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The Contribution of the Management of Landscape Features to Soil Organic Carbon Turnover among Farmlands

Gemma Chiaffarelli *, Fulvia Tambone and Ilda Vagge

Department of Agricultural and Environmental Sciences, University of Milan, Via Celoria 2, I-20133 Milan, Italy; fulvia.tambone@unimi.it (F.T.); ilda.vagge@unimi.it (I.V.)
* Correspondence: gemma.chiaffarelli@unimi.it

Abstract: Background: Landscape features (LF—i.e., the natural and semi-natural areas in agricultural landscapes) positively contribute to soil organic carbon (SOC) sequestration and storage among farmlands. LF-related SOC partitioning still needs context-specific investigation to properly address climate change mitigation goals. Not many studies address LF phytocoenoses traits relation with SOC partitioning. Our study investigates SOC partitioning (total organic carbon [TOC]; labile dissolved organic carbon [DOC]; stable recalcitrant organic carbon [ROC]) between arable fields (AGR) and semi-natural/natural components (NAT: herbaceous field margins, young/mature hedgerows, young/mature woods) in a temperate alluvial pedoclimatic context (Po Plain, North-western Italy). Methods: We compared topsoil SOC and its fractions (0–20 cm depth) between: AGR-NAT sites; hedgerows (HED)-AGR sites; and different ecological quality degrees (phytocoenoses were classified by Biological Territorial Capacity [BTC] values and Index of Vegetation Naturalness categories [IVN]--). Results: Our results confirmed a significantly different SOC partitioning behaviour between AGR and NAT sites (NAT: +79% TOC; +409% ROC); AGR sites were negatively correlated with ROC. TOC was a robust ROC predictor. HED had significantly higher TOC (+71%) and ROC (+395%) compared to arable fields, with the highest values in mature hedgerows. DOC showed contrasted behaviours. A linear regression model on BTC and IVN (predictors) and TOC and ROC showed significant positive relationships, especially for ROC. Conclusions: Our study confirmed the LF role in long-term SOC storage among farmlands, which should be coupled with AGR management (with prevalent short-term SOC fractions). LF ecological quality was a determining factor in total and long-term SOC. Proper LF management is pivotal to aligning climate change mitigation goals with other ecological benefits.

Keywords: landscape features; agroforestry; ecological quality; soil organic carbon persistence; carbon farming; climate change mitigation

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1. Introduction

The conservation and management of natural and semi-natural areas within the agricultural landscape (the so-called landscape features—LF) are nowadays recognised as key strategies to counterbalance the current widespread impacts of decades of intensive agricultural land use [1,2]. LF management among farmland (such as hedgerows, treelines, windbreaks, riparian corridors, groves, and woody areas) is part of the agroforestry approach [3]. Agroforestry practices (AGF) contribute to a wide range of ecological functions and services, and deep scientific evidence is available on this [4–7]. European policies directly recognise AGF and, specifically, LF value and support their implementation through different tools [1]. Specifically, the EU Biodiversity Strategy 2030 sets a target for 10% of agricultural land to incorporate landscape features [8]. The recently approved Nature Restoration Law requires an increasing trend toward high-diversity landscape features in agricultural land by 2030 [9]; hedgerows and groves insertion and management among farmland are directly supported by CAP eco-schemes (GAEC 8—Biodiversity and landscape objective) within National CAP Strategic Plans [10]. Among the different agri-environmental contributions of LF, specific attention is given to AGF as a Carbon Farming strategy [2,11], which can contribute to Climate Change Mitigation through organic carbon (OC) sequestration and storage in both above- and below-ground biomass and soil. Other agricultural practices also increase soil organic carbon (SOC) storage, such as conservation agriculture, compared to conventional practices [12–15], and these practices could be usefully integrated with AGF (and specifically, LF management) to foster carbon farming effectiveness [11,16–18].

Many studies have already deeply investigated the contributions of LF management to OC stocks, specifically SOC, in agricultural landscapes, highlighting their generally positive contributions. Drexler's meta-analysis of 83 temperate case studies accounted for an increase of +32% in SOC stocks in hedgerows (95% confidence interval ranging from 15 to 51%) compared to adjacent arable fields (28.4 cm average soil sampling depth, ranging from 5 to 60 cm) [18]. Holden et al. (2019) study in northern England accounted for hedgerows to contribute to about +60% SOC values in near-surface soil (2–7 cm soil depth) compared to arable fields [19]. A certain variability on SOC behaviour is acknowledged due to the complexity of interacting factors [20–22]. Topsoil shows the highest differences between arable fields and semi-natural land uses, with higher depths being less influenced [11,23]. For instance, Wenzel et al. [24] resume several studies where the highest SOC stock differences between hedgerows and arable fields are found in the mineral topsoil (0–20 cm depth) [24–29]. Viaud and Kunneman [21] found the highest differences at 0–30 cm depth.

Generally, the positive influence of LF on SOC storage increases with LF age [11,23,30], thanks to deeper rooting and long-term recalcitrant litter inputs [22,31,32], as well as the absence of soil disturbance (compared to arable fields), which reduces SOC losses and increases the residence time of SOC [11,33,34]. For instance, a recent study [29] highlighted a positive contribution of long-term (more than 10 years) hedgerows to SOC stock in the upper 100 cm, with higher SOC values at all sub-depths (10 cm intervals) compared to adjacent crop fields, independently from soil types. Biffi et al. [35] recently compared SOC stocks in the top 50 cm (10 cm depth intervals) in hedgerows and adjacent grasslands, finding a higher SOC stock contribution from hedgerows (+31.3%), confirming a positive gradient from younger to older hedgerows. Concerning other LF types (groves and woodlands), Gregg et al. [22] state that 10 to 30 years are needed for newly inserted woodlands to become significant SOC sinks. Laganière et al. [36] review reported that 32–35 years after afforestation allow for only moderate SOC gains in temperate continental climates, whereas in temperate maritime climates, the greatest SOC gains can be found early as 18.5 years after afforestation [36]. Del Galdo et al. [37] found significant increases in SOC values 20 years after mixed deciduous afforestation compared to arable fields (Northeastern Italy) [37]. Most SOC studies assessing the influence of agricultural land uses, specifically landscape features management, focus on SOC stocks [ton/ha] and sequestration [ton/ha/yr] capacity. Less attention has been given to landscape features' influences on SOC stability and turnover over time, specifically, its partitioning between labile and stable fractions (biochemical recalcitrance and physical protection) [38,39]. Nonetheless, studying SOC partitioning dynamics is pivotal for understanding effective contributions to climate change mitigation (avoiding net SOC losses, highly stable, slowly accumulating SOC pools), as SOC sequestration and storage require persistence over long periods [11].

Soil organic carbon, due to its dynamism, can be considered a measure of soil quality that can positively affect chemical, physical, and biological soil characteristics [40]. Soil organic matter can be divided into different fractions. The labile fraction is affected by a high turnover, is influenced by soil management systems, and dissolved organic carbon (DOC) is part of the labile fraction [41]. Arable soils generally have the lowest content of the carbon labile fraction because it is continuously disturbed by tillage practices and the harvesting of crop residues [42]. On the other hand, the soil organic carbon stable fraction, which can amount to up to 90% of the total organic carbon, due to its recalcitrance is not easily affected by land use or management practices. It is resistant to microorganism decomposition because it is strongly adsorbed to clay particles or because it is intrinsically recalcitrant. It is generally the so-called soil humic fraction [40].

These fractions are reported to be significantly influenced by land use, due to the type of vegetation and plant litter inputs [43,44]. AGF and, specifically, LF, should better contribute to SOC loss reduction and SOC stabilisation compared to crop field management practices [11]. Despite this, not many studies exist on LF influences on SOC partitioning. Wenzel et al. [24] investigated hedgerows' contributions to long-term SOC sequestration and storage in Austrian agricultural landscapes by separating Particulate Organic Matter (POM) and Mineral-associated Organic Matter (MOAM) [45,46]; more than half of the SOC sequestered in hedgerows' topsoil was allocated to stable MOAM, with hedgerow age explaining 70% of the variation. Different studies accounted for higher stable SOC values in forested sites compared to their agricultural counterparts by comparing soil fine (more stable), medium, and coarse (more labile) fractions [47–49]. Baah-Acheamfour et al. specifically compared hedgerows with agricultural land uses, showing significant differences in stable SOC fractions (higher values in hedgerows) [50]. In a study in Northeastern Italy, SOC partitioning related to afforestation on arable fields was evaluated through isotopic C signature: 20 years after afforestation, low residence time carbon pools were predominant in forested sites [37], which might imply an influence of stand age on more stable SOC storage. Viaud & Kunneman [21] also showed a positive influence of hedges on POM fractions (labile, quicker turnover), whereas MOAM (slower turnover) did not show significant relations (30 cm depth); in this case, hedges' age had no significant effect on SOC fractions. Generally, Dissolved Organic Matter (DOM) concentrations are reported to vary, with land use, in the order forest > grassland > arable in temperate climates [43], even if the same review reports how several management practices can affect this trend, give contrasting results, and highlight the need for further testing in field conditions to better understand short-term and long-term effects.

To synthesise, we can state from the literature that: LF stores higher SOC amounts compared to agricultural land uses; LF age positively influences SOC values; LF generally shows higher values for both stable and labile SOC values compared to agricultural land uses; contrasting information is available on LF age influence on short- and long-term SOC stabilisation.

LF age is an attribute that only partly represents LF status. Under the same age and/or dynamic stage, a landscape feature could be composed of phytocoenoses related to primary dynamic series as well as secondary series showing synanthropic traits (generally related to higher instability traits), depending on human disturbance intensity and frequency over time [51,52]. Old LF (long persistence over time) might have undergone intense or light chronic anthropic disturbance and be composed of highly disturbed phytocoenoses, low-structured and degraded, related to secondary dynamic series (progressive or regressive trends), which entail higher vulnerability traits (lower resistance capacity) [51,53–55]. Parallelly, young or middle-aged LF might show well-structured, highly diversified phytocoenoses if lower disturbance occurred during their development and primary dynamisms were favoured [51,56]. These primary/secondary dynamic traits significantly influence LF ecological quality and health status [57,58], and this might also influence SOC storage and turnover behaviour, as a co-occurring factor with LF age. Several synthetic indicators have been developed to assess phytocoenoses naturalness (opposite to human disturbance level) and maturity degrees (opposite to both natural and human disturbance level); both types can be considered descriptors of phytocoenoses ecological quality [56,58]. For instance, we can find in the literature: Hemerobiotic degrees [56,59], Biological Territorial Capacity (BTC) [60–62], Index of Vegetation Naturalness (IVN) [63], Index of Synthetic Maturity (IMS) [64,65], and Ecological Index of Maturity (EIM) [66].

