D2 REPORT: QUALITY AND QUANTITY OF DATA AVAILABLE FOR EACH IDENTIFIED CROP/LIVESTOCK CARBON FARMING PRACTICE

ACTION A.2

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C·FARMs CARBON FARMING CERTIFICATION SYSTEM

INTRODUCTION

By virtue of the high scientific value of the research conduct and accompanying results, which makes a novel contribution to the knowledge gap identified for the mitigation potential of CO_2 emissions by sustainable management of agricultural European soils, the present communication represents a lighter, albeit, representative version of the final report for action A2. Specifically, some sections are temporarily omitted as a precaution measure to avoid possible trade-offs which may arise during the submission procedure of a manuscript – which includes such sections- for a scientific journal and the subsequent peer-review phase. The full version of the Report will be provided for public consultancy within the end of C-FARMs project (31/05/2023).

Action A2 of the Carbon-Farming Certification System project aims to identify and quantify the potential for CO2 sequestration and/or emissions reduction of carbon-farming practices applied to agricultural soils of the Italian region of Lombardy while accounting for the climatic zones and soil texture classes that characterize said region. Hereunder we present our research methodology as well as the set of reviewed carbon-farming practices with their respective estimated mitigation potential for climate change and/or carbon sequestration.

1. MATERIALS AND METHODS

We conducted a review of the scientific literature aimed at identifying the potential of carbon-farming practices for carbon dioxide sequestration and/or emissions reduction in European agricultural soils.
The search was conducted on common online bibliographic sources using a combination of keywords corresponding to soil quality indicators (organic carbon, organic matter) and agricultural practices both for annual and perennial crops.
We included only studies that calculated the carbon sequestration/retention rate (ΔSOC) by applying either the *STOCK difference method (IPCC, 2006*), which aims at gauging carbon stock increases over time for a given agricultural practice, or the *pairwise comparison method*, which is aimed at comparing the ability of two different practices to contribute to organic carbon soil retention. The included studies had to

report the ΔSOC (*t C ha^{-1} yr^{-1}*) or, alternatively, the experimental difference in either the concentration of soil organic carbon (SOC) (g/kg) or soil carbon stocks (t C/ha) with respect to baseline SOC (STOCK *difference method*) or to the control (*pair comparison method*).

For each study included in this review, information regarding the following descriptive variables was collected in a dataset:

- Tested carbon farming practice
- Type of control
- Type of crop
- Sampling depth
- Years of experimentation
- Location and geographic coordinates
- Climate
- Soil type (FAO or USDA classification) and texture (% sand, silt, clay)
- Carbon sequestration/retention rate
- Type of publication (report, conference proceedings, scientific article)
- Type of study (experimental, model, LCA)

1.1 Carbon sequestration/retention rate calculation

When not explicitly reported in the reviewed studies, the carbon sequestration rate (ΔSOC) for a given practice was calculated according to the STOCK difference method (IPCC, 2006):

ΔSOC t C ha-1 yr-1 = (SOC STOCK t1 - SOC STOCK t0) / years   (eq 1.)

where:

SOC STOCK t1: follow-up carbon stock, i.e., carbon stock measured after the experiment in the treatment plot, expressed in tons per hectare;

SOC STOCK t0: baseline carbon stock, i.e., carbon stock measured before the experiment in the treatment plot, expressed in tons per hectare;

years: duration of the experiment in years.

In the case of studies aimed at drawing comparisons between two or more practices applied on adjacent plots with the same carbon content (pair comparison method), wherever baseline carbon stock measurements were absent, the ΔSOC of a practice was calculated as the average yearly difference in the follow-up SOC STOCK levels between the treatment and control plot:

$\Delta SOC\ t\ C\ ha^{-1}\ yr^{-1} = SOC\ STOCK\ tr\ (t1) - SOC\ STOCK\ c\ (t1)\ /\ years$ (eq. 2)

where:

SOC STOCK tr (t1): follow-up carbon stock for the treatment plot, i.e., carbon stock measured after the experiment in the treatment plot, expressed in tons per hectare;

SOC STOCK c (t1): follow-up carbon stock for the control plot, i.e., carbon stock measured after the experiment in the control plot, expressed in tons per hectare;

years: duration of the experiment in years.

For studies implementing the pair comparison method on plots with differing baseline organic carbon contents, the ΔSOC of a practice versus its control was calculated as the average yearly difference in the respective carbon stock variations (difference-in-differences estimation):

$\Delta SOC\ t\ C\ ha^{-1}\ yr^{-1} = (\Delta\ SOC\ STOCK\ tr - \Delta\ SOC\ STOCK\ c)\ /\ years$ (eq. 3)

where:

ΔSOC STOCK tr: carbon stock variation (i.e., difference between follow-up and baseline values) for the treatment plot, expressed in tons per hectare;

ΔSOC STOCK c: carbon stock variation for the control plot, expressed in tons per hectare;

years: duration of the experiment in years.

