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No-Till Soil Organic Carbon Sequestration Patterns as Affected by Climate and Soil Erosion in the Arable Land of Mediterranean Europe

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Abstract: No-tillage (NT) has been considered an agronomic tool to sequester soil organic carbon (SOC) and match the *4p1000* initiative requirements of conservative soil management. Recently, some doubts have emerged about the NT effect on SOC sequestration, often because observations and experimental data vary widely depending on climate and geographic characteristics. Therefore, a suitable SOC accounting method is needed that considers climate and morphology interactions. In this study, the yearly ratio between SOC in NT and conventional tillage (CT) ($RR_{NT/CT}$) collected in a previous study for flat (96 samples) and sloping (44 samples) paired sites was used to map the *overestimation* of SOC sequestration. It was assumed that there would be an *overestimation* of NT capacity in sloping fields due to lower erosion processes with respect to CT. Towards this aim, Geographical Information System (GIS) techniques and an extensive input database of high spatial resolution maps were used in a simplified procedure to assess the *overestimation* of SOC stocks due to the sloping conditions and spatial variability of the Aridity Index (AI). Moreover, this also made it possible to quantify the effects of adopting NT practices on soil carbon sequestration compared to CT practices. The method was applied to the arable lands of five Mediterranean countries (France, Greece, Italy, Portugal and Spain) ranging between the 35° and 46° latitude. The results showed an *overestimation* of SOC sequestration, when the AI and soil erosion were considered. The average *overestimation* rate in the studied Mediterranean areas was 0.11 Mg ha^{-1} yr^{-1}. Carbon stock *overestimation* ranged from 34 to 1417 Gg for Portugal and Italy, respectively. Even if *overestimation* is considered, *4p1000* goals are often reached, especially in the more arid areas. The findings of this research allowed us to map the areas suitable to meet the *4p1000* that could be achieved by adopting conservative practices such as NT.

Keywords: soil carbon accounting; Mediterranean environment; soil erosion; arable land; *4p1000* initiative

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1. Introduction

At the 21st Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC), The Paris Agreement and the *4p1000* initiative (http://4p1000.org (accessed on 13 July 2022)) were proposed with the aim of increasing soil organic carbon (SOC) stocks through the adoption of agricultural best management practices (BMP). When adopting these BMP targets, an annual increase in the *4p1000* of SOC at the 0–40 cm soil depth must be achieved to contribute to climate change mitigation [1,2]. However, there has been some criticism and debate regarding the *4p1000* initiative. Some scholars have defined this initiative as idealistic [3,4], whereas other research has suggested that the goal is achievable under sustainable soil management techniques [5,6].

Importantly, no-tillage (NT) and, more generally, conservative soil management has been considered the most operative agronomic tool to sequester SOC and match the *4p1000* initiative requirements. In fact, during the past few years, a fair amount of experimental evidence has shown the potentiality of NT soil management to promote SOC sequestration. Results from extensive literature show that SOC sequestration under NT conditions widely varies with management practices and site characteristics [5,7]. West and Post [8] estimated a SOC sequestration potential of 0.57 Mg C ha^{-1} yr^{-1} for NT systems worldwide, and several studies on United States agriculture reported SOC sequestration values ranging from 0.40 to 0.45 Mg C ha^{-1} yr^{-1} and from −0.07 to 0.30 Mg C ha^{-1} yr^{-1} in the southern and the northern areas, respectively [9–11]. In European Mediterranean countries, it has been estimated that NT can increase SOC stock by 0.85 and 0.77 Mg ha^{-1} yr^{-1} in Spain and Italy, respectively [12], but lower values were estimated by Alvaro-Fuentes and Cantero-Martinez [13] that indicated a SOC increase of 0.23 Mg ha^{-1} yr^{-1} and by Aguilera et al. [14] of about 0.44 Mg ha^{-1} yr^{-1}. In southern Italy, in a long-term trial spanning two decades, an average 0.13 Mg ha^{-1} yr^{-1} SOC sequestration was observed [15]. In contrast, Luo et al. [16] showed that the conversion from conventional tillage to NT significantly increased topsoil SOC (3.15 Mg C ha^{-1} at 0–10 cm) but did not enrich the total SOC stock in the whole soil profile.

The findings of surveys carried out by Poeplau and Don [17] showed a wide variability of SOC sequestration by NT from 4.94 Mg C ha^{-1} yr^{-1} to −11.0 Mg C ha^{-1} yr^{-1}. The contribution of NT to SOC sequestration is determined by climate and, generally, a high NT ability in dry areas [18–20] is found due to the high relative carbon input production by NT [21]. Some doubts are emerging and, recently, various meta-analyses have shown that it is necessary to establish the role of NT in SOC sequestration, while also considering the climate and soil type that determine wide variability and site-specific responses [22–26]. These doubts are often justified by methodological constraints that lead to incorrect assessments of the carbon sequestration capacity attributable to NT land management, creating false expectations of NT as a mitigation tool [11,27]. These constraints are caused by a lack of bulk density measurements as well as by considering different soil layers. The commonly used "paired sites comparison" approach may relax those constrains, providing more suitable SOC accounting, especially when the relative ratio ($RR_{NT/CT}$) between SOC in NT and SOC in CT is calculated [28,29].

The paired sites approach in the sloping areas affected by soil erosion certainly influences the SOC $RR_{NT/CT}$ because NT-managed land has a different soil carbon erosion control ability with respect to CT-managed land. Indeed, NT practices have a significant effect on soil erosion control due to the residues retained on the soil surface [30,31], limiting SOC redistribution and losses [32].

Little has been attempted to address this aspect as a cause of an *overestimation* of SOC sequestration, mainly when paired sites comparisons are carried out without baseline data [11,33]. Yang et al. [34] showed that the positive effect of CT on SOC was only reliable in severely eroded soils or steeply sloping farmland, and it was not evident in flat areas.