To our knowledge, not much scientific evidence is available on the relationship between LF phytocoenoses ecological quality and SOC partitioning. Nonetheless, LF ecological quality indicators are commonly used for the assessment of their agri-environmental contributions, and their coupling with SOC partitioning patterns might disclose useful pathways for LF contributions assessment and monitoring. Concerning LF ecological quality–SOC assessments, Thiel et al. found a significant correlation between the α-biodiversity traits of hedgerows' woody perennial vegetation and SOC storage properties [67]. However, woody perennial vegetation biodiversity does not completely reflect the overall phytocoenoses biodiversity traits, and in this case, it was inversely related to hedgerows' age [67]. An interesting study comes from Sitzia et al. [20], who investigated the differences in topsoil (0–15 cm depth) labile and more recalcitrant SOC by comparing Dissolved Organic Matter (DOM) to Humic Substances (HS) in Eastern Po Plain hedged landscapes (North of Italy), showing how the variation of biochemical properties of hedge topsoils may be explained by vegetation variation. This study highlighted positive hedgerows' contributions to higher humification levels and also inter-hedges variability in both HS and DOM, related to hedges' vegetation type. Specifically, plant species were distributed along a gradient of soil humification, going from degraded, disturbed soils (higher presence of herbaceous species typical of open disturbed habitats) to more stable ones (higher presence of herbaceous species typical of more shaded and relatively moist habitats) [20]. These interesting results open the ground for further investigating the relationship between LF phytocoenoses ecological quality indicators and SOC stocking capacity over time.

Our study directly aims at enhancing the database and our understanding of such themes, by investigating SOC turnover in relation to different types of LF in a temperate alluvial pedoclimatic context (Po Plain, Northwestern Italy). Specifically, we assess an agroforestry-based farm management model, where linear (hedgerows) and areal (groves and woodlands) LF are included (hereafter called semi-natural and natural components—NAT) in between annual arable fields (agricultural components—AGR). Details on the implemented agroforestry model and its related contributions to the local agricultural landscape ecological quality and ecosystem services delivery can be found in previously published papers on the same case studies [68–70]. In this paper, we delve into its contributions to the climate change mitigation regulating ecosystem service. We test on our local dataset the following hypotheses: 1. NAT components among farmlands significantly contribute to SOC storage, especially in its stable fractions, in line with pre-existing evidence; 2. the management of field margins through hedgerow insertion or conservation promotes higher SOC storage among farmland, especially in its stable fractions, in line with pre-existing evidence; 3. such contributions depend on LF phytocoenoses ecological quality (a poorly investigated hypothesis).

To test hypothesis 1, we compare the SOC concentrations and SOC turnover behaviours (dissolved organic carbon (DOC) and recalcitrant organic carbon (ROC) [41]) between all NAT and AGR components of the agricultural landscape to assess their relative contributions to SOC short- and long-term turnover among farmlands. Then, we make a comparison between the hedgerow subset of NAT components, compared to the AGR ones, to test hypothesis 2. To test hypothesis 3, we then specifically address the relation between different ecological quality degrees of AGR and NAT components and SOC content and turnover (DOC and ROC values). To this third aim, we classify phytocoenoses ecological quality through BTC reference values (Biological Territorial Capacity) [60–62] and IVN categories (Index of Vegetation Naturalness) [63]. Both indicators reflect the ecological health of phytocoenoses [58] (which we here refer to as 'LF ecological quality'), but they depict different facets of it. BTC is a measure of phytocoenoses metastability and is positively related to phytocoenoses biomass, maturity, vegetation dynamism, and resistance capacity; it is inversely related to both natural and human disturbance degrees [60,61] (Figure 1). IVN assesses the degree of naturalness, which is indirectly related to human disturbance, but which is not linearly related to biomass, maturity, or vegetation dynamism [56]. Indeed, according to the synphytosociological approach [52], all dynamic stages (recolonisation stage, shrubs stage, pre-wood stage, mature wood stage) can be related to both primary (high naturalness) or secondary (low naturalness) series. Along secondary vegetation series stages, too, we can find a gradient of human disturbance according to its intensity and frequency: highly intense and frequent human disturbance keeps dynamisms to initial stages, whereas highly intense but infrequent or lowly intense but chronic human disturbance brings to secondary wood stages. BTC and IVN might be complementary, as they both represent the disturbance degrees, the first one better reflecting phytocoenoses maturity/structuring (dynamic stages) and the second one better isolating the human disturbance effect on phytocoenoses (their maturity is a secondary-level classification parameter) (Figure 1).

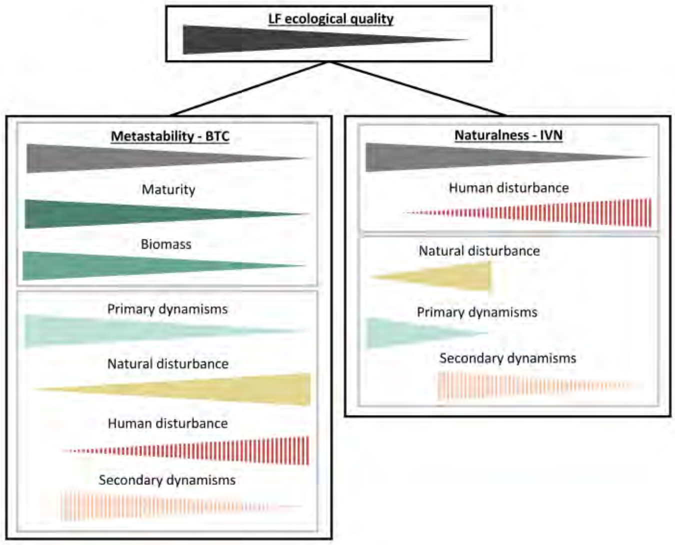

Figure 1. The different relationships between BTC and IVN values (descriptors of two different facets of landscape features (LF) ecological quality) with phytocoenoses maturity degree, biomass, primary and secondary vegetation dynamism, and human and natural disturbance degree.

2. Materials and Methods

2.1. Case Studies

The study was conducted across four sites (C, G, P, D) located in the Western Po Plain district (North of Italy) (Figure 2), an alluvial context dominated by intensive agricultural land use (rice, corn, and feed crops, intensive livestock), undergoing several environmental pressures [2]. The case studies belong to similar (but not identical) climatic and bioclimatic contexts, with a temperate continental macro-bioclimate [71–73]. They differ slightly in their main pedological traits, related to Holocene, Wurm, and Riss fluvial alluvial terraces [74,75], as resumed in Table 1 and described in the pedological map (Appendix A, Figure A1) [74,75] and soil profile photos (Appendix A, Figure A2) [76,77]. The current potential vegetation of the case studies belongs to the vegetation series of the western lower neutral-acidophilus Po Plain, with *Quercus robur* L. and *Carpinus betulus* L. (All. *Carpinion betuli* Isler 1931), except for hygrophilous belts along watercourses [78]. This series is linked to ancient alluvial terraces. The most advanced stage in the serial succession is a lowland forest with tree species like *Quercus robur* L., *Carpinus betulus* L., *Fraxinus excelsior* L. subsp. *excelsior*, *Acer pesudoplatanus* L., *Acer campestre* L., and shrub species like *Corylus avellana* L., *Crataegus monogyna* Jacq., *Cornus mas* L., *Ligustrum vulgare* L., *Euonymus europaeus* L., *Rosa canina* L., *Prunus spinosa* L. subsp. *spinosa*. The herbaceous undergrowth is rich in mesophilous and sciaphilous species like *Vinca minor* L., *Polygonatum multiflorum* (L.) All., *Salvia glutinosa* L., *Anemonoides nemorosa* (L.) Holub, *Primula vulgaris* Huds., *Pulmonaria officinalis* L. Under anthropic disturbance, such woods are easily modified by the arrival of invasive alien species like *Robinia pseudoacacia* L., *Prunus serotina* Ehrh., *Acer negundo* L. and *Ailanthus altissima* (Mill.) Swingle. These alien species tend to deplete the forest ecosystem quality, reduce biodiversity values, and sometimes lead to anthropogenic vicariant phytocoenoses dominated by invasive alien species [78–81]. Shrub and grassland stages result in degraded vicariants too (*Ulmus minor* Mill. and *Sambucus nigra* L. shrublands; *Aegopodium podagraria* L. clearings and edges). Grassland stages are normally made of uncultivated meadows invaded by widely distributed ruderal species and alien herbaceous species [82]. Along watercourses and water basins (also the artificial ones, if the banks' slope is not excessive), we find hygrophilous phytocoenoses, such as shrub willows in riverbeds or on gravel ditches' banks, and riparian woods with *Populus nigra* L., *Populus alba* L., *Salix alba* L. in ordinarily flooded areas. In case of anthropogenic disturbance, the latter are substituted by *Robinia pseudoacacia* woods. On first alluvial terraces and along ditches, we find *Alnus glutinos*a (L.) Gaertn. hygrophilous woods. The banks of ditches, ponds and hydric basins (also the artificial ones), with loamy-silty, low-slope banks, are colonised by hygrophilous and hydrophilous herbaceous species, like *Phragmithes australis* (Cav.) Trin. Ex Steud., *Typha latifolia* L., *Lythrum salicaria* L., *Butomus umbellatus* L., and *Limniris pseudacorus* (L.) Fuss, shaping phytocoenoses that are often invaded by alien invasive species, like *Solidago gigantea* Aiton, *Reynoutria japonica* Houtt., and *Helianthus tuberosus* L. Generally, the local scale landscape context of case studies is dominated by conventional agricultural land use, with landscape over simplification patterns (lack of interspersed natural and semi-natural patches supporting stepping stones, connectivity, buffering, and source areas functions). These landscape ecological traits, related to intensive anthropisation and long-term anthropogenic disturbance, explain the widespread substitution series of phytocoenoses, as we recently synthesised in a landscape ecology study on D site [68].