1.2 Absolute and relative carbon sequestration

Carbon sequestration implies transferring atmospheric CO_2 into long-lived C pools, such as soil and woody biomass (Lal et al., 2018). Reductions in soil emissions cannot be regarded as carbon sequestration, but rather as carbon retention. By analyzing the three equations presented hereabove, it is possible to note that positive ΔSOC values calculated using the STOCK difference method imply real carbon sequestration in the soil (Figure 1. a, b, d), that is, an absolute SOC STOCK increase over time or, in other words, carbon sequestration as defined by Lal et al (2018). This can usually be observed when there is a consistent deviation from the potential SOC STOCK saturation level, whereby the latter varies according to land-use, land management, climate, texture, soil type and pH.

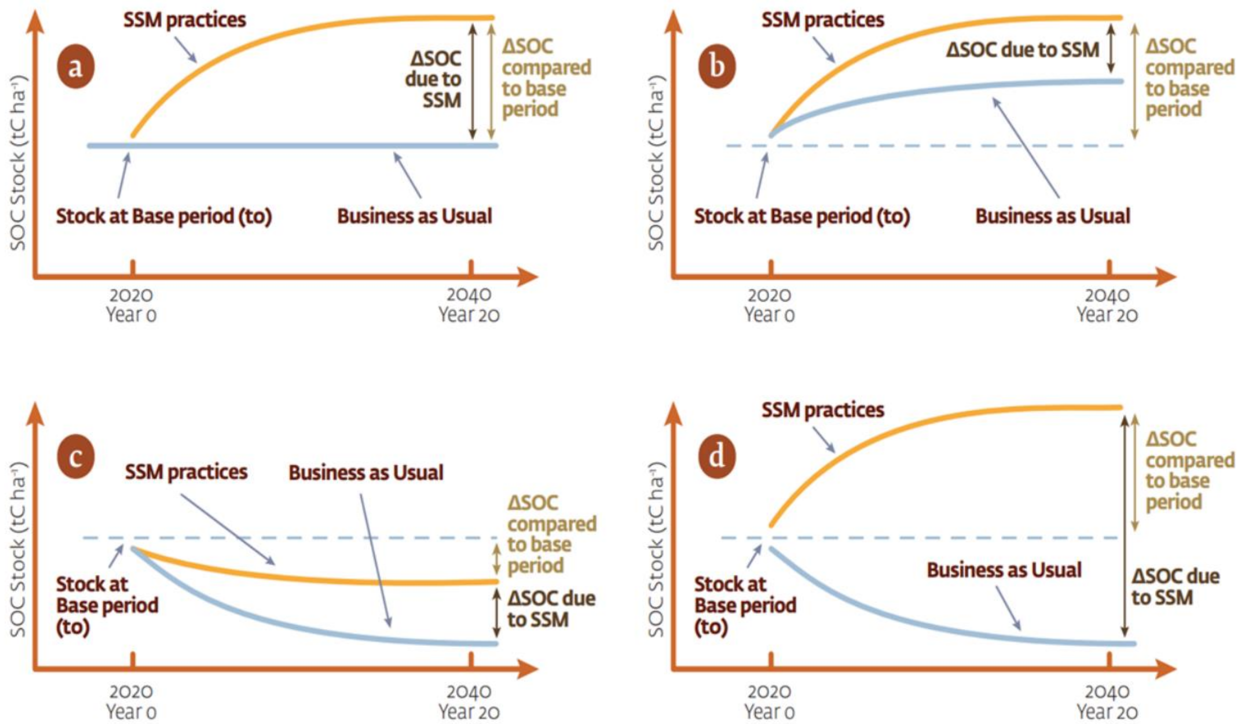

Figure 1. Soil organic carbon theoretical evolutions under business-as-usual (BAU) practices as compared to the adoption of sustainable soil management (SSM) practices. Every graph represents a different scenario: (a) lands where SOC levels have reached equilibrium and it is possible to increase levels through SSM; (b) lands where SOC is increasing but can be further increased through SSM; (c) lands where SOC is decreasing and it is possible to stop or mitigate losses in SOC levels, or (d) even reverse such fall through SSM. Source: FAO. 2022. Global Soil Organic Carbon Sequestration Potential Map – GSOCseq v.1.1. Technical report. Rome. https://doi.org/10.4060/cb9002en

From a positive ΔSOC value calculated using the *pair comparison method* it is only possible to infer that the sustainable management practice is slowing carbon losses in the soil (Figure 1. c) compared to the business-as-usual trend, unless there is evidence that the SOC STOCK in the business-as-usual (BAU) was in equilibrium-state at the beginning of the experiment (neither losing nor gaining carbon, Figure 1. a). In the other conditions (see "1b", "1c" and "1d"), without the initial SOC level measurement, it is not possible to determine whether a positive ΔSOC_{REL} is connected to an increase in SOC stock or to a mitigation of losses.

Therefore, in accordance with FAO (2022), in this report we will refer to the ΔSOCs calculated by implementing the STOCK difference method as "absolute carbon sequestration rate" (ΔSOC_{ABS}) while those calculated by implementing the pair comparison method as " carbon retention rate" (ΔSOC_{REL}).

1.3 Soil organic carbon stock calculation

In the absence of both the carbon sequestration/retention rate (ΔSOC_{ABS}; ΔSOC_{REL}) and the SOC STOCKs for control or treatment plots, the organic carbon stored in the soil was calculated by applying the following equation:

SOC STOCK = BD x OC x dm (eq. 4)

where:

BD: soil bulk density in the sampled soil profile, expressed as t_{soil}/m^3

OC: organic carbon concentration, expressed as g/kg or kg/t

dm: sampling depth, expressed as decimeters

1.4 Conversion of soil organic matter concentration into SOC

The following equation was used to convert soil organic matter concentration (SOM) values to soil organic carbon concentration (SOC) (Nelson & Sommers, 1982).