Recently, in a specific extensive paired sites long-term survey, Novara et al. [7] demonstrated the important influence of slope [35] and the AI [19] on the SOC $RR_{NT/CT}$ evaluation in durum wheat within the Mediterranean climatic belt. Specifically, the average yearly SOC $RR_{NT/CT}$ was 0.008 in 140 paired sites, ranging between 0.0061 and 0.012 for flat and sloping conditions, respectively. It was hypothesized that a paired sites comparison would result in an *overestimation* of NT capacity in sloping areas due to losses by erosion processes. Because of the influence of climate on the SOC $RR_{NT/CT}$, a large-scale spatial analysis of the AI could be useful in detecting the feasibility of the national *4p1000* initiatives.

Freely available remote sensing data from satellite sensors with large spatial coverage have become available in the last decades, and they can be used to determine advantages over the large-scale mapping with flexibility, efficiency, and low operating cost. A recent Remote Sensing Special Issue "CORINE Land Cover System: Limits and Challenges for Territorial Studies and Planning" interestingly focused on the limitations and possible solutions related to the use of CORINE data. Thanks to these tools, we addressed the objectives of this work that can be summarized as follows:

1. Detecting the feasibility of achieving *4p1000* targets in European Mediterranean arable land, considering the effects of climate and slope on the spatial SOC $RR_{NT/CT}$ computation;
2. Calculating and mapping the *overestimation* of SOC sequestration due to soil erosion processes;
3. Investigating NT practices' actual ability to match the *4p1000* goal.

2. Materials and Methods

The analysis was performed for Mediterranean arable lands, including five countries (France, Greece, Italy, Portugal and Spain), all overlooking the Mediterranean Sea, located at latitudes between 35–46° and characterized by a very different morphology and climate, and where durum wheat is mostly cultivated.

In flat areas (FA) with no erosion risk, the SOC relative ratio ($RR_{NT/CT}$) only depends on the carbon input (C) and on the soil's ability to stabilize biomass inputs. Therefore, the SOC relative ratio ($RR_{NT/CT}$) is a valuable indicator of the *effective SOC* sequestration under NT with respect to CT. $RR_{NT/CT}$ values higher than zero indicate that NT has sequestered more C through biomass inputs than CT or that over time NT has decreased the mineralization rate of the organic matter, reducing SOC stock losses in comparison to CT.

In sloping areas (SA), SOC sequestration explained by the $RR_{NT/CT}$ values must be considered an *apparent* sequestration because NT SOC sequestration is overestimated due to the higher C erosion with CT than with NT. Conceptually, in areas characterized by similar climate conditions, C sequestration/depletion can be considered almost equal in FA and SA; consequently, the differences between *apparent* and *effective* C sequestration/depletion can be attributed to C erosion reduction in NT, according to the following relationship:

$$\textit{apparent SOC sequestration} = \textit{effective SOC sequestration} + \textit{SOC losses by erosion} \quad (1)$$

where the *apparent* SOC sequestration is the $RR_{NT/CT}$ in SA, the *effective* SOC sequestration/depletion is the $RR_{NT/CT}$ in FA and C losses by erosion is the specific contribution of the erosion processes on $RR_{NT/CT}$ dependent on the differences in SOC erosion control ability by NT and CT (estimated at 1:4 by Panagos et al. [36]). Of course, in FA where no erosion processes occur, *apparent* SOC sequestration is equal to *effective* SOC sequestration.

Using 140 paired sites, located at latitudes between 35° and 45°, almost matching the latitude range investigated in the present work, Novara et al. [7] studied the relationship between the $RR_{NT/CT}$ and Aridity Index (AI) independently for sloping areas (SA) and flat areas (FA), showing different behaviour according to topographic conditions. In particular, Novara et al. [7] derived the following linear regressions:

$$RR_{\ NT/CT} = -0.0144\ AI + 0.0173 \quad \text{for FA} \quad (2)$$

$$RR_{\ NT/CT} = -0.0014\ AI + 0.0130 \quad \text{for SA} \quad (3)$$

where $RR_{NT/CT}$ indicates the yearly relative ratio between SOC in NT and CT, whereas the AI [37] is a climatic variable able to explain the relative ratio ($RR_{\ NT/CT}$) of crop productivity and SOC sequestration under NT management [7,21,38].

Equations (2) and (3) were derived at a local scale through data from 140 paired sites. In this paper, before upscaling them to the investigated area for the two equations, an ANOVA was carried out. The analysis was performed for FA (Table 1) to determine whether the explanatory variable (AI) contributes significant information (null hypothesis H0) to Equation (2) and to know whether Equation (2) is valid to provide the mean to describe the whole population, or if the information brought by the AI is of value or not.

Table 1. Regression analysis of variance for the 96 FA data ($RR_{NT/CT}$).

Source	DF	Sum of Squares	Mean Squares	F	Pr > F
Model	1	0.002 [1]	0.002	11.815	0.001
Error	95	0.012	0.000		
Corrected total	96	0.014			

[1] Computed against the model Y = Mean (Y).

Given the fact that the probability corresponding to the F value is lower than 0.001, we would be taking a lower than 0.1% risk in assuming that the null hypothesis (no effect of the AI) is wrong. Therefore, we can conclude with confidence that the AI does contribute a significant amount of information in explaining the $RR_{NT/CT}$. Statistical parameters (Table 2), show that the 95% confidence range of the AI parameter and the one for the intercept are very narrow.

Table 2. Model parameters for the 96 FA data ($RR_{NT/CT}$).

Source	Value	Standard Error	t	Pr > ∣t∣	Lower Bound (95%)	Upper Bound (95%)
Intercept	0.0173	0.003	5.022	<0.0001	0.010	0.024
AI	−0.0144	0.004	−3.437	0.001	−0.023	−0.006

For FA, Figure 1 shows the data together with the regression line, the prediction band (black lines) and the confidence interval (dotted lines) on its mean for a given AI value. Figure 1 clearly shows that there is a linear trend, although variability around the line occurs, and that the 3 observations that are outside the [−1.96, 1.96] interval (the value of the 97.5 percentile point of the standard normal distribution) are outside the second confidence interval as well. An analysis of variance was not performed for the sloping areas, since the regression line is almost horizontal (very low angular coefficient −0.0014, F = 0.033).