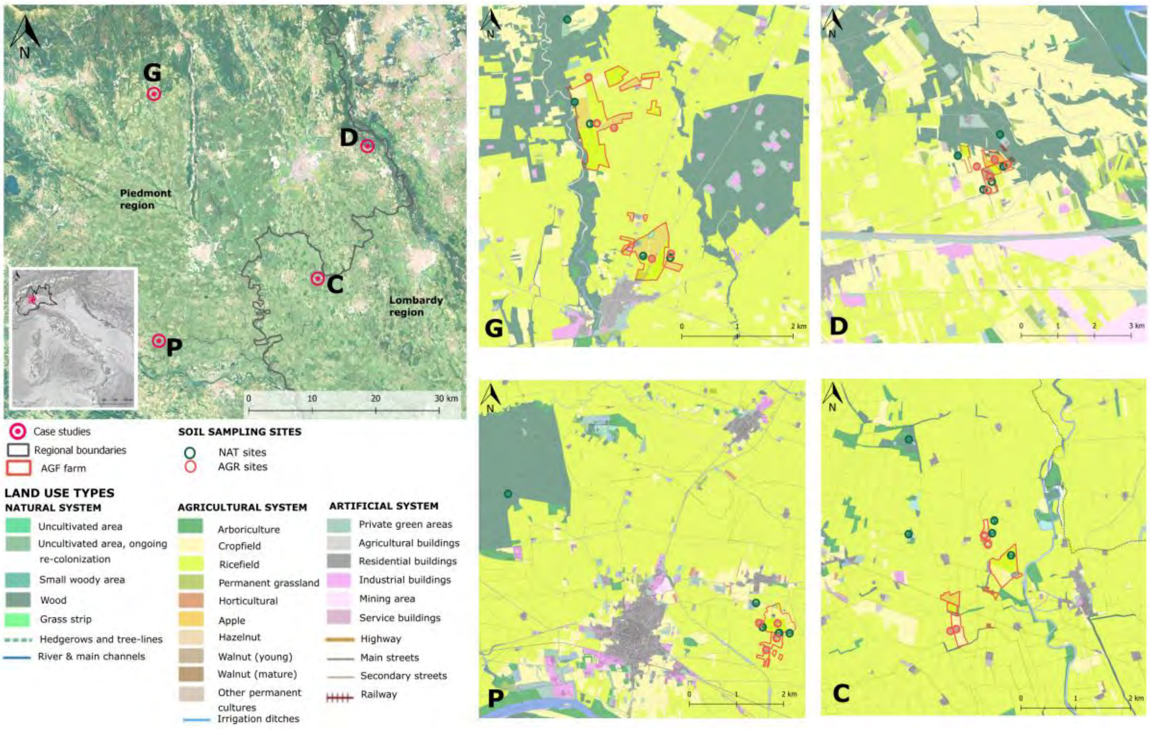

Figure 2. Left side: Case studies location (C, G, P, D). Right side: Land use maps showing the 4 agroforestry-based farms (AGF farms, in red) and soil sampling sites (green circles: natural/semi-natural sites–NAT; red circles: agricultural sites–AGR).

In each case study, an agroforestry-based farm is represented (AGF farm), where between field linear (hedgerows) and areal (groves and woodlands) landscape features are implemented and managed in-between organic arable fields (managed through soil conservation practices–minimum tillage, cover crops) (Figure 2). In each case study, we also selected neighbouring conventional arable fields to represent different management options.

Table 1. The main pedological, climatic, and bioclimatic traits of the 4 case studies (World Reference Base (WRB) and Soil Taxonomy (ST) pedological groups).

		CASE STUDIES			
		C	G	P	D
PEDOLOGY	ST/WRB classes	Luvisols; Arenosols	Alfisols (ancient terraces); Inceptisols	Inceptisols; Entisols	Inceptisols
	Geomorphology	Fluvial terrace	Riss alluvial terrace	Fluvial deposits	Fluvial terrace
	Main soil texture	Loamy-sand; Sandy-loam	Fine silty	Loamy-coarse; Loamy-sand	Loamy-skeletal
	Development	Medium pedogenesis	Intense pedogenesis	Low pedogenesis	Low pedogenesis
	Permeability	Medium-low permeability	Surface hydromorphy	Medium permeability	High permeability
	pH	Sub-Acid [5.5–6.5]	Acid [4.6–5.4]	Sub-alkaline to alkaline [7.4–8.4]	Acid to Sub-acid [5.3–6.3]
	Land use capacity	IIw (waterlog)	III (oxygen availability)	II (oxygen availability)	III (stoniness)
	Specific traits				Dark epipedon
CLIMATE [1990–2022 data]	Annual rainfall [mm]	668	872	737	973
	Annual mean Temperature [°C]	13.1	12.3	13.2	11.8
	Average Maximum Temperature [°C]	18.6	18.9	18.8	17.9
	Average Minimum Temperature [°C]	8.19	7.0	8.5	6.4
BIOCLIMATE [1990–2022 data]	Bioclimate (variant)	Temperate oceanic (submediterranean)	Temperate continental (steppic)	Temperate continental (steppic)	Temperate continental
	Bioclimatic belt	Upper mesotemperate Low humid	Upper mesotemperate Upper subhumid	Upper mesotemperate Low subhumid	Upper mesotemperate Low humid

2.2. Natural and Agricultural Components Characteristics

To represent the overall contributions given by the diversified management of productive, semi-natural, and natural areas among farmland, we studied SOC behaviour related to different land use types (Figures 2 and 3), representing two different agricultural management models (Figure 3):

- Agroforestry model (AGF): Organic rice and other crop production implementing conservation agriculture practices (minimum tillage, cover crops), crop rotations, with no chemical inputs (AGR_AGF); also encompassing the management of natural and semi-natural areas among farmland (hedgerows, small woody areas, wetlands, etc.) with different degrees of maturity (young (NAT_1) and mature (NAT_2) hedgerows, young (NAT_3) and mature (NAT_4) woody areas).
- Conventional model (CV): No semi-natural area management; farmland is composed only of agricultural land uses (crop fields, mainly conventional monoculture, with tillage, no cover crops, and intensive chemical inputs) (AGR_CV) and herbaceous field margins (periodically disturbed by herbicides and mowing) (NAT_CV).

As synthetised in Figure 3, NAT and AGR components are represented in both AGF and CV management models.

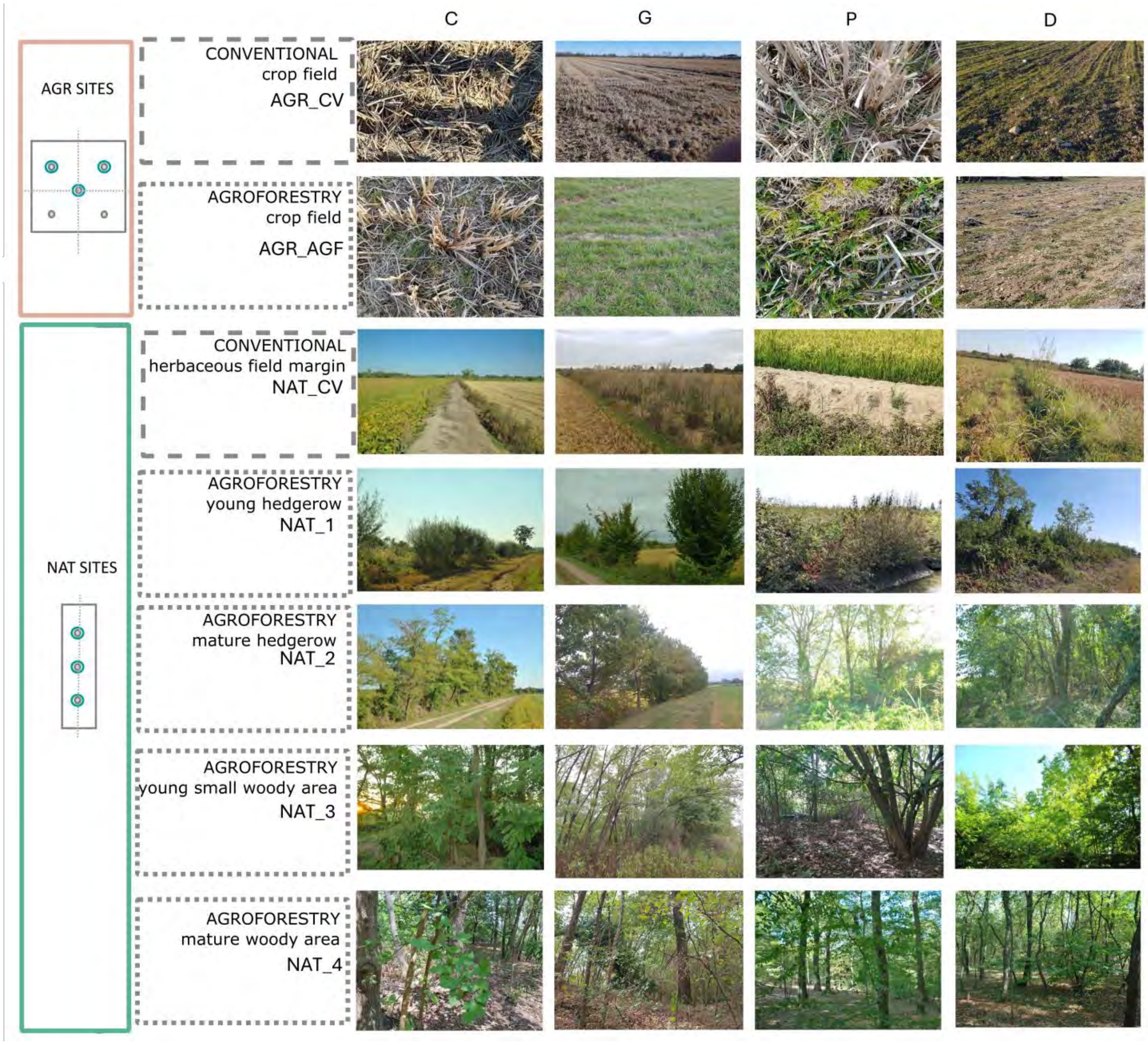

Figure 3. The different monitored land use types (rows), related to the agricultural (AGR) and semi-natural/natural (NAT) components of conventional (CV) and agroforestry (AGF) farms, with some examples from the 4 case studies (columns: C, G, P, D). The applied sampling scheme in AGR and NAT sites is shown on the left side.

2.3. Phytocoenoses Ecological Quality Classification.

As reported in the Introduction section, for each case study we classified the different land uses according to their ecological quality, referring to:

- Biological Territorial Capacity (BTC), a synthetic indicator that evaluates the metastability of the vegetated landscape mosaic, based on the resistance stability concept [83], the main vegetated ecosystems of the biosphere [84], and their metabolic data [60–62]. BTC evaluates the energetic flux that an ecological system must expend to maintain its level of organisation and metastability [Mcal/ha/yr] [61], and it is inversely related to anthropic disturbance. It can be considered an estimator of the maturity degree of phytocoenoses, and its mean values for land use types have already been estimated for the Northern Italy context (reference ranges for each main phytocoenosis type). In this study, we referred to Ingegnoli's BTC unitary value ranges identified for the Po Plain context [61,62], which we attributed to each sampling site according to its actual state.