SOC = SOM / 1.72 (eq. 5)

1.5 Data harmonization - Climate, texture, thickness and sampling depth

Owing to the heterogeneity in the classification system of certain environmental parameters across the reviewed studies, we proceeded to reclassify soil texture by converting the percentages of sand, silt and clay into the USDA soil texture classes (USDA, online source). For climate standardization we agreed on the use of the European climatic stratification described by Metzger *et al* (2005) with adjoint dataset (Metzger, 2018): based on its geographical coordinates, each experimental station was assigned one of the climatic classes identified by the aforementioned study.

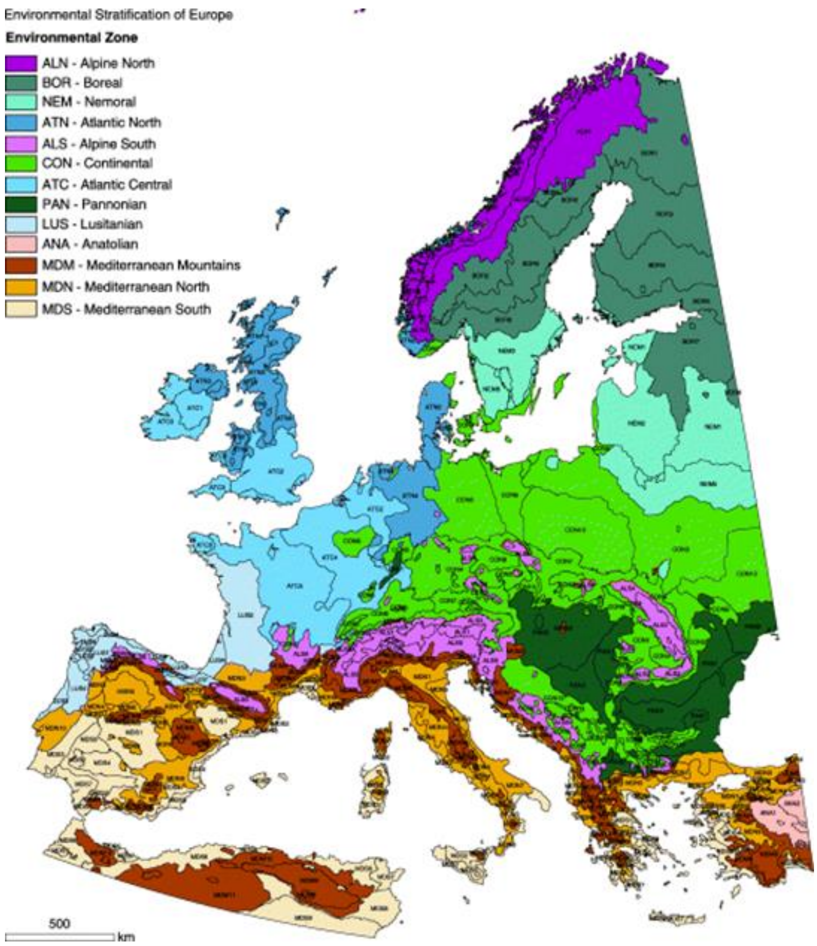

Figure 1. The Environmental Stratification of Europe. From: Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005). "A climatic stratification of the environment of Europe". Global Ecology and Biogeography 14: 549-563

In order to enable comparisons and aggregation of ΔSOC measurements across different studies, we harmonized the reporting of carbon sequestration/retention rates at the surface soil depth 0-30 cm. In the case of ΔSOCs stemming from samplings carried out at depths greater than 30 cm we applied proportional rescaling, that is, we assumed organic carbon (OC) as a constant function of soil depth. In contrast, so as to avoid the risk of overestimation, no rescaling was applied to ΔSOCs from samplings obtained at depths lower than 30 cm under the assumption that for these more superficial samplings the observed sequestered/retained carbon represents all and only the carbon sequestered/retained in the 0-30 cm soil depth.

1.6 Data aggregation

Absolute carbon sequestration rates (ΔSOC_{ABS}) obtained via the *STOCK difference method* were treated separately from carbon retention rates (ΔSOC_{REL}) obtained via the *pairwise comparison method*. Carbon-farming practices were initially grouped according to the maximum degree of detail/specificity (e.g.: no-tillage, minimum tillage, reduced tillage) and subsequently clustered into broader practice categories (to continue the example: reduced soil disturbance practices). ΔSOC_{REL}s were aggregated for distinct combinations of treatment macro-category and control macro-category: because they incorporate a difference from a control condition, it is not possible to aggregate ΔSOC_{REL}s for a given practice evaluated with respect to different controls. Such principle does not apply to ΔSOC_{ABS}s, as the latter are calculated by difference from the baseline *SOC STOCK t_0* value of the treatment plot.