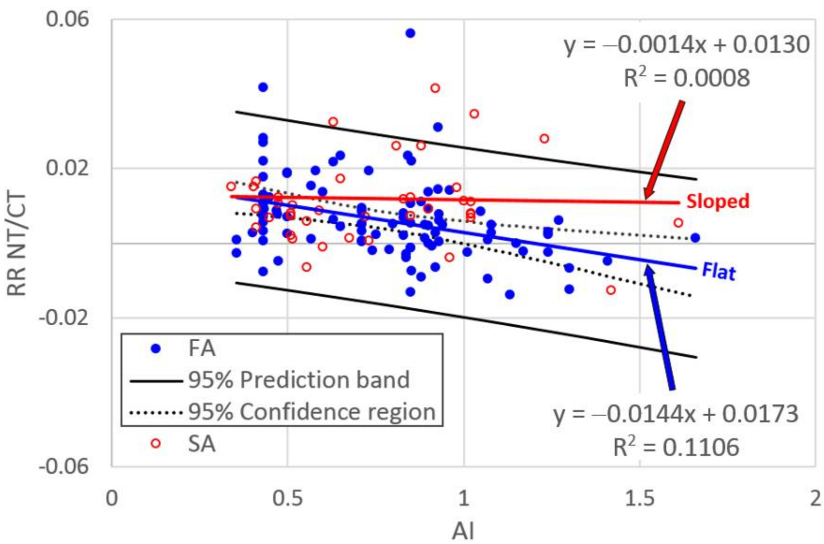

Figure 1. Regression lines for FA and SA and corresponding data. For FA, the prediction band and confidence region are also reported (modified with permission from ref. [7], Copyright 2021, Elsevier (Amsterdam, The Netherlands).

Considering that the SA regression line lies outside of the of the FA confidence region, we can conclude that the two datasets (FA and SA) belong to different populations and can be separately analysed, and the differences between the two regression lines can be attributed to the soil erosion processes.

The methodological framework is summarized in the flowchart of Figure 2 where input and output data flow are reported. For the *apparent* $RR_{NT/CT}$ determination, a spatial query according to an erosion threshold (discussed later) made it possible to identify FA and SA areas where Equation (2) or Equation (3) were applied, respectively. The *apparent* and the *effective* SOC sequestration (Mg ha^{-1}) were calculated by multiplying the RRs maps for the SOC map obtained by Lugato et al. [39] and compared to *4p1000* SOC (Mg ha^{-1}).

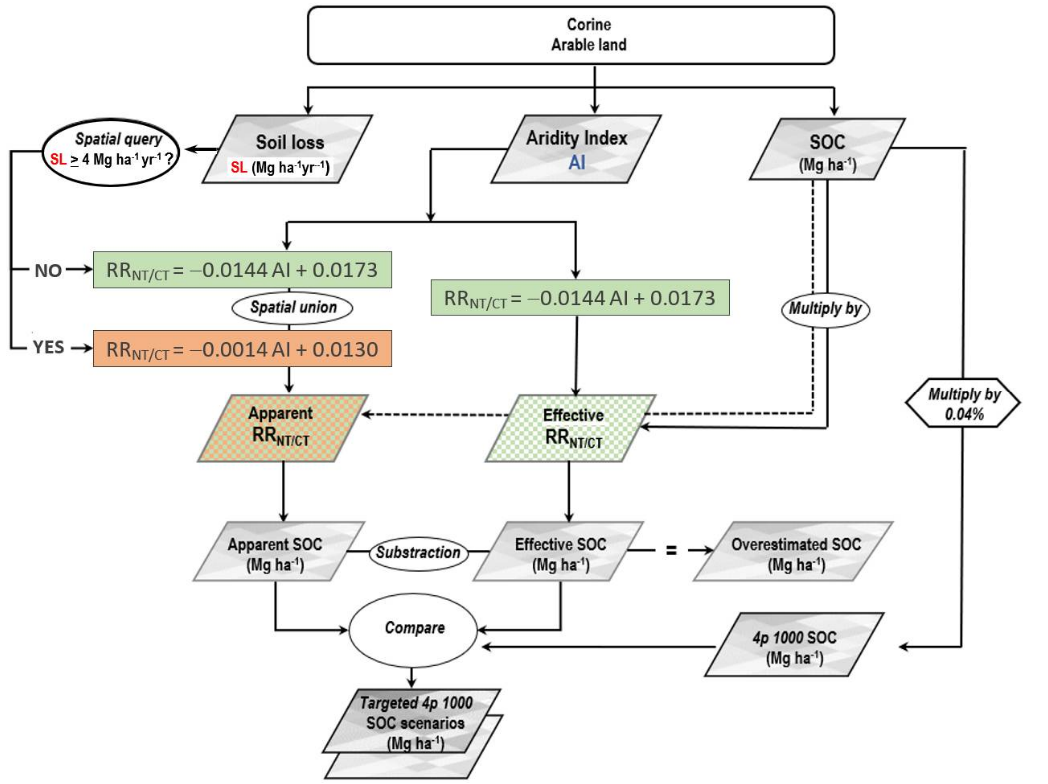

Figure 2. Flowchart of the proposed procedure. Linear regressions refer to the relationship between $RR_{NT/CT}$ and Aridity Index, AI, and for slope and flat areas [7].

The input data used in this paper were obtained from different geographical databases developed to support the scientific community and to focus on the arable lands of Mediterranean countries (France, Greece, Italy, Portugal and Spain), which are where annual cereals can potentially be cultivated.