- Index of Vegetation Naturalness (IVN), an indicator that evaluates the landscape naturalness degree based on phytosociological syntaxa classification into degrees of naturalness, reflecting a decrease in human impact on vegetation types. In this study, we referred to IVN natural category values, as identified by Ferrari [63,85], which were attributed to each sampling site.

The BTC and IVN category values assigned to each land use type were obtained as the arithmetic mean of each sampling site's values, assessed based on actual phytocoenoses traits and literature comparison [60–63,85].

2.4. Soil Sampling and Organic Carbon Partitioning Analysis

AGR soil samples were collected in late winter 2022 and NAT samples in late summer 2022. Two AGR_CV and two neighbouring AGR_AGF sampling sites were identified in each of the four case studies. For NAT sites, one sampling site for each NAT land use type (five NAT sampling sites for each case study) was identified. For AGR sampling sites, a sampling scheme (according to similar experiences in the Po Plain context [86]) was adopted; three vertices were sampled to obtain a composite sample for each sampling site. For NAT sampling sites, the same protocol was applied but with a transect sampling scheme, in accordance with previous similar experiences in the Po Plain context [20].

At each sampling point, a topsoil slice sample (approximately 5 × 10 × 20 cm^3) was taken with a spade after litter removal, representing the 0–20 cm depth. The sub-samples were dried at room temperature, sieved at 2 mm, homogenised and a random extraction was made from the composite sample for each sampling site.

For DOM extraction, 10 g of each soil sample were taken, air-dried and sieved at 2 mm; a 1:10 suspension was created and shaken in a Dubnoff thermostatic bath at 80 oscillations per min for 2 h at 25 °C. After that, the suspension was centrifuged at 10,000 rpm for 20 min, and the supernatant was filtered through a 0.45 μm glass filter to recover the water extract [87]. For recalcitrant organic matter (ROM), the extraction was performed in a 250 mL Erlenmeyer flask with 0.1 N NaOH plus 0.1 M $Na_4P_2O_7$ under N_2 at 65 °C for 24 h at 80 oscillations per min in a Dubnoff thermostatic bath. The sample was then cooled to room temperature and centrifuged at 10,000 rpm for 20 min. This extract represents the so-called humic-like fraction. The organic carbon content in the original soil samples, DOM, and ROM extracts was determined by the dichromate method [88] on an aliquot of the volume extracted, obtaining TOC, DOC, and ROC values (g/kg).

2.5. Data Analysis

TOC, DOC, and ROC contents in the soils were evaluated by comparing:

- The four pedological contexts (for the entire dataset, both NAT and AGR data (n = 36)), to identify possible significant differences that might be related to the different pedological contexts.
  Differences were investigated using ANOVA or non-parametric Kruskal-Wallis rank tests when the data distribution did not meet the assumption of normality. In cases of significant differences ($p < 0.05$), these were followed by Tukey's pairwise test or Mann-Whitney pairwise test. In some cases, we applied BOX-COX transformation to obtain normally distributed data.
- AGR and NAT sites (n = 36), to report on the effect of arable fields (AGR: AGR_CV; AGR_AGF) on OC turnover and the role of LF management (NAT) in balancing possible negative patterns among farmlands (first research question). We first included and then excluded NAT_CV components (conventional herbaceous field margins) from NAT sites to separately compare all field margins case histories (both herbaceous and hedged margins) and then those related to agroforestry-based hedgerow management. TOC, DOC, and ROC relations were investigated for the entire dataset,

and then for the separated NAT and AGR components, also through Ordinary Least Squares Regression with TOC as the independent variable and DOC and ROC as dependent variables.

Differences between AGR and NAT groups were investigated with a *t* test for equal means (Monte Carlo permutation non-parametric test) and the Mann-Whitney U test for equal medians (non-parametric test). Tests were run on BOX-COX transformed data to get closer to normal distribution, which was not attained for all AGR and NAT sub-samples.

Differences and OC turnover patterns were also investigated through correlation analysis (Spearman's rs correlation coefficient) of TOC, DOC, and ROC content (all NAT and AGR data; n = 36) with:

a. agricultural management (AGR);
b. natural management (NAT), excluding NAT_CV;
c. the different TOC fractions (TOC, DOC, ROC)

- Hedgerows (HED: NAT_1; NAT_2) and arable fields (AGR: AGR_CV; AGR_AGF) (n = 24), to specifically investigate the contribution of hedgerow management among crop field farmlands (second research question). We investigated differences between HED and AGR using a *t* test for equal means (Monte Carlo permutation non-parametric test) and the Mann-Whitney U test for equal medians (non-parametric test). Tests were run on BOX-COX transformed data to get closer to a normal distribution, which was not attained for all AGR and HED sub-samples.

To investigate the relation between TOC, DOC, and ROC content and the different ecological quality degrees of the AGR and NAT components (BTC; IVN) (third research question), we conducted Spearman's rs correlation analysis and Ordinary Least Squares Regression analysis with BTC and IVN as independent variables and TOC and ROC as dependent variables (BOX-COX transformed data).

All analyses were conducted using Past4.13 software.

3. Results

3.1. Entire Dataset

Appendix A, Table A1 resumes the main descriptive statistics for TOC, DOC, and ROC values for the entire dataset. Data are not normally distributed, even when log-transformed. TOC and ROC values show higher variance, coefficients of variation are also high, due to the variety of case histories and the limited sample size (n = 36).

Table 2 compares the four pedological contexts under study (C, D, G, P) with respect to TOC, DOC, and ROC values. A BOX-COX transformation was applied to TOC values, obtaining a normal distribution (Shapiro-Wilk normality test: W = 0.988; *p*(normal) = 0.9581; n = 36). ANOVA test was applied to BOX-COX transformed TOC values, whereas DOC and ROC values were tested for differences between sites using the Kruskal-Wallis non-parametric test (Table 2). D site significantly differed from G and C sites in TOC values, showing higher values, in coherence with the pedological Cartographic Unit it belongs to (described as soils with a dark epipedon, derived from the abundant humus layer linked to historical wood soil cover [89]). G-C have the highest probability of having similar TOC values, P is intermediate. DOC values showed no significant difference between case studies, whereas D significantly differed from all other case studies in ROC values.

Table 2. TOC, DOC, and ROC values [g/kg] differences between the four case studies (* = $p < 0.05$; ** = $p < 0.01$).

	TOC g/kg		DOC g/kg		ROC g/kg	
SITE	Mean	Std. error	Mean	Std. error	Mean	Std. error
C	16.22	1.38	0.15	0.02	7.11	2.07
D	37.02	8.46	0.19	0.03	28.29	9.33

G	17.17	2.51	0.16	0.02	7.52	2.52
P	20.45	1.86	0.16	0.01	8.49	2.80
	Anova		Kruskal-Wallis		Kruskal-Wallis	
p(same)	0.001326	**	0.6965		0.02546	*
df	3					
F	6.615					
Leven's test *p*(same)	0.1288					
Residuals *p*(normal)	0.6242					
	Tukey's		Mann-Whitney		Mann-Whitney	
p value D-C	0.004785	**	0.5365		0.01044	*
p value D-G	0.002146	**	0.7911		0.01342	*
p value D-P	0.2116		0.9296		0.02728	*
p value C-G	0.9907		0.7239		1	
p value C-P	0.3589		0.2164		0.9296	
p value G-P	0.2238		0.4268		1	

3.2. Differences between NAT and AGR Sites

Data show a clear separated OC partitioning behaviour between AGR and NAT sites (except for three AGR cases from D case study, which show higher TOC and ROC values similar to the other case studies of NAT sites) (Figure 4A). TOC values are highly positively correlated with ROC values ($p = 1.08 \times 10^{-7}$), whereas no significant correlation is found with DOC values ($p = 0.18$) (Table 3). NAT sites tend to have higher TOC values for the same DOC values, whereas AGR data show higher DOC values for lower TOC values (even if some internal variability is highlighted) (Figure 4A). The lowest DOC values are found in NAT sites. A clear positive TOC/ROC trend is highlighted (Figure 4A), especially for NAT data, with ROC increasing with TOC. AGR and NAT sites have a clearly separated TOC/ROC behaviour (except for D site AGR data): AGR data have lower ROC ratios for the same TOC values. Linear bivariate regression between TOC (independent variable) and ROC values (dependent variable) was highly significant for the entire dataset (NAT and AGR data) ($p(\text{slope}) = 1.55 \times 10^{-23}$; $r^2 = 0.95$) (Figure 4B; Appendix A, Table A2), with the highest descriptive capacity of the model when considering NAT data separately ($p(\text{slope}) = 5.58 \times 10^{-16}$;$r^2 = 0.98$). Nonetheless, a significant deviation from the linear model occurs at low TOC values (<20 g/kg), where AGR and NAT components behave differently, and higher variability occurs in ROC values independently from TOC values. This also occurs in the NAT sites subset, where the strongest relation between TOC and ROC values is observed for TOC values > 20 g/kg. For AGR data, the linear regression model was also significant, with a lower (but consistent) descriptive capacity ($p(\text{slope}) = 5.06 \times 10^{-5}$; $r^2 = 0.70$) (Figure 4B; Appendix A, Table A2). The model is less reliable for TOC values > 18 g/kg, where significant deviation from the linear model occurs: this corresponds to high (and less common) TOC values for arable fields, and the unpredicted relation to ROC values may be due to site-specific peculiarities.

According to these results and specifications, TOC values could be a robust predictor of more stable ROC values, especially when considering NAT components of the agricultural landscape (such as hedgerows, groves, and woodlands) with medium-to-high TOC values (>20 g/kg). Differently, we found no significant TOC/DOC relation (Appendix A, Table A2). Nonetheless, the DOC/ROC graph (Figure 4A) better highlights the NAT and AGR separated behaviour: for the same DOC values, NAT land uses show higher ROC values.