1.7 Selection of carbon-farming practices for the Lombardy pedo-climatic context

In order to estimate the effect of carbon farming practices in the Lombard pedo-climatic context, the data were filtered and grouped according to the following *multistep procedure*:

- Selection of the experimental studies conducted in the 3 climatic zones of Lombardy (Mediterranean North, Mediterranean Mountain, and Alpine South);
- Clustering of studies at the preceding point into the 4 soil texture groups representative of the Lombard agricultural context:
  1. Sandy Loam – Sand - Loamy Sand
  2. Loam
  3. Clay Loam – Clay - Sandy Clay Loam - Sandy Clay
  4. Silt Loam - Silty Clay Loam - Silty Clay
- Exclusion of all practices whose meta-data were obtained from less than 3 ΔSOC_{ABS}/ΔSOC_{REL}.
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2. RESULTS

Based on the above selection/classification procedure, 15 carbon-farming practices applicable to annual crops were selected for Lombardy (table 3a.), together with 3 practices applicable to perennial crops (table 4a.). For all the remaining/excluded practices, it is possible to refer to the meta-data obtained from the general database of experimental studies conducted in Europe (tables 3b and 4b). Indeed, the scant availability of experimental studies matching the specific pedo-climatic conditions of the Lombard agricultural environment should not limit the assessment/promotion of practices that have shown potential for carbon soil sequestration or emissions mitigation in other European climatic conditions.

The further classification of practices according to the specific texture classes found in Lombardy is reported only as an attachment (ANNEX 1) and will be discussed in the context of action A4.

2.1 Table of carbon-farming practices for annual crops for the Lombardy pedo-climatic context

3a. CARBON SEQUESTRATION/RETENTION RATE (tC ha^{-1} yr^{-1}) FOR C-FARMING PRACTICES -ANNUAL CROPS - LOMBARDY						
	CONTROL	*PRACTICE*	AVERAGE	MEDIAN	n. VALUES	DATA SOURCE
1.	-OA	OA	0.54	0.41	8	Maris *et al.* (2021); Ceotto *et al.* (2006); Nardi *et al.*, (2004); Farina *et al.*, (2018)
2.	-R	R	0.15	0.15	6	Morari *et al.*, (2006); Lugato *et al.*, (2006); Troccoli *et al.*, (2022)
3.	BS	-BS	0.51	0.45	16	Maris *et al.* (2021); Mazzoncini *et al.*, (2011); Plaza-Bonilla *et al.*, (2016); Fiorini *et al.*, (2022); Forte *et al.*, (2017); Farina *et al.*, (2018); Perego *et al.*, (2019)
4.	BS	CC (GM) / (Mu) + OA	0.98	0.97	4	Farina *et al.*, (2018)
5.	CF	OA	0.68	0.52	4	Morari *et al.*, (2006); Forte *et al.*, (2017)
6.	CONV	CONS	0.68	0.70	5	Brenna *et al.*, (2016); Brenna *et al.*, (2010),
7.	CONV	ORG	0.94	0.92	7	Sacco *et al.*, (2015); Lazzerini *et al.*, (2014); Farina *et al.*, (2018)

8.	CRO	LUC / SET-A-SIDE	1.28	1.03	12	Maris *et al.* (2021); Alberti *et al.*, (2011); Chiti *et al.*, (2018); Brenna *et al.*, (2010)
9.	CT	RSD	0.31	0.23	24	Cillis *et al.*, (2018); Fiorini *et al.*, (2020); Mazzoncini *et al.*, (2016); Álvaro-Fuentes *et al.*, (2007, 2008, 2014); Troccoli *et al.*, (2022); Francaviglia *et al.*, (2008); Perego *et al.*, (2019); Plaza-Bonilla *et al.*, (2010).
10.	CT-R	RSD + R	0.68	0.53	23	Sombrero& D e Benito, (2010); Fiorini *et al.*, (2020); Álvaro-Fuentes *et al.*, (2006); Sanctis *et al.*, (2012).
11.	SOC STOCK$_{t0}$	CONS *	0.73	0.84	5	Fiorini *et al.*, (2022).
12.	SOC STOCK$_{t0}$	CC (GM) / (Mu) + OA *	1.00	0.96	3	Farina *et al.*, (2018).
13.	SOC STOCK$_{t0}$	OA *	0.50	0.36	4	Bertora *et al.*, (2009).
14.	SOC STOCK$_{t0}$	ORG *	0.85	0.91	4	Lazzerini *et al.*, (2014); Farina *et al.*, (2018).
15.	SOC STOCK$_{t0}$	RSD + CC (Mu) + R + CF + IR *	0.82	0.84	5	Mazzoncini *et al.*, (2011); Fiorini *et al.*, (2022).
3b. CARBON SEQUESTRATION/RETENTION RATE (tC ha^{-1} yr^{-1}) FOR C-FARMING PRACTICES - ANNUAL CROPS – EUROPE						
	CONTROL	*PRACTICE*	AVERAGE	MEDIAN	n. VALUES	DATA SOURCE
16.	CCS	IR	0.21	0.15	7	Manojlović *et al.*, (2008); Holeplass *et al.*, (2004); Martinello *et al.*, (2012).

