Minacapilli, M. No-Till Soil Organic Carbon Sequestration Patterns as Affected by Climate and Soil Erosion in the Arable Land of Mediterranean Europe. *Remote Sens.* **2022**, *14*, 4064. [CrossRef]
47. Farina, R.; Marchetti, A.; Francaviglia, R.; Napoli, R.; Bene, C.D. Modeling Regional Soil C Stocks and CO_2 Emissions under Mediterranean Cropping Systems and Soil Types. *Agric. Ecosyst. Environ.* **2017**, *238*, 128–141. [CrossRef]
48. Stamati, F.E.; Nikolaidis, N.P.; Schnoor, J.L. Modeling Topsoil Carbon Sequestration in Two Contrasting Crop Production to Set-aside Conversions with RothC—Calibration Issues and Uncertainty Analysis. *Agric. Ecosyst. Environ.* **2013**, *165*, 190–200. [CrossRef]
49. Giannini, V.; Raimondi, G.; Toffanin, A.; Maucieri, C.; Borin, M. Agronomic Management Strategies to Increase Soil Organic Carbon in the Short-Term: Evidence from on-Farm Experimentation in the Veneto Region. *Plant Soil* **2023**, *491*, 561–574. [CrossRef]
50. da Gama, J.T.; Rato Nunes, J.; Loures, L.; Lopez Piñeiro, A.; Vivas, P. Assessing Spatial and Temporal Variability for Some Edaphic Characteristics of Mediterranean Rainfed and Irrigated Soils. *Agronomy* **2019**, *9*, 132. [CrossRef]
51. Zornoza, R.; Rosales, R.M.; Acosta, J.A.; De La Rosa, J.M.; Arcenegui, V.; Faz, Á.; Pérez-Pastor, A. Efficient Irrigation Management Can Contribute to Reduce Soil CO_2 Emissions in Agriculture. *Geoderma* **2016**, *263*, 70–77. [CrossRef]
52. Bell, S.M.; Terrer, C.; Barriocanal, C.; Jackson, R.B.; Rosell-Melé, A. Soil Organic Carbon Accumulation Rates on Mediterranean Abandoned Agricultural Lands. *Sci. Total Environ.* **2021**, *759*, 143535. [CrossRef] [PubMed]
53. Nadal-Romero, E.; Rubio, P.; Kremyda, V.; Absalah, S.; Cammeraat, E.; Jansen, B.; Lasanta, T. Effects of Agricultural Land Abandonment on Soil Organic Carbon Stocks and Composition of Soil Organic Matter in the Central Spanish Pyrenees. *Catena* **2021**, *205*, 105441. [CrossRef]

54. Rühl, J.; Gristina, L.; La Mantia, T.; Novara, A.; Pasta, S. Afforestation and Reforestation: The Sicilian Case Study. In *The Greenhouse Gas Balance of Italy*; Environmental Science and Engineering; Valentini, R., Miglietta, F., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 173–184. ISBN 978-3-642-32423-9.
55. Deng, L.; Zhu, G.; Tang, Z.; Shangguan, Z. Global Patterns of the Effects of Land-Use Changes on Soil Carbon Stocks. *Glob. Ecol. Conserv.* **2016**, *5*, 127–138. [CrossRef]
56. Vesterdal, L.; Ritter, E.; Gundersen, P. Change in Soil Organic Carbon Following Afforestation of Former Arable Land. *For. Ecol. Manag.* **2002**, *169*, 137–147. [CrossRef]
57. De Baets, S.; Meersmans, J.; Vanacker, V.; Quine, T.A.; Van Oost, K. Spatial Variability and Change in Soil Organic Carbon Stocks in Response to Recovery Following Land Abandonment and Erosion in Mountainous Drylands. *Soil Use Manag.* **2013**, *29*, 65–76. [CrossRef]
58. Abdelbaki, A.M. Evaluation of Pedotransfer Functions for Predicting Soil Bulk Density for U.S. Soils. *Ain Shams Eng. J.* **2018**, *9*, 1611–1619. [CrossRef]
59. Peter, C.; Fiore, A.; Hagemann, U.; Nendel, C.; Xiloyannis, C. Improving the Accounting of Field Emissions in the Carbon Footprint of Agricultural Products: A Comparison of Default IPCC Methods with Readily Available Medium-Effort Modeling Approaches. *Int. J. Life Cycle Assess.* **2016**, *21*, 791–805. [CrossRef]
60. Bellassen, V.; Cienciala, E.; Lehtonen, A.; Korosuo, A.; Blujdea, V.; Rossi, S.; Grassi, G. *Moving to Higher Tiers for Soil Carbon*; Publications Office of the European Union: Luxembourg, 2023.
61. Pereira, T.C.; Amaro, A.; Borges, M.; Silva, R.; Seabra, T.; Canaveira, P. *Portuguese National Inventory Report on Greenhouse Gases, 1990–2021*; Portuguese Environmental Agency: Amadora, Portugal, 2023; p. 7.