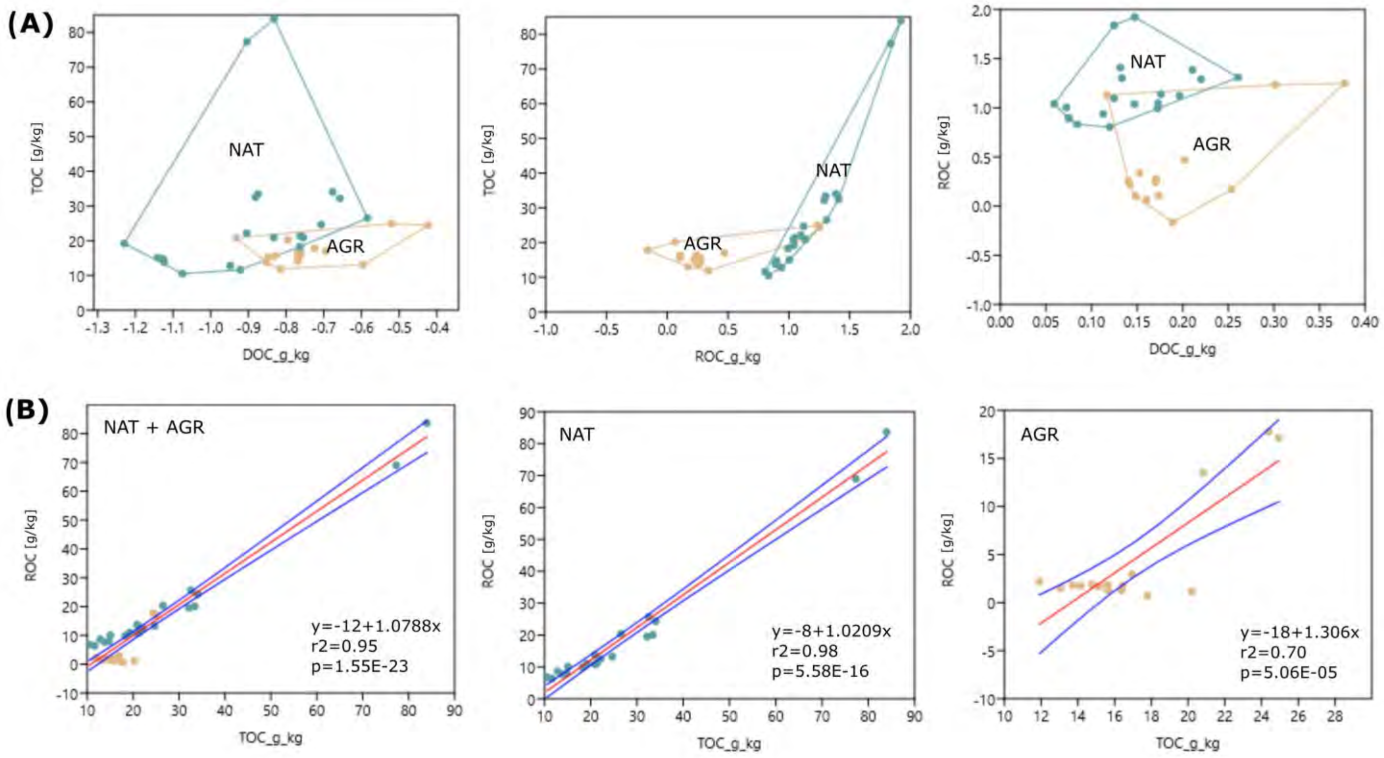

Figure 4. (**A**) Relation between TOC, DOC, and ROC values in AGR (light brown dots) and NAT sites (dark green dots; also including NAT_CV sites) (AGR sites convex hulls: light brown line; NAT sites convex hulls: dark green line; log y transformed data); (**B**) Ordinary Least Squares Regression run on TOC values as the independent variable, DOC and ROC values as dependent variables, for the entire dataset (NAT and AGR) and then separately for NAT and AGR data (AGR sites: light brown dots; NAT sites: dark green dots; blue line: 95% regression confidence intervals; red line: linear function straight line).

Table 3. Spearman's rs correlation coefficients values (top side) and *p* values (bottom side) between TOC, DOC, and ROC values and AGR and NAT land uses (excluding NAT_CV from NAT).

	NAT	AGR	TOC g/kg	DOC g/kg	ROC g/kg
NAT		−1	0.49	−0.23	0.69
AGR	0		−0.49	0.23	−0.69
TOC g/kg	0.00467	0.00467		0.24	0.78
DOC g/kg	0.20508	0.20508	0.18014		0.02
ROC g/kg	1.22×10^{-5}	1.22×10^{-5}	1.08×10^{-7}	0.92544	

We tested the significance of the detected differences between AGR and NAT data, both including NAT_CV (herbaceous conventional field margins) and excluding it (Figure 5A; Appendix A, Table A3). The data show significant differences between AGR and NAT data for TOC (+61% in NAT sites; $p < 0.05$), DOC (−26% in NAT sites; $p < 0.05$), and ROC (+348% in NAT sites; $p < 0.001$) values. If we exclude NAT_CV (herbaceous conventional margins) from the NAT dataset, to better represent LF behaviour compared to arable fields, NAT shows significantly higher TOC (+79% in NAT sites; $p < 0.01$) and ROC (+409% in NAT sites; $p < 0.001$) values, whereas differences in DOC values diminish (−17% in NAT sites) and are not significant (NAT_CV highly disturbed field margins increased the NAT mean DOC content) (Appendix A, Table A3). Each case study (C, G, P, D) generally shows the same AGR-NAT patterns identified for the aggregated data (all case studies), even though differences are not significant in some cases (C and G TOC values) (Figure 5B). The "anomalous" D site does not show different patterns for TOC and ROC values compared to the other three sites; only the differences in DOC values between AGR and NAT are more marked in D, but still not significant.

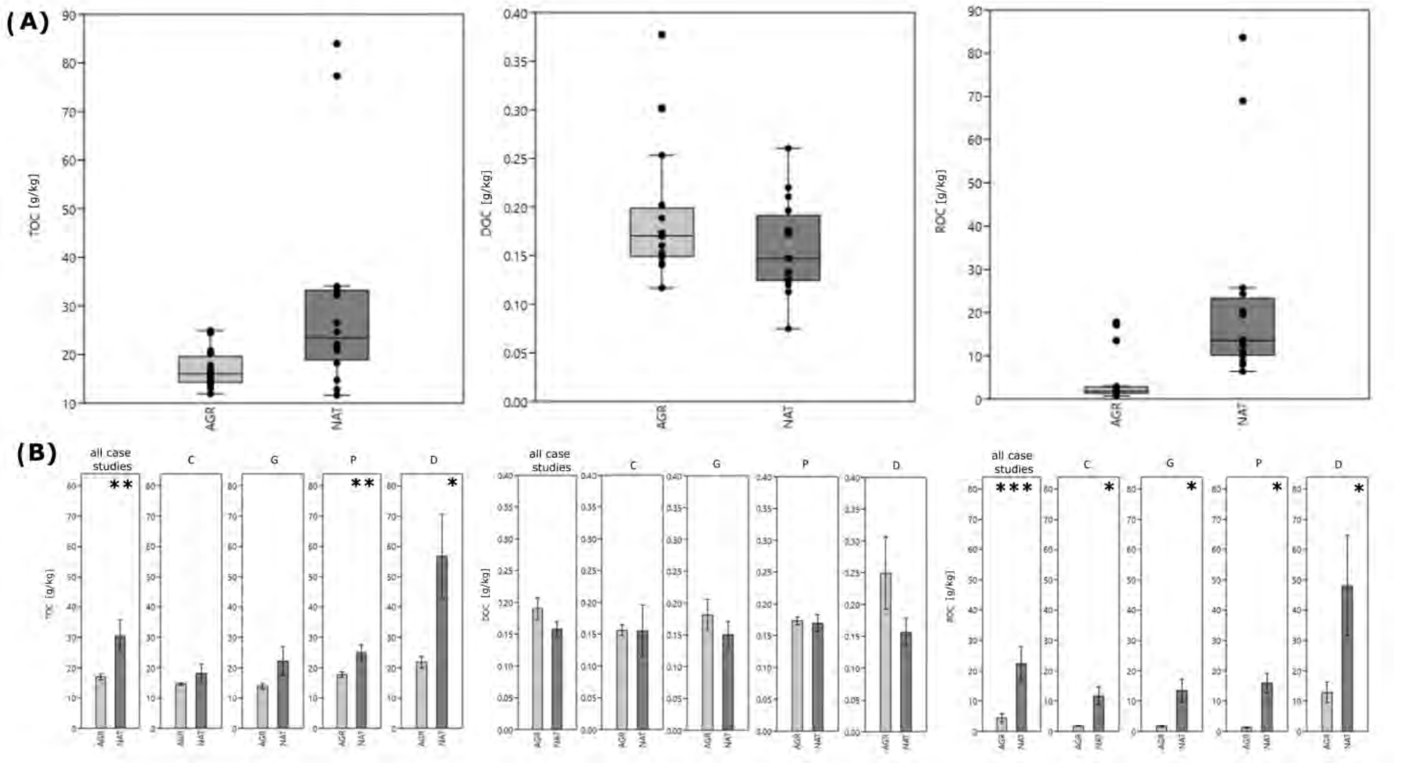

Figure 5. (**A**) Comparison of TOC, DOC, and ROC values (all site data) found in AGR (light grey) and NAT (dark grey) components (NAT_CV is excluded from the NAT category). (**B**) Bar plots representing TOC, DOC, and ROC mean values for all case studies and for each single case study (whiskers represent standard error; asterisks represent *t* test results (Monte Carlo permutation), applied on BOX-COX transformed data (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).Black dots represent jittered data points, whiskers and boxes represent the 0th, 25th, 50th, 75, 100th percentiles.

The influence of NAT and AGR land uses on OC partitioning is further confirmed by Spearman's rs correlation analysis (Table 3). Agricultural land use (AGR) is significantly negatively correlated with both TOC and ROC values (respectively, $p = 0.00467$; $p = 1.22 \times 10^{-5}$). Semi-natural and natural land uses (NAT; excluding NAT_CV) show the opposite correlation pattern, with the same significances. No significant correlation is detected between either AGR or NAT land uses and DOC values.

3.3. Differences between Hedgerows and AGR Sites

Hedgerows (HED: NAT_1 and NAT_2) show significantly higher TOC and ROC values than AGR sites (AGR_CV and AGR_AGF) (respectively, *p*(TOC same mean) = 0.0141; *p*(ROC same mean) = 0.0015; *t* test, Monte Carlo permutation) (Figure 6A; Appendix A, Table A4). DOC values are lower in hedgerows, with no significant differences (*p*(DOC same mean) = 0.3796). Considering all sites, hedgerows show a +71% mean TOC concentration compared to arable fields, and +395% ROC values (Appendix A, Table A4). Similar TOC and ROC patterns between HED and AGR are found in each case study (even though high variability is detected in D), whereas DOC values show not identical patterns between sites (Figure 6A).The *t* test could not be applied to single case study data because of the low HED group sampling size (n = 2).