17.	CCS	DC	0.10	-0.19	8	Sanchez-Navarro *et al.,* (2020).
18.	CT + CCS	RSD + IR	0.14	0.10	6	Hernanz Martos *et al.*, (2002); Lopez-Fando & Pardo (2001).
19.	MC	INT (GM)	0.28	0.25	6	Poeplau *et al.*, (2015)
20	CT + BS	RSD + CC (Mu)	0.49	0.55	3	Autret, *et al.*, (2016); Mazzoncini *et al.*, (2011); Perego *et al.*, (2019)
21.	SOC STOCK$_{t0}$	R *	0.16	0.12	3	Triberti *et al.*, (2008); Bertora *et al.*, (2009).

Table 3. The upper part of the table (**3a.**) reports mean and median ΔSOC values for carbon farming practices applied to annual crops that are *relevant to Lombardy*, provided a minimum of 3 observations. The lower part of the table (**3b.**) reports mean and median ΔSOC values from *European studies* on carbon farming practices applied to annual crops, provided a minimum of 3 observations.
Note: the sign (-) indicates a subtraction and corresponds to non-application of the given practice; the sign (+) indicates an additional practice. The sign (/) indicates either one or the other practice but not both at the same time (exclusive disjunction).
* a star is attributed to ΔSOC_{ABS} (as opposed to ΔSOC_{REL})

2.2 Table of carbon-farming practices for perennial crops for the Lombardy pedo-climatic context

4a. CARBON SEQUESTRATION/RETENTION RATE (tC ha^{-1} yr^{-1}) FOR C-FARMING PRACTICES - PERENNIAL CROPS – LOMBARDY						
	CONTROL	*PRACTICE*	AVERAGE	MEDIAN	n. VALUES	DATA SOURCE

1.	BS	CC (GM/Mu/Gr)	1.04	0.91	4	Ramos *et al.*, (2010); Almagro *et al.*, (2016).
2.	CF	OA	2.39	1.12	4	Regni *et al.*, (2017); Baldi *et al.*, (2018).
3.	CT + BS	RSD + CC (Mu)	1.13	1.34	5	Peregrina et al., (2010); Cucci et al., (2016); Nieto et al., (2012)
4b. CARBON SEQUESTRATION/RETENTION RATE (tC ha^{-1} yr^{-1}) FOR C-FARMING PRACTICES - PERENNIAL CROPS – EUROPE						
	CONTROL	*PRACTICE*	AVERAGE	MEDIAN	n. VALUES	DATA SOURCE
4.	-OA	OA	2.35	1.40	4	Lozano-García & Parras-Alcántara (2013).
5.	-R	R.	7.01	5.3	4	Rodríguez-Entrena *et al.*, 2012; Lozano-García & Parras-Alcántara (2013).
6.	SOC STOCK$_{t0}$	CC (GM) / (Mu) *	0.64	0.58	4	Cucci *et al.*, (2016); Repullo-Ruibérriz de Torres *et al* (2021); Garcia *et al.*, (2013).
7.		ORG *	0.73	0.63	8	Mohamad *et al.*, (2016); Novara *et al.*, (2019);
8.		RSD + CC (Mu) *	2.06	1.36	21	Garcia *et al.*, (2013); Lopez-Bellido *et al.*, (2016); Repullo-Ruiberriz De Torres *et al.*, (2018); Ruibérriz *et al.*, (2012); Sastre *et al.*, (2018).

Table 4. The upper part of the table (**4a.**) reports mean and median ΔSOC values for carbon farming practices applied to *perennial crops* that are *relevant to Lombardy*, provided a minimum of 3 observations. The lower part of the table (4**b.**) reports mean and median ΔSOC values from *European studies* on carbon farming practices applied to *perennial crops*, provided a minimum of 3 observations.
Note: the sign (-) indicates a subtraction and corresponds to non-application of the given practice; the sign (+) indicates an additional practice. The sign (/) indicates either one or the other practice but not both at the same time (exclusive disjunction). OA group includes fresh and composted olive-mill waste. R group includes olive leaves cleanings from the mill-factory.
* a star is attributed to ΔSOC_{ABS} (as opposed to ΔSOC_{REL}).

Legend for controls

-OA	Absence of organic amendment
-R	Removal of crop residues
BS	Bare soil between crop rotations characterized by the absence of vegetation (application of herbicides or plowing)
CCS	Continuous cropping systems: monoculture (i.e., growing one crop species in a field at a time) and continuous cropping (same crop every year in the same field)
CCS-R	Continuous cropping systems associated with the removal of crop residues
CF	Application of inorganic fertilizer
CONV	Conventional crop management (plowing, continuous cropping systems, application of inorganic fertilizer, bare fallow between crop rotations)
CRO	Annual cropland as land-use category
CT	Conventional tillage (moldboard plowing)
CT-R	Conventional tillage associated with the removal of crop residues
CT + BS	Conventional tillage with presence of bare fallow in annual cropland or bare soil in perennial cropland
CT + BS + CCS	Conventional tillage with presence of bare fallow in annual cropland associated with continuous cropping systems
SOCK STOCK	Soil carbon stock at baseline, i.e., prior to the implementation of a carbon-farming practice
MC	Monoculture, i.e., growing one crop species in a field at a time (as opposed to inter-cropping and multiple-cropping systems)
CT + CCS	Conventional tillage with continuous cropping systems