The Copernicus Global Land Service (CGLS) CORINE land use map of the European Community was used to obtain the spatial distribution of arable land in the study area [40]. The CGLS inventory was initiated in 1990 and updates have been produced in 2000, 2006, 2012 and 2018. It consists of an inventory of land cover in 44 classes. CLC uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena. The CLC is produced by the visual interpretation of high-resolution satellite imagery combined with semi-automatic satellite image processing as well as GIS integration. In our study we used the 2018 version of CGLS that was the first version based on Sentinel-2 and Landsat-8 satellite image products with an MMU of 100 m. In particular, the 211 class CORINE legend was chosen to identify arable land with a resolution of 100 m × 100 m. The climate database for Europe (ClimateEU) was used to map two key meteorological variables [41]: yearly rainfall, R_a, yearly reference evapotranspiration and ET_0 [37]. Both were retrieved using a 1 km × 1 km spatial resolution. The European Soil Database (ESDAC) has been used as a source of high spatial resolution (100 m × 100 m) of soil erosion rates and SOC stocks of agricultural soils. In particular, the European Soil erosion map produced by Panagos et al. [36] was used to identify erosive and non-erosive areas, whereas the European SOC stock map of agricultural soils developed by Lugato et al. [39] was used to estimate the *4p1000* target and *effective* and *apparent* SOC sequestration as well as possible *overestimations* [30,31]. A threshold value of 1.4 Mg ha^{-1} yr^{-1} was chosen to discriminate the erosive areas (values higher than 1.4 Mg ha^{-1} yr^{-1}) as sloping areas and flat areas (values lower than 1.4 Mg ha^{-1} yr^{-1}). The threshold value of 1.4 Mg ha^{-1} yr^{-1} was determined in relation to tolerable soil erosion, as suggested by Verheijen et al. [42].

Considering that the SOC stock values obtained by Lugato et al. [39] refer to the 0–30 cm depth, whereas the *4p1000* strategy refers to a 0–40 cm depth, in this study the SOC stock data obtained by Lugato et al. [39] were adjusted according to Poulton et al.'s [3] suggestion for most of the topsoil data to give an increase of 5%. The input data was managed using standard Geographical Information System (GIS) techniques. Specifically, the data were stored in a raster format (geotiff) and were projected in a unique geographical system (ETRS89 Lambert Azimuthal Equal Area). In this way, raster map-algebra techniques were used to overlap all raster data and to calculate outputs following the flowchart of Figure 2.

3. Results

3.1. Climate and Soil Erosion

In the studied area, the climate described in terms of the Aridity Index (AI) shows an average value of 0.57 (from 0.2 to 1.2), with significant differences among the studied countries, ranging from 0.43 to 0.82 for Greece and France, respectively. Considerable uniformity was found for Spain, Portugal, France and Greece; in contrast, Italy showed significant AI differences from the north to the south and the largest standard deviation (Table 3, Figure 3).

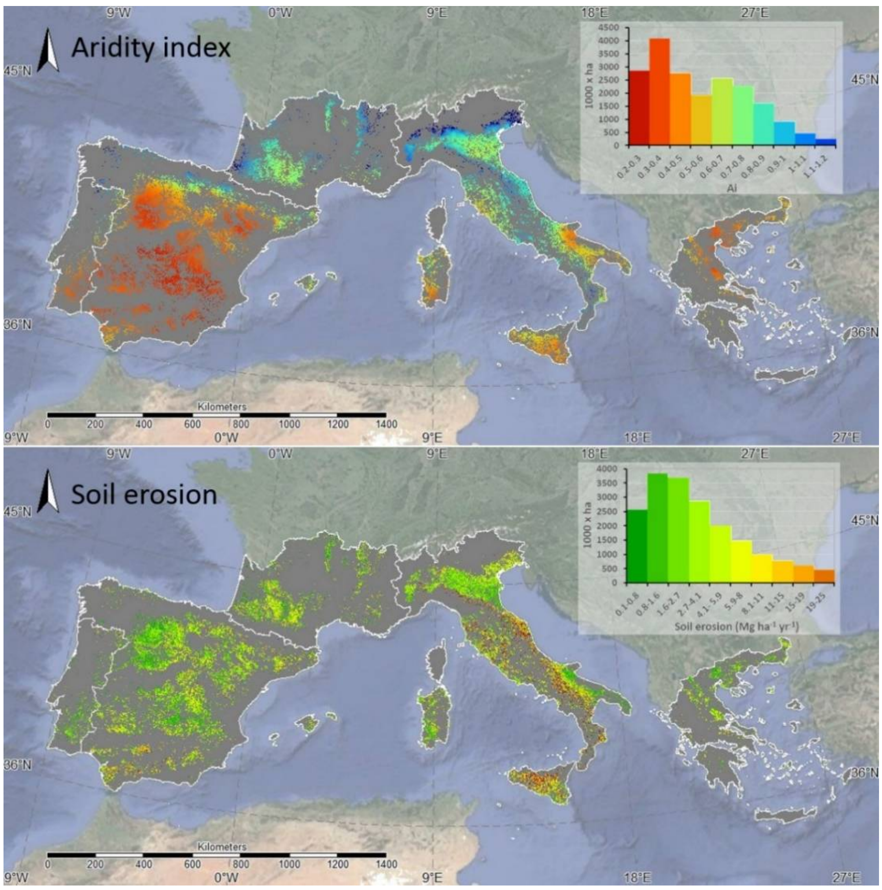

Figure 3. Distribution of Aridity Index within the study area (https://sites.ualberta.ca/~ahamann/data/climateeu.html, accessed on 1 September 2020) and soil erosion (Mg ha^{-1} yr^{-1}) (Panagos et al. [36], (https://doi.org/10.1016/j.landusepol.2011.07.003, accessed on 1 September 2020).

Table 3. Analysis of variance ($RR_{NT/CT}$).

Country	Aridity Index (AI)	St. Dev.	Soil Erosion (Mg ha^{-1} yr^{-1})	St. Dev.
France [1]	0.82	0.17	3.66	4.16
Greece	0.43	0.10	3.06	3.42
Italy	0.72	0.22	7.18	8.17
Portugal	0.46	0.20	2.20	2.79
Spain	0.39	0.16	3.60	4.24
Average	0.57		3.90	

[1] Only the Mediterranean area is considered (see Figure 2).

The average value of soil erosion in the study area was 3.9 Mg ha^{-1} yr^{-1} (from 0.1 to 19.1 Mg ha^{-1} yr^{-1}) and ranged from 2.20 Mg ha^{-1} yr^{-1} in Portugal to 7.18 Mg ha^{-1} yr^{-1} in Italy, where the highest variability was observed (Table 3, Figure 3).

3.2. Soil Organic Carbon in Arable Land and the 4p1000 Target

In European Mediterranean countries, the potential areas for NT management cover a total of 21,917 (ha × 1000) (Table 4).

Table 4. Soil organic carbon stocks in the arable lands of five Mediterranean countries.