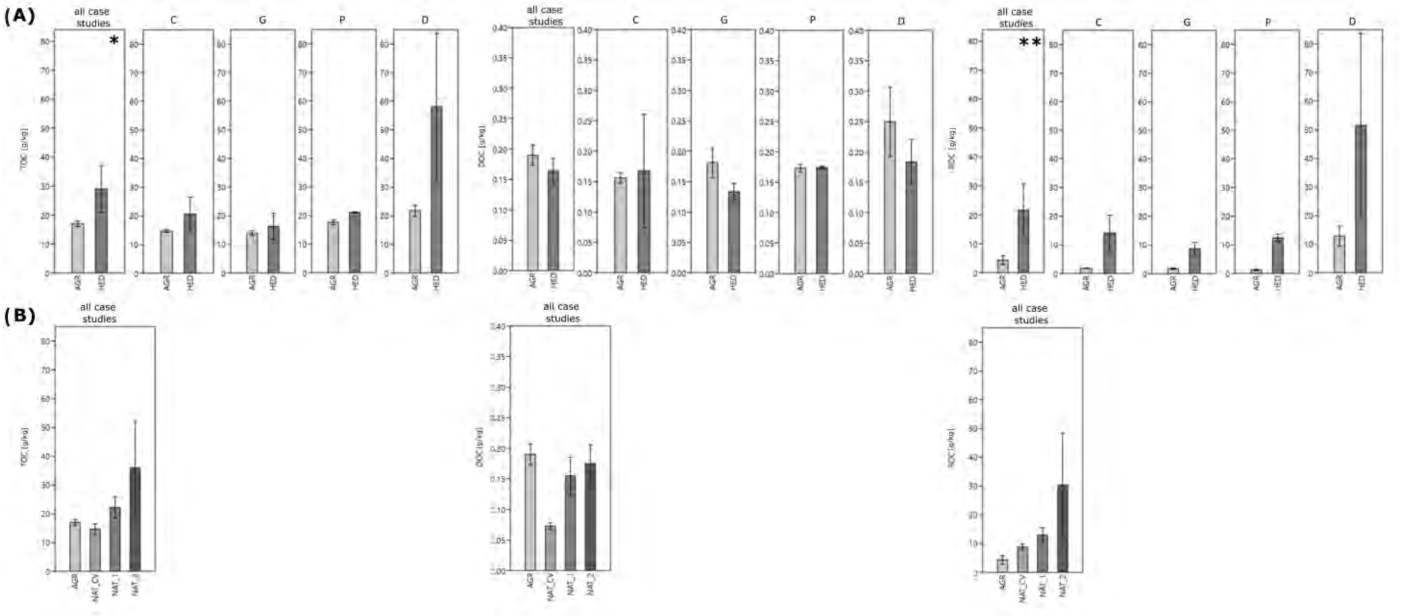

Figure 6. Bar plots representing TOC, DOC, and ROC mean values for: (**A**) hedgerows (HED: NAT_1; NAT_2) and agricultural sites (AGR: AGR_CV; AGR_POLY) across all case studies, and for each single case study; (**B**) arable fields (AGR), herbaceous conventional field margins (NAT_CV), and each hedgerow type (NAT_1; NAT_2). Whiskers represent standard error; asterisks represent *t* test results (Monte Carlo permutation) on all site data, applied on BOX-COX transformed data (* = $p < 0.05$; ** = $p < 0.01$). The *t* test could not be applied to single case study data due to low sample size.

To further understand the influence of different hedgerow types (young and mature hedgerows), we compared TOC, DOC, and ROC values between arable fields (AGR) and the different field margins management (NAT_CV, NAT_1, NAT_2) (Figure 6B). Concerning TOC values, NAT_CV herbaceous conventional field margins behave similarly to agricultural sites (AGR), whereas NAT_2 mature hedgerows show the highest values (but also high in-between group variability, due to the D case study). A gradient is shown going from NAT_CV to NAT_1 to NAT_2, but no significant differences are detected (Kruskal-Wallis test: *p*(same) = 0.1472) (Appendix A, Table A4). Significant differences are highlighted in DOC values, with NAT_CV (conventional field margins) showing the lowest values, significantly differing from both AGR land uses and mature hedgerows (NAT_2) (Appendix A, Table A4). ROC values show a clear gradient, going from AGR sites to NAT_CV, NAT_1, and NAT_2; significant differences are detected between AGR-NAT_1 and AGR-NAT_2.

3.4. Phytocoenoses Ecological Quality and SOC Turnover Behaviour

The BTC and IVN category values assigned to each land use type are synthetised in Table 4. Concerning agricultural vegetation, organic arable fields (AGR_AGF) have slightly higher BTC values than conventional ones (AGR_CV), due to lower soil disturbance (no tillage/minimum tillage), vegetative cover persisting during all year (winter polyphyte cover-crops), and the presence of in-field linear embankments with perennial herbaceous species, shrubs, and trees in one case study (G). For semi-natural vegetation (see Table 2), NAT_CV variability in BTC values (SE = 0.058) is due to evidence of chemical weed control in conventional field margins of two sites (C, P) (Figure 3). Young hedgerows (NAT_1) show variability in BTC values due to differences in linear phytocoenoses development, continuity, and stratification degree across the four case studies (Figure 3). Mature hedgerows (NAT_2) show higher BTC values due to greater development, continuity, and stratification degree; however, the IVN original values do not allow us to distinguish them from young hedgerows. Young small woody areas (NAT_3) show slightly higher BTC values compared to mature hedgerows, due to greater areal development and better horizontal structure. IVN categorisation places all NAT_3 under sub-natural vegetation. Mature woody areas (NAT_4) represent the highest BTC values (higher phytocoenoses maturity and higher biomass). In all case studies, NAT_4 belonged to the natural vegetation IVN category.

Table 4. The BTC and IVN category values assigned to each land use type under study (mean value between the four case studies and standard error [SE]).

		BTC		IVN	
LAND USE		Mean [Mcal/ha/yr]	SE	Mean	SE
AGR_CV	Arable fields: conventional agriculture	1.025	0.075	2	0.000
AGR_AGF	Arable fields: organic, conservation agriculture	1.25	0.050	2	0.000
NAT_CV	herbaceous field margin	1.6	0.058	5	0.000
NAT_1	young hedgerow	2.675	0.125	7	0.000
NAT_2	mature hedgerow	3.45	0.096	7	0.000
NAT_3	young small woody area	4.475	0.048	8	0.000
NAT_4	mature woody area	7.975	0.125	11.25	0.479

BTC values are significantly positively correlated with TOC (Spearman's rs = 0.37; $p = 0.02652$) and especially ROC values (Spearman's rs = 0.58; $p = 0.00018$) (Table 5). No significant correlation is observed with DOC values. IVN natural categories show a stronger correlation with both TOC values (Spearman's rs = 0.47; $p = 0.004116$) and ROC values (Spearman's rs = 0.70; $p = 1.69 \times 10^{-6}$).

Table 5. Spearman's rs correlation coefficients values (top side) and *p* values (bottom side) between TOC, DOC, and ROC values and BTC values, and IVN category values.

	BTC	IVN	TOC (g/kg)	DOC (g/kg)	ROC (g/kg)
BTC		0.96	0.37	−0.26	0.58
IVN	1.27×10^{-19}		0.47	−0.22	0.70
TOC (g/kg)	0.02652	0.00412		0.34	0.75
DOC (g/kg)	0.13295	0.19329	0.04017		0.02
ROC(g/kg)	0.00018	1.69×10^{-6}	1.37×10^{-7}	0.89567	

Regression analysis on TOC and ROC as dependent variables and BTC and IVN as predictors (Ordinary Least Squares Regression on BOX-COX transformed data) showed:

- A significant positive effect of both BTC and IVN on TOC values (Figure 7): the linear regression models are significant ($p < 0.01$ in both cases), even though they have limited descriptive capacity (respectively: $r^2 = 0.25$; 0.23) (Appendix A, Table A5);
- A stronger positive effect of both BTC and IVN on ROC values (Figure 7; Appendix A, Table A5), with higher model significance and better performance of the IVN model (BTC: $p < 0.0001$; IVN: $p < 0.000001$). The IVN linear regression model showed higher descriptive capacity (BTC: $r^2 = 0.42$; IVN: $r^2 = 0.56$) (Appendix A, Table A5).

Residuals are not normally distributed, so we referred to 95% bootstrapped confidence intervals (N = 1999) for all regression analyses (Appendix A, Table A5). Also, the absence of residuals autocorrelation was not strictly respected in BTC and IVN models ($p = [0.02–0.04]$ for BTC; $p = [0.490–0.491]$ for IVN) (Appendix A, Table A5).