Legend for practices

OA	Application of organic fertilizer (farmyard manure / compost / anaerobic digestate)
R.	Maintenance of crop residues in the field
-BS	Avoiding bare soil and bare fallow by introducing green manure or mulch cover crops
GM / Mu + OA	Green manure or mulch cover crops associated with the application of organic amendment
IR	Improved crop rotation (against continuous cropping)
R + IR	Crop rotations associated with the maintenance of crop residues
CONS	Conservation agriculture (no-till, minimum till or reduced tillage, combined with maintenance of crop residues, crop rotations and cover crops, inorganic fertilizer and herbicides application)
ORG	Organic farming (conventional tillage, crop rotation, organic fertilizer, maintenance of crop residues, green manure cover crops, absence of synthetic fertilizers and herbicides)
LUC / SET A SIDE	Conversion from annual cropland to perennial cropland or set-a-side of cropland
RSD	Reduction of soil disturbance (no-till, minimum till or reduced tillage at depths less than 25 cm, without inversion of the soil layers)
RSD + R	Reduction of soil disturbance and maintenance of crop residues
RSD + CC (Mu)	Reduction of soil disturbance and cover crops as living or dead mulch
RSD + CC (Mu) + IR	Reduction of soil disturbance and cover crops as living or dead mulch associated with crop rotations
RSD + CC (Mu) + R + IR	Reduction of soil disturbance and cover crops as living or dead mulch associated with crop rotations and maintenance of crop residues
GM / Mu + OA	Cover crops as green manure or mulch and application of organic amendment
RSD + CC (Mu) + R + CF + IR	Reduction of soil disturbance, cover crops as green manure or mulch, crop rotations, maintenance of crop residues and application of inorganic fertilizer
INT (GM)	Cover crops intercropped with the main crop and used for green manure
DC	Double cropping of crops of economic interest without the presence of bare fallow

3. DISCUSSION

3.1 Annual crops - Practices that lead to an increase in carbon stocks

Based on the results of our research and selection of practices for the Lombardy Region (Table 3a.), the introduction of cover crops for green manure and/or mulch combined with the application of high inputs (20-40 t / ha / yr) of farmyard manure or compost (GM / Mu + OA) show the highest carbon sequestration potential in soils, equal to 0.96 tC ha^{-1} yr^{-1}. However, this estimate presents a high degree of uncertainty, since the value is obtained from only n = 3 data entries, and thus requires further investigation and experimental studies. The application of organic fertilizer (OA), as a single practice, results in an annual increase of carbon per hectare (ΔSOC_{ABS}) of 0.36 tC ha^{-1} yr^{-1}, with greater effects for biochar, compost, mature manure and anaerobic digestate than for slurry, by virtue of the high content of recalcitrant and humified substances. Although experimental studies on biochar, charcoal and anaerobic digestate are lacking for the MDM, MDN and ALS European climatic zones, we suggest further investigation on SOC effects for such amendments. Indeed, biochar has a long-permanence in mineral soil, and the effects on SOC may last for centuries due to highly recalcitrant organic carbon content (Gross, *et al.*, 2021) while anaerobic digestate may offset emissions for fossil fuel since it is coupled with biogas production (Møller et al., 2009).