Country	SOC Stored			*4p1000* Target		
	(Gg)	(Mg ha^{-1})	St. Dev.	SOC to be Stored (Gg yr^{-1})	Sequestration Rate (Mg ha^{-1} yr^{-1})	Potential NT Area (1000 ha)
France [1]	161,122	59.9	22.1	806	0.30	2692
Greece	53,905	47.3	15.2	270	0.24	1141
Italy	337,154	43.8	13.3	1686	0.22	7702
Portugal	25,307	38.2	19.1	127	0.19	663
Spain	532,633	54.8	21.7	2663	0.27	9719
	1,110,120	**48.8**		*5552*	**0.24**	**21,917**

[1] Only the Mediterranean area is considered (see Figure 2); the average in bold; the sum in italics.

The SOC map analysis indicates that the soil of the arable land in the Mediterranean areas considered in this study store close to 1,110,120 Gg of C in the upper 40 cm (Figure 4), ranging between 20 and 100 Mg ha^{-1}. The highest SOC values were recorded in France, followed by Spain, Greece, Italy and Portugal, with an average ranging from 59.9 Mg ha^{-1} to 38.2 Mg ha^{-1}. Due to the large arable land area, Spain stores about 532,633 Gg of SOC. Only 25,307 Gg of SOC is stored in Portugal (Table 4).

Based on this estimation of total SOC stocks, 5552 Gg of SOC (0.24 Mg ha^{-1}) per year should be sequestered in the arable land soils of the studied areas to achieve the *4p1000* goal (Table 4). In relation to the NT potential area, 2662 Gg are needed for Spain and only 127 Gg for Portugal. The SOC sequestration rate to achieve the *4p1000* goal is higher for France and Spain (0.30 and 0.27 Mg ha^{-1} yr^{-1}) and lower for Italy and Portugal (0.22 and 0.19 Mg ha^{-1} yr^{-1}, respectively).

Figure 4 shows that the SOC sequestration needed to achieve *4p1000* lies in a range from 0.05 to 0.65 Mg ha^{-1} yr^{-1}, and that it is strongly influenced by SOC stocks and is also correlated with the AI trend from the north to the south.

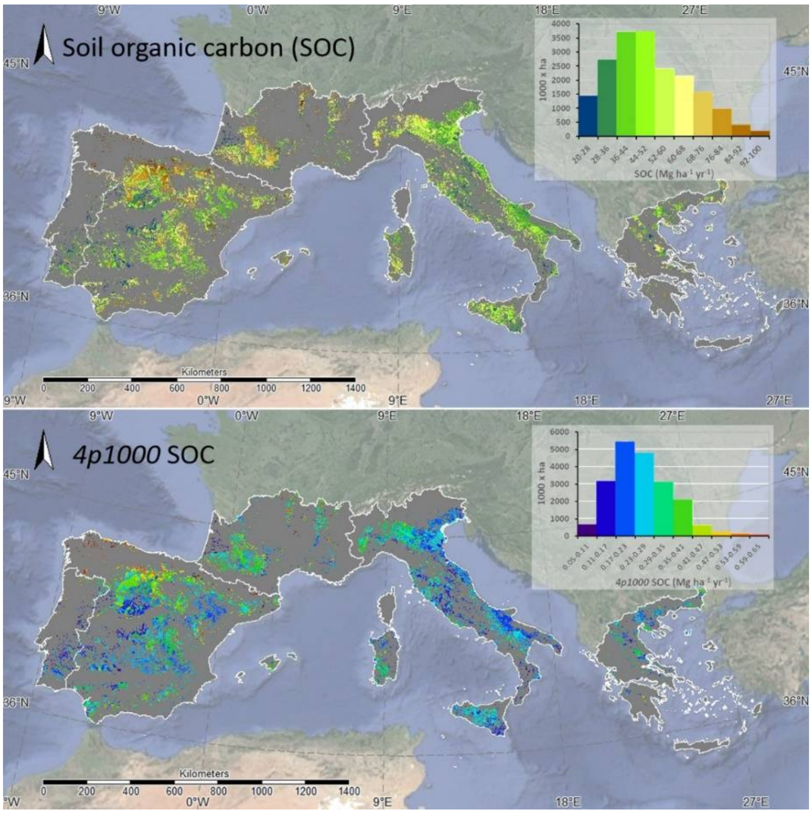

Figure 4. Distribution of SOC (Mg ha^{-1}) needed to achieve the *4p1000* target (Mg ha^{-1}).

3.3. Apparent, Effective SOC Sequestration and Overestimation, in the Mediterranean Arable Land

According to the flowchart reported in Figure 2, to estimate the *apparent* and *effective* SOC sequestration, Equations (2) and (3) were applied in a spatially distributed way over flat areas (no erosion processes) and sloping areas (erosion processes), respectively. As reported in Table 5, 12,585 Gg resulted in the *apparent* potential SOC sequestration through NT practices, with a total of 4443 Gg representing the SOC *overestimation* (Table 5). The different Mediterranean areas showed a variable *overestimation*, because of the interaction between the slope and AI effects but also due to the original SOC stock, ranging from 34 to 1417 Gg for Portugal and Italy, respectively.

Table 5. Apparent and effective soil organic carbon sequestration and *overestimation* in the arable land of five countries. A/E is the ratio between apparent and effective SOC sequestration.

Country	SOC Stored			*4p1000* Target			
	Apparent	Effective	Over Estimation	Apparent	Effective	Over Estimation	A/E
France [1]	1545	895	1009	0.57	0.33	0.24	1.73
Greece	645	592	94	0.57	0.52	0.05	1.09
Italy	3708	2292	1787	0.48	0.30	0.18	1.62
Portugal	288	254	90	0.43	0.38	0.05	1.13
Spain	6399	5950	1463	0.66	0.61	0.05	1.08
	12,585	*9983*	4443	**0.54**	**0.43**	**0.11**	**1.33**

[1] Only the Mediterranean area is considered (see Figure 2); the average in bold; the sum in italics.