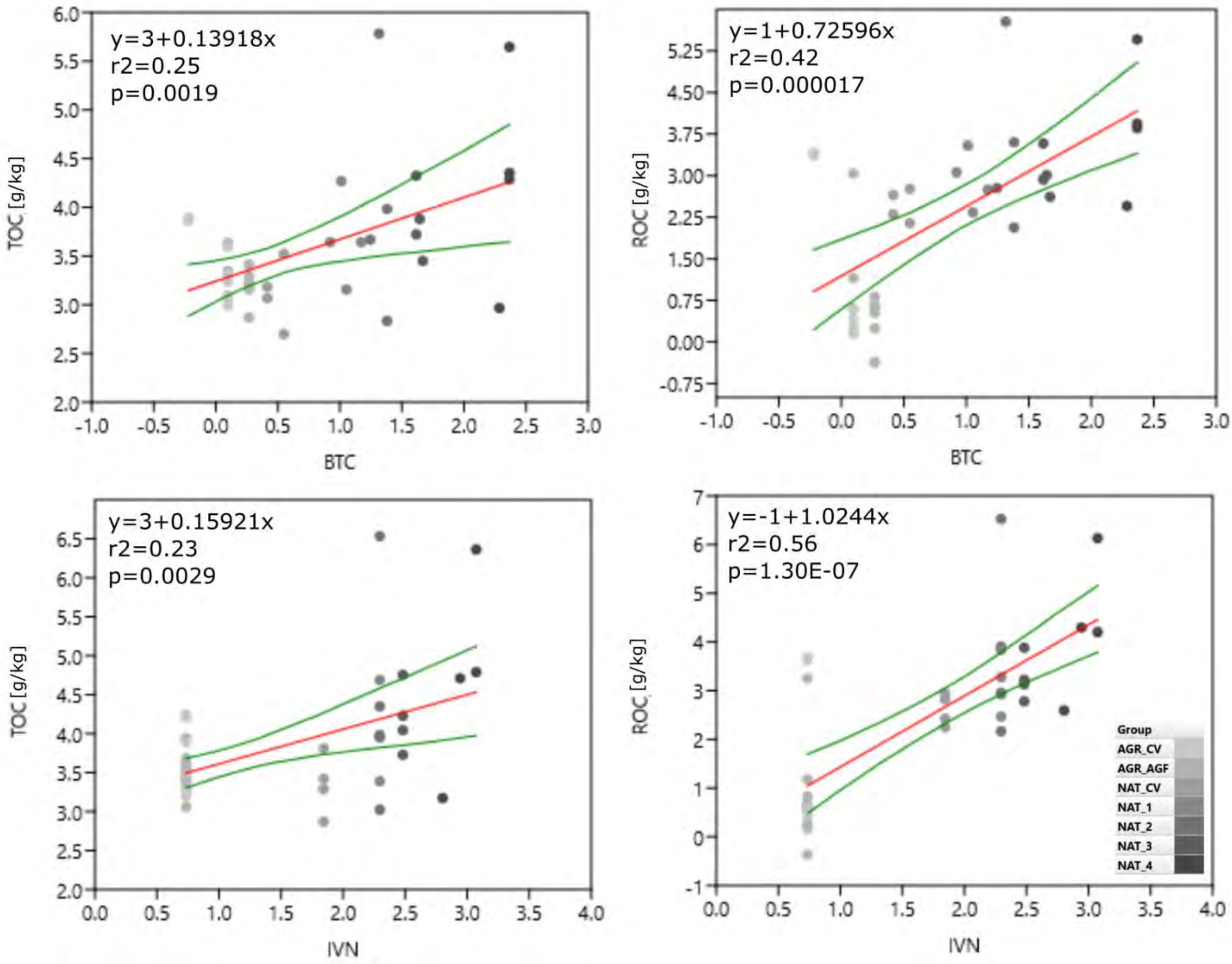

Figure 7. Relation between BTC (**top**), IVN (**bottom**) and TOC (**left**) and ROC (**right**) values (Ordinary Least Squares Regression on BOX-COX transformed data). Green line: 95% bootstrapped confidence intervals (N = 1999); red line: linear function straight line. Dotches graysscale represents the seven AGR and NAT land use categories (from the lowest ecological quality (lightest grey) to the highest (darkest grey) (see Table 4)).

4. Discussion

4.1. Natural/Semi-Natural Components Significantly Contribute to Medium-Long Term SOC Storage among Farmlands

Concerning our first research question on NAT components contributions to SOC turnover among farmland, our Northern Italy (Po Plain) study highlighted the following SOC turnover patterns:

- A clear separated SOC partitioning behaviour between arable fields (AGR) and LF (NAT), concerning long-term SOC fraction (ROC). This confirms previous literature experiences results (see Introduction paragraph), showing how the management of LF among farmland (hedgerows, groves, and woodlands): i. significantly increases mean TOC values (+79%) compared to arable fields; ii. significantly contributes to medium-long term SOC turnover (mean ROC values; +409%), improving the SOC stock functions of farmlands over time. NAT and AGR land uses are mostly distinguished by long-term SOC partitioning processes (ROC), whereas the readily available SOC fraction (DOC) does not show significant differences. Nonetheless, DOC data show a general rising trend in arable fields (AGR) compared to LF (NAT), as AGR land uses are significantly negatively correlated with ROC values. The detected relation between arable fields and DOC values is coherent to the typical soil disturbance traits characterising AGR fields (if compared to more stable semi-natural and natural sites), which are related to the agricultural need for readily available, soluble organic compounds, easily degraded and acting as an energy source for soil biota. This is also coherent to the typical in-field spontaneous phytocoenoses ecological traits, as highlighted in a recent study conducted in three of the four case studies presented here[90]. The detected in-field weed communities show medium to high soil nutrient content needs and are dominated by therophytes, which have short life cycle strategies (in temperate agricultural contexts, they are generally related to frequent soil disturbance traits and readily available soil nutrients).

- TOC values were a robust predictor of ROC values when considering the entire dataset (NAT and AGR sites;$r^2 = 0.95$), with the highest descriptive capacity when considering the LF subset (NAT sites; $r^2 = 0.98$), and lower, but still consistent, descriptive capacity when considering the arable fields subset (AGR sites; $r^2 = 0.70$). In the studied contexts, TOC value assessment could be considered a proxy for long-term organic carbon stocking capacity (ROC), especially for NAT sites showing medium-to-high TOC values (>20 g/kg). Lower predictability could be attained on AGR sites, especially for sites with uncommonly high TOC values (>18 g/kg).

4.2. Hedgerows Promote Higher Medium-Long Term SOC Storage among Farmland by Age

Concerning our second research question on the influence of hedgerows on SOC turnover among farmland, our results showed:

- Significant differences between TOC and ROC values in hedgerows (HED), compared to arable fields (AGR), are in line with pre-existing studies in other temperate regions. Hedgerow TOC was +71% higher than that in arable fields: these differences were higher than those registered in previous studies (Drexler's meta-analysis reported a 15–51% range in temperate case studies (95% confidence interval)) [18]. ROC differences between hedgerows and arable fields were particularly high: +395% ROC values in hedgerows. ROC differences with arable fields were significant for both young and mature hedgerows. Arable fields showed the highest DOC values, which were significantly higher than those in herbaceous conventional field margins. This could be explained by typical temporal variations in soil DOC values due to soil management and the sampling period. For example, Al-Graiti et al. [91] detected higher DOC concentrations in spring. Embacher et al. [92] reported that DOM exhibited seasonal fluctuations in several soil types, although limited information is available on how DOM properties in arable soils respond to the combined effects of sampling dates and agrotechnical effects. Furthermore, soil tillage can accelerate organic matter decomposition. This may explain why arable fields showed the highest DOC values.
- A positive gradient of TOC values was observed, increasing from arable fields to young hedgerows to mature ones.

4.3. Landscape Features of Higher Ecological Quality Promote Higher Medium-Long Term SOC Storage among Farmland

Concerning our third research question, related to the influence of phytocoenoses ecological quality on SOC turnover patterns, our results confirmed our hypothesis:

- The two selected indicators representing the LF phytocoenoses ecological quality (BTC, IVN) showed significant positive relations with TOC values, and even more so with ROC values. That means, that the ecological status of AGF phytocoenoses, their stability over time, and their degree of naturalness (here intended as the different degrees of anthropic disturbance influencing spontaneous phytocoenoses dynamic trends) are strictly positively related to higher SOC stock capacity and, specifically, to higher long-term SOC turnover processes. The linear models built for the three ecological quality selected indicators showed good performance, with the best ones in IVN influences on ROC values ($r^2 = 0.56$).

5. Conclusions

The agroforestry model, by combining agricultural, semi-natural, and natural components (landscape features, LF) among farmland, parallelly addresses productive functions and ecological functions that directly and indirectly support productive ones, among which we can find climate change mitigation and soil health goals. Our study on temperate alluvial case studies confirmed that soil organic carbon turnover among farmlands is significantly shaped by LF presence, as evidenced by the following patterns: 1. Natural/semi-natural components significantly contribute to medium-long term SOC storage among farmlands, compared to agricultural components (+79% TOC; +409% ROC); 2. Hedgerows promote higher medium-long term SOC storage among farmland by age, with significantly higher values compared to arable fields (+71% TOC; +395% ROC); 3. These contributions depend on LF phytocoenoses ecological quality.

Specific attention should be given to point 3. The different types of natural components generally included in the AGF approach can be related to different phytocoenoses ecological quality. Depending on their ecological quality, they support the ecological health of agroecosystems to different degrees and at different scales. In our study, they also showed differential contributions to SOC turnover over time. Specifically, the phytocoenoses ecological quality (here represented by BTC values and IVN categories) was found to be strictly related to TOC stocking capacity and, even more, to long-term SOC turnover (ROC). These results could positively orient the strategic management of natural components among farmland to attain positive climate change mitigation contributions, in parallel to other ecological benefits strictly coupled to LF ecological quality. Interventions on landscape features need proper design to reach climate change mitigation goals; species choice and planting patterns are pivotal to attain well-structured and diversified phytocoenoses, that will quickly reach higher ecological quality traits, as we recently synthetised in a study specifically related to LF rehabilitation strategies in a Po Plain case study [93].

To date, little scientific literature is available on LF ecological quality relation to SOC turnover. Our study results suggest the opportunity to further investigate the relation between BTC values and IVN categories (maybe coupled with other LF ecological quality indicators) at other sites to strengthen the comprehension of their relationship with SOC turnover behaviour. This may lead to the use of such low-cost and low time-consuming indicators as context-specific proxies for the climate change mitigation contributions provided by different farmland management approaches.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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

Appendix A

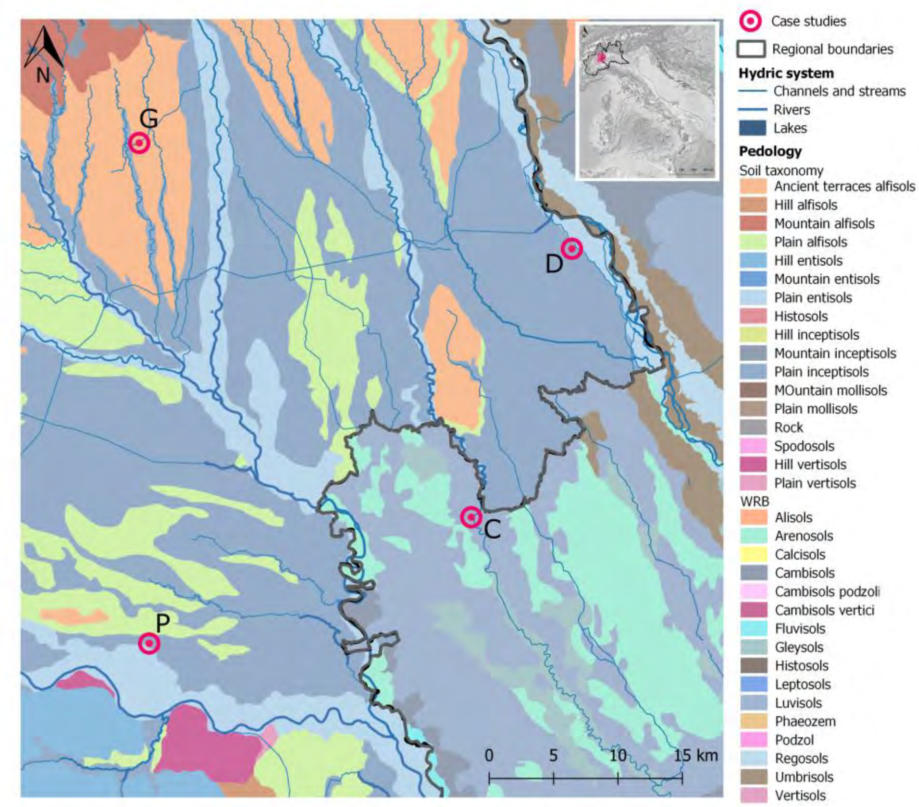

Figure A1. The main pedological traits (ST and WRB pedological classes) of the four case studies (C, G, P, D).