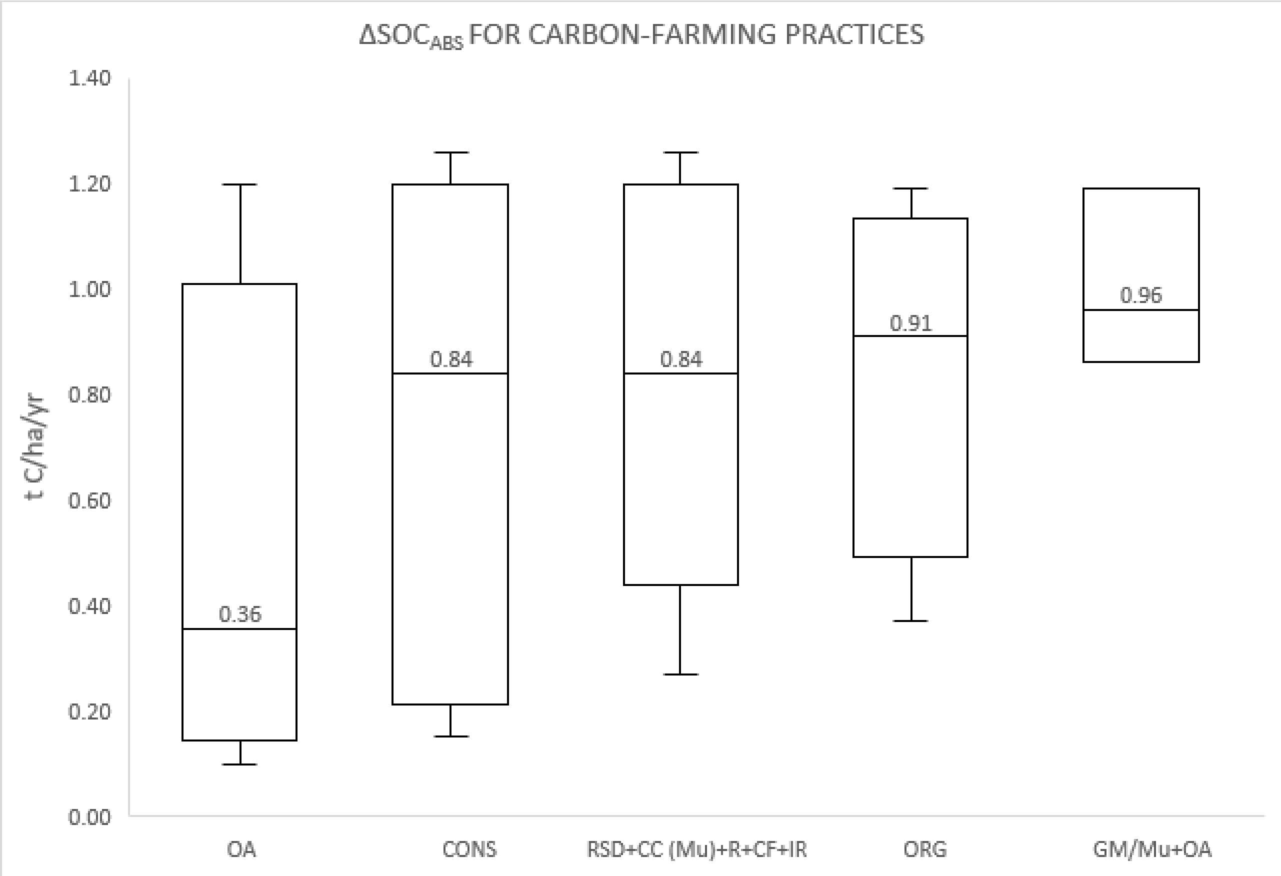


Figure 1. ΔSOC_{ABS} median values associated with single agronomic practices, combinations of practices and agronomic management for *annual croplands* in Lombardy Region
where:
OA: Mature farmyard manure or compost
CONS: Conservation agriculture (either no-till, minimum till or reduced tillage, combined with maintenance of crop residues, crop rotations and cover crops, inorganic fertilizer and herbicides application)
RSD + CC (Mu) + R + CF + IR: Reduction of soil disturbance, cover crops as green manure or mulch, crop rotations, maintenance of crop residues and application of inorganic fertilizer
ORG: Organic farming (i.e., conventional tillage, crop rotation, organic fertilizer, maintenance of crop residues, green manure cover crops, absence of synthetic fertilizers and herbicides)
GM / Mu + OA: Cover crops as green manure or mulch, and application of organic amendment

Conservation farming and organic farming show a consistent annual increase in carbon stocks, equal to 0.84 and 0.91 tC ha^{-1} respectively. In fact, these management choices involve the application of a series of practices capable of sequestering CO_2 and/or mitigating its release from the soil. The practices adopted in the studies evaluating the effect of conservation agriculture on the increase of carbon stocks refer to a combination of reduced soil disturbance (RSD), mulch cover crops (CC (Mu)), crop residue maintenance in the fields (+ R), crop rotations (IR) and use of synthetic fertilizers, so much so that the median value of ΔSOC_{ABS} associated with management in conservation agriculture corresponds to the ΔSOC_{ABS} value of the combination of these practices (RSD + CC (Mu) + R + CF + IR). It should be noted, however, that the carbon farming potential of conservation farming techniques is limited by the use of synthetic fertilizers and herbicides (practices that reduce carbon stocks) and by an increased release of methane and nitrous oxides in anaerobic conditions as a result of no-till on clayey substrates and in humid climates.

In organic farming, despite plowing, the combination of crop rotations (IR), crop residues (+ R), humified fertilizers of organic origin (OA), and green manure (CC (GM)), results in a somewhat more positive effect on organic carbon in the soil, probably due to the high input of manure/compost aimed at not compromising yields vis-à-vis conventional management crops. It can be inferred that organic agricultural management with a high input of organic fertilizer (20-40 t / ha / year), combined with the introduction of the mulching technique and a reduction in soil disturbance and/or the frequency of mechanical tillage (especially in soils subject to severe erosion), may represent the agronomic management practice with greater potential in arable land used for annual crops.

3.2 Annual crops - Reduction of C-CO 2 emissions

3.2.1. The use of cover crops to avoid bare fallow

Bare fallow in crop rotation, which is generally plowed and kept free from vegetation (BS: *bare soil*), is subject to erosion, leaching and percolation of mineral nutrients with progressive loss of organic carbon. Francaviglia *et al* (2017) in their review of experimental studies for arable crops in the Mediterranean Basin countries estimate a loss of 0.11 t C ha^{-1} yr^{-1} for bare fallow periods.