The average *overestimation* rate was 0.11 Mg ha^{-1} yr^{-1}, with a large variability among the studied Mediterranean areas (Table 5). The distributions of the *apparent* and *effective* SOC sequestration rates (Figure 5) showed the effect of the interactions between the AI and slope in determining the SOC sequestration *overestimation*. The lowest values of SOC *overestimation* arose in the most arid areas, such as Sicily, despite evident soil erosion processes, and in central Spain and Greece. The ratio between the *apparent* and *effective* SOC sequestration (A/E) was 1.33 on average but was strongly variable among the Mediterranean areas, only 1.08 and 1.09 for Spain and Greece, and up to 1.62 and 1.73 for Italy and France, respectively (Table 5).

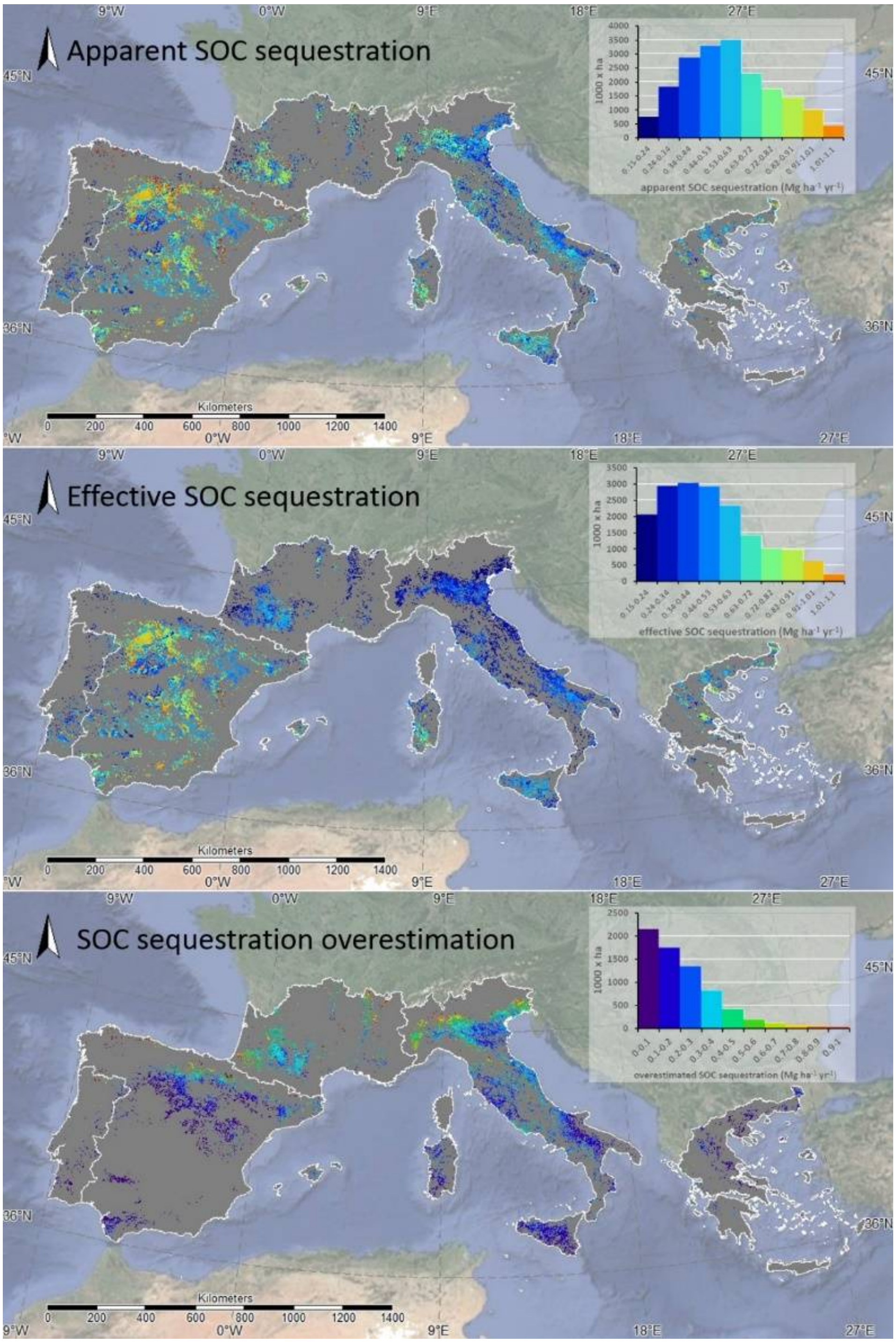

Figure 5. Distribution of apparent, effective and *overestimation* of SOC sequestration (Mg ha^{-1} yr^{-1}).

3.4. Matching the 4p1000 Goal

The percentage of arable land area (%) in which NT management introduction can meet *4p1000* goals is shown in Figure 6 separately for the *apparent* (Figure 6a) and *effective*

SOC sequestration rates (Figure 6b). The percentage of the arable land area and the relative NT SOC sequestration capacity make it possible to identify the percentage of arable lands suitable to match the *4p1000* initiative through NT introduction.