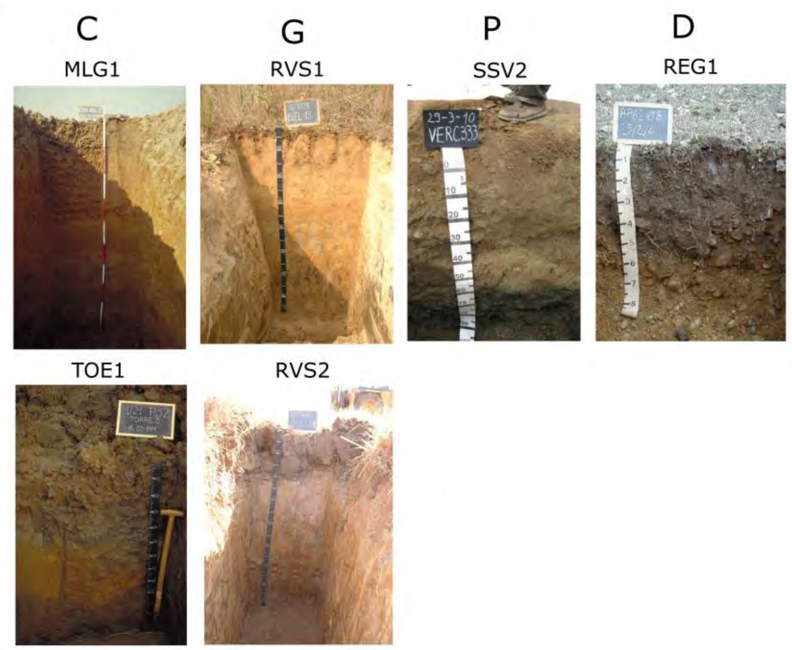

Figure A2. Photos of the soil profiles of the most characteristic soils of the four case studies (C, G, P, D), taken from regional environmental agencies databases. C site: coarse-loamy MLG1 and TOE1 soil series phases [76]; G site: fine-silty typic phase (RVS1) and anthraquic phase (RVS2) [77]; P site: loamy-coarse SSV2 soil series phase [77]; D site: loamy-skeletal typic REG1 soil series phase [77].

Table A1. Descriptive statistics for TOC, DOC, and ROC data (g/kg and % values) for the entire data set (AGR and NAT sites).

	TOC		DOC		ROC	
	g/kg	%	g/kg	%	g/kg	%
N	36	36	36	36	36	36
Min	10.49	1.05	0.06	0.16	0.69	3.86
Max	83.96	8.40	0.38	1.94	83.66	99.65
Sum	817.79	81.77	5.85	30.66	462.63	1642.56
Mean	22.72	2.27	0.16	0.85	12.85	45.63
Std. error	2.60	0.26	0.01	0.06	2.88	4.70
Variance	243.75	2.44	0.00	0.14	298.95	794.08
Stand. dev	15.61	1.56	0.06	0.37	17.29	28.18
Median	18.02	1.81	0.16	0.86	9.26	54.43
25 percentil	14.75	1.48	0.12	0.56	1.81	12.48
75 percentil	24.60	2.46	0.19	1.06	16.30	66.73
Skewness	3.06	3.06	1.18	0.44	3.03	−0.19
Kurtosis	9.92	9.91	2.63	0.94	10.14	−1.31
Coeff. var	68.73	68.78	39.74	43.78	134.55	61.76

Table A2. Results of Ordinary Least Squares Regression run on TOC values as an independent variable, with DOC and ROC values as dependent variables, for the entire dataset (NAT and AGR data) and then separately for NAT and AGR data. The "correlation" and "residuals" rows show the correlation analysis results (r^2: squared correlation coefficient—coefficient of determination for simple linear regression; p(uncorr): probability that columns are not correlated) and residuals analysis results (verification of the absence of positive autocorrelation, homoskedasticity, and normality of residuals—Shapiro Wilk test).

		NAT + AGR data		NAT data	AGR data
		TOC-DOC	TOC-ROC	TOC-ROC	TOC-ROC
REGRESSION	Slope a:	−0.00478	1.0788	1.0209	1.306
	Std. error a:	0.000894	0.042943	0.037987	0.2273
	Intercept b:	0	−12	−8	−18
	Std. error b:	0.24896	1.1784	1.2677	3.9514
	t:	0	25	27	6
	p(slope):	0.72898	1.55×10^{-23}	5.58×10^{-16}	5.06×10^{-5}
CORRELATION	r^2:	0.003577	0.94888	0.97568	0.70221
	p(uncorr.):	0.72898	1.55×10^{-23}	5.58×10^{-16}	5.06×10^{-5}
RESIDUALS	p(no pos. Autocorr.)	0.14615	0.22735	0.97731	0.3962
	p(homoskedasticity)	0.98696	0.59042	0.066902	0.1845
	Shapiro-Wilk W	0.9198	0.9802	0.9857	0.9544
	p(normal)	0.01243	0.7523	0.9856	0.5616

Table A3. TOC, DOC, and ROC mean values [g/kg] and standard errors (SE) for NAT and AGR sites (including NAT_CV in NAT sites and excluding it); t test and Mann-Whitney test results on differences between AGR and NAT sites, based on BOX-COX transformed data (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

	Including NAT_CV						Excluding NAT_CV					
	TOC g/kg		DOC g/kg		ROC g/kg		TOC g/kg		DOC g/kg		ROC g/kg	
LAND USE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
AGR	16.99	0.95	0.19	0.02	4.38	1.48	16.99	0.95	0.19	0.02	4.38	1.48
NAT	27.30	4.40	0.14	0.01	19.63	4.55	30.46	5.22	0.16	0.01	22.31	5.51

	t TEST		*t* TEST		*t* TEST		*t* TEST		*t* TEST		*t* TEST	
p(same mean) Monte Carlo permutation	0.0292	*	0.0111	*	0.0001	***	0.0036	**	0.1032		0.0001	***
	Mann-Whitney Test		Mann-Whitney Test		Mann-Whitney Test		Mann-Whitney Test		Mann-Whitney Test		Mann-Whitney Test	
p(same median)	0.058195		0.037048	*	0.00010971	***	0.007044	**	0.20674		0.0001306	***

Table A4. TOC, DOC, and ROC mean values [g/kg], standard errors (SE), and differences between: (A) HED and AGR sites; *t* test and Mann-Whitney test results, based on BOX-COX transformed data; (B) AGR and each field margin management type (NAT_CV; NAT_1; NAT_2); Kruskal-Wallis and Mann-Whitney test results based on BOX-COX transformed data (* = $p < 0.05$; ** = $p < 0.01$).

	TOC g/kg		DOC g/kg		ROC g/kg	
(A)	Mean	SE	Mean	SE	Mean	SE
AGR	16.99	0.95	0.19	0.02	4.38	1.48
HED	29.02	8.16	0.16	0.02	21.70	9.03
	t TEST		*t* TEST		*t* TEST	
p(same mean) Monte Carlo permutation	0.0217	*	0.2982		0.002	**
	Mann-Whitney Test		Mann-Whitney Test		Mann-Whitney Test	
p(same median)	0.07084		0.6027		0.002436	**

(B)	Mean	SE	Mean	SE	Mean	SE
AGR	16.99	0.95	0.19	0.02	4.38	1.48
NAT_CV	14.65	1.80	0.07	0.01	8.90	0.99
NAT_1	22.19	3.63	0.15	0.03	13.01	2.47
NAT_2	35.85	16.33	0.18	0.03	30.38	18.00
	Kruskal-Wallis		Kruskal-Wallis		Kruskal-Wallis	
p(same)	0.1472		0.02373	*	0.009528	**
	Mann-Whitney		Mann-Whitney		Mann-Whitney	
p value AGR-NAT_CV			0.002916	**	0.06539	
p value AGR-NAT_1			0.6707		0.02638	*
p value AGR-NAT_2			0.7409		0.01597	*
p value NAT_CV-NAT_1			0.1124		0.1939	
p value NAT_CV-NAT_2			0.03038	*	0.3123	
p value NAT_1-NAT_2			0.8852		0.665	

Table A5. Results of Ordinary Least Squares Regression run on BTC and IVN data as independent variables, with TOC and ROC values as dependent variables (BOX-COX transformed data). The "correlation" and "residuals" rows show the correlation analysis results (r^2: squared correlation coefficient—coefficient of determination for simple linear regression; *p*(uncorr): probability that columns are not correlated) and residuals analysis results (verification of the absence of positive autocorrelation, homoskedasticity, and normality of residuals—Shapiro Wilk test).

		BTC-TOC	BTC-ROC	IVN-TOC	IVN-ROC
REGRESSION	Slope a:	0.13918	0.72596	0.15921	1.0244
	Std. error a:	0.73279	1.7575	0.72202	1.933)
	Intercept b:	3	1	3	−1
	Std. error b:	3.4605	1.7855	3.5169	0.81433
	t:	3	5	3	7
	p(slope):	0.0018829	0.000016966	0.0029317	1.30×10^{-7}

CORRELATION	r^2:	0.25041	0.42413	0.23206	0.56431
	p(uncorr.):	0.0018829	0.000016966	2.93×10^{-3}	1.30×10^{-7}
RESIDUALS	*p*(no pos. Autocorr.)	0.043962	0.020288	0.049096	0.0491
	p(homoskedasticity)	0.056663	0.22153	0.043679	0.61232
	Shapiro-Wilk W	0.9017	0.9343	0.8987	0.8133
	p(normal)	3.79×10^{-3}	3.39×10^{-2}	3.15×10^{-3}	3.03×10^{-5}

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