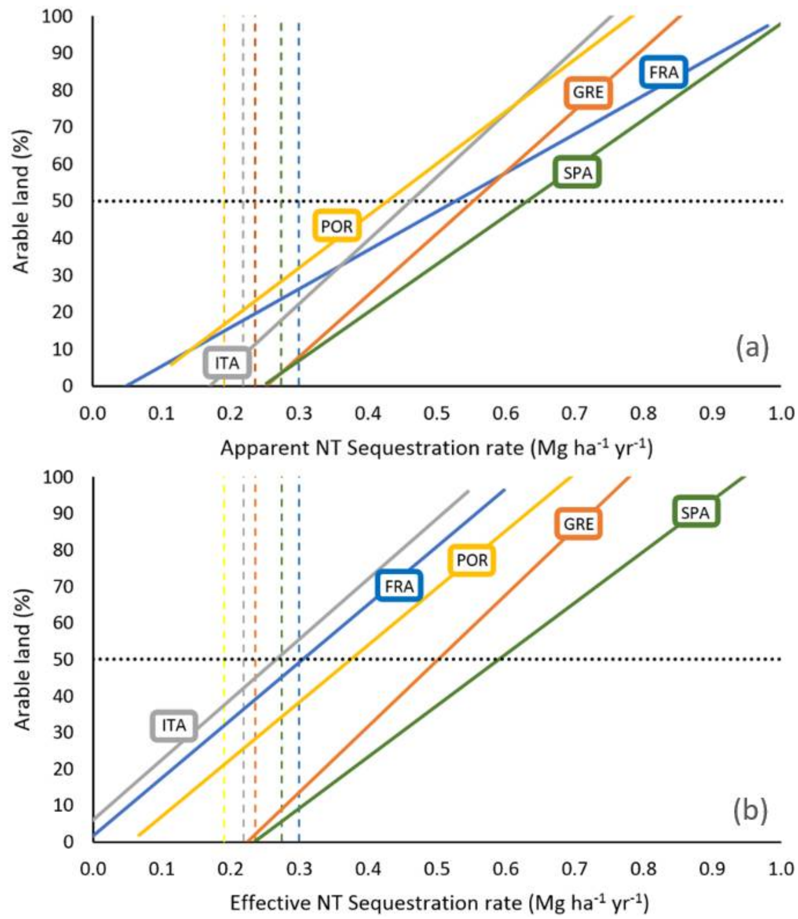

Figure 6. The cumulative frequency distribution of apparent (**a**) and effective (**b**) SOC sequestration rate under NT management in relation to arable land percentage area. For each country, vertical lines represent the average SOC sequestration rates to match the *4p1000* target. The horizontal line is the average SOC sequestration rate.

In each country, the SOC sequestration rate varied widely from *apparent* to *effective*. When *apparent* SOC sequestration is considered, the average values ranged from 0.45 to 0.65 in Portugal and Spain, respectively. Considering the *effective* SOC sequestration, a larger interval was found (0.25 and 0.55 in Italy and Spain, respectively) (Figure 6).

Changes in SOC sequestration from *apparent* to *effective* are related to the areas considered and mainly depend on the AI variability and arable land morphology. In Spain and Greece, where the lowest AI values are present, areas not able to reach the *4p1000* threshold are very low for both *apparent* and *effective* SOC sequestration (Figure 6). For the other countries, the percentage of arable land not suitable to match the *4p1000* ranged between 9% and 27% when the *apparent* SOC sequestration rate is considered and from 22% to 50% when the *effective* SOC sequestration is considered.

For both *apparent* and *effective* SOC sequestration, the distribution of the potential *4p1000* matching areas was elaborated as the difference between the SOC sequestration rate and the *4p1000* SOC map. No differences were found between the *apparent* and *effective* SOC sequestration rate in Spain and Greece (Figure 7a,b). More consistent differences were found for all of the other countries, mainly in the more arid parts of Italy (islands and southern Italy).

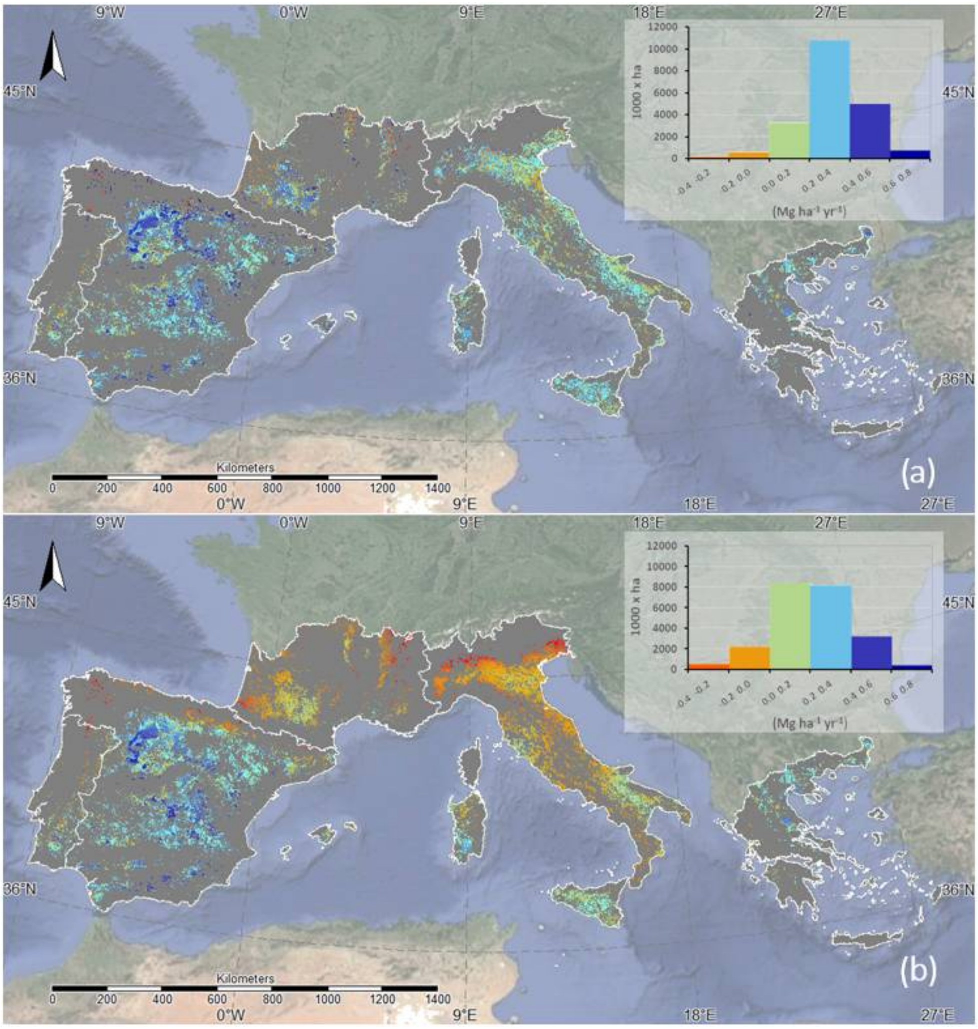

Figure 7. Distribution of apparent (**a**) and effective (**b**) differences between SOC sequestration rate and *4p1000* SOC target.

4. Discussion

The objective of this study was to suggest a reliable estimate of SOC sequestration attributable to the application of NT management practices in relation to (i) the high variability of climate in European Mediterranean regions and (ii) the evident effect of soil erosion on SOC losses.

Using spatialized input data (raster maps) and two simplified relationships derived from an extensive survey, the proposed approach made it possible to obtain a set of output maps of SOC sequestration under NT driven by two spatial input factors (AI and soil erosion).

The European Conservation Agriculture Federation (ECAF) reported that SOC sequestered by the application of NT management practices would easily reach the set targets by 2030 [12]. This analysis considers the sequestration rate under NT very homogeneous among the considered countries except for France, around 0.8 Mg ha^{-1} yr^{-1}.

The ECAF data show a very high potential to match *4p1000* targets by NT, but this result should be viewed critically since its analysis is based on a single long-term experiment that generally leads to uncorrected estimates (*overestimation*) of NT SOC sequestration when applied to larger areas.

For Spain, Portugal, Italy and Greece, the average sequestration rates under NT, showed in the ECAF report, were higher than those estimated in this study, both in the case of *apparent* and *effective* rates (0.54 and 0.43 Mg ha^{-1} yr^{-1}, respectively). A mere 0.20 Mg ha^{-1} yr^{-1} is reported for France, but this rate probably comes from Atlantic trials and is not appropriate for Mediterranean areas. In Spain, where several studies have been carried out in different areas, Gonzales-Sanchez et al. [43] found an average SOC sequestration by NT equal to 0.72 Mg ha^{-1} yr^{-1} but observed a large variability between 0.09 and 2.01 Mg ha^{-1} yr^{-1} in relation to climate. Furthermore, by upscaling the same data to study the effect of NT applications on SOC, Moreno-García et al. [44] found an average SOC sequestration of 0.43 Mg ha^{-1} yr^{-1} and an almost similar variability.

The spatial approach proposed in this study made it possible to determine a value of 0.6 Mg ha^{-1} yr^{-1} (on average for all of Spain) in between the range 0.43 and 0.72 Mg ha^{-1} yr^{-1}. Furthermore, 0.41 Mg ha^{-1} yr^{-1} and 0.34 Mg ha^{-1} yr^{-1} were estimated using data retrieved from Moreno-Garcia et al. [44], for *apparent* and *effective* SOC sequestration, respectively, by also applying the approach developed in this study.

This paper's analysis showed lower SOC sequestration than that proposed by González-Sánchez [43], but in any case, the latter suggests that there is a greater potential for the *4p1000* initiative, even if *effective* SOC sequestration is considered, especially when and where agricultural intensification and climatic conditions (low AI) have determined a reduction in carbon stock content.

In fact, the SOC content generally depends on climatic and edaphic conditions, but also on agricultural management [45,46]. Moreover, the introduction of conservative agricultural practices is very powerful when soils have been subjected to long-term stress, such as deep plowing, inversion and frequent tillage [44]. Determining the separate influences of two driving factors, the AI and the role of soil erosion processes, on SOC *overestimation* allows for the determination of a more accurate and site-specific response of NT.

In conclusion, the need to adopt different agro-environment policies in relation to different contexts to support and improve the spread and farmers' acceptance of NT should be advisable. A diversified policy approach should also consider economic and competitive aspects as well as environmental benefits of NT. For the farmers, benefits would lay in incentives, whereas the environmental benefits would have to be considered site by site.

5. Conclusions

This paper presents a spatial approach to verify the opportunity of NT to match the national objectives of SOC sequestration in relation to the *4p1000* goal. Specifically, the potential effect of the application of NT on cereal crops has been studied in European Mediterranean areas, also considering the *overestimation*, which may determine errors in SOC accounting, such as that determined by soil erosion processes. The suggested approach made it possible to identify the potential of applying NT practices to meet the *4p1000* initiative by introducing the idea of *apparent* SOC sequestration, driven by soil erosion processes, and an *effective* NT sequestration ability.

The analysis showed that arable land has considerable potential to increase SOC storage rates above the *4p1000* target in the Mediterranean climate, also due to the relatively low SOC stock levels. The results demonstrated that NT management could increase SOC stocks, often at rates higher than *4p1000* per year (in the 0–40 cm depth), but its effectiveness is strongly site-specific despite the proven *overestimation*. Of course, any contribution to mitigating climate change is welcome, if considering that even a small increase in SOC has a large impact on several physical properties of soil [3], and any initiative aimed at increasing SOC, such as the *4p1000*, should be promoted [2]. In this context, we believe that the proposed methodology can be considered an example of an initiative that can provide an opportunity to link policy and research interests, connecting potential soil carbon storage and the need to improve the adoption of sequestration measures at large scales as suggested by Pozza and Field [47].

In fact, adopting NT management practices in areas subjected to erosion will reduce soil loss due to the protection of the soil surface and will maintain productivity and SOC when compared to areas under conventional tillage. In any case, the adoption of NT on erodible sites may positively affect food security as well reduce other negative effects of erosion on SOC storage across landscapes, even if particular attention must be paid to correct SOC accountability [19].

Considering the interest for the *4p1000* initiative in the European Mediterranean areas, it is essential to encourage NT management as an alternative to CT to increase SOC sequestration and contribute to climate change mitigation by using incentive payments as well as other means.

Given the importance of NT for environmental sustainability, economic incentives must be adopted to support this management strategy. For these reasons, the proposed approach can be considered as a helpful decision tool for farmers and policymakers to target incentives in relation to the effective ability to sequester atmospheric CO_2 or SOC loss reduction by NT.

In the same way, support granted to farmers to shift from conventional to conservation agriculture provided in Italy by agri-environmental climate compensation payments, to be more effective, should consider a more reliable SOC sequestration account under shifting soil management techniques while also supporting cooperation for innovation.

This study shows the need to adopt different agro-environment policies in relation to different contexts to support and improve the spread and farmers' acceptance of NT. A diversified policy approach must also consider economic and competitive aspects as well as the environmental benefits of NT according to the second pillar of the common agricultural policy.

Finally, it should be noted that the study performed here is of course affected by uncertainties that lay in the large-scale applications of the literature dataset that was considered to derive the study maps.

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