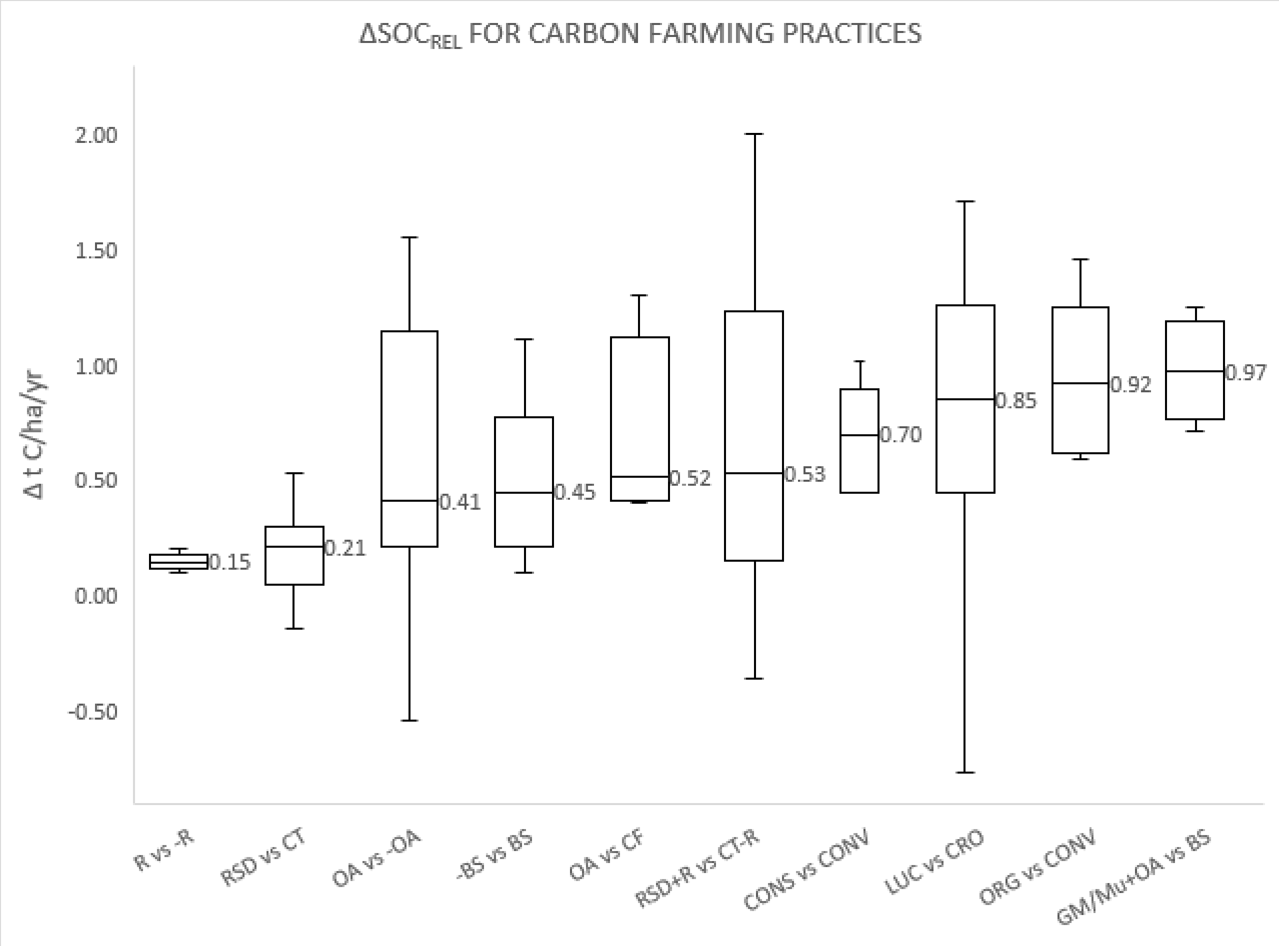


Figure 2. Median values of ΔSOC_{REL} for annual crops associated with single agronomic practices, combinations of practices and agronomic management

In our review we estimate a positive ΔSOC_{REL} of 0.45 t C ha^{-1} yr^{-1} in annual croplands for the introduction of green manure or mulch cover crops (-BS) with respect to bare fallow (BS), and of 0.97 if the former practices are supplemented with the application of organic amendment (CC (GM / Mu) + OA). The introduction of green manure or mulch cover crops, as a single practice or in combination with other practices, by virtue of the contribution of biomass to the soil, shows in all cases a clear mitigation effect on the loss of organic carbon that results from bare fallow. The effect of incorporating the biomass of cover crops depends primarily on the quantity and quality (C/N ratio) of biomass incorporated and on the time of cover crop termination. Some authors (Martens, 2000; Lorenz & Lal, 2005; Triberti *et al.*, 2016) argue that the higher the lignin content (which reaches a maximum in the final stages of the vegetative cycle of a plant species), the higher the C/N ratio (which is high in grasses, low in legumes) found in biomass soil inputs, and the more stable and recalcitrant is the organic carbon that forms in the soil.

In support of this thesis, Maris *et al* (2021) demonstrate a greater potential for carbon sequestration resulting from the use of rye compared to hairy vetch in a sandy-loam soil in the pedo-climatic context of Northern Italy. However, it should be noted that an imbalance in the C/N ratio can lead to negative agronomic effects: the decomposition of biomass with high C/N operated by the microfauna and telluric microflora leads to nitrogen immobilization with negative consequences for the growth and yield of marketable crops grown in succession. Conversely, following a 15-year experiment, Mazzoncini *et al* (2011) report greater increases in carbon stocks with the use of nitrogen-fixing cover crops (0.42 t C ha^{-1} yr^{-1} on average) compared to a mixture of grasses and brassicas (0.17 t C ha^{-1} yr^{-1}) in a sandy-loam soil in Central Italy. This effect is probably due to a greater productivity of the crops in rotation owing to the greater nitrogen supply of soils cultivated with nitrogen-fixing cover crops. A worldwide meta-analysis conducted by Jian *et al.*, (2020) reveals, on the contrary, a higher carbon sequestration of soil carbon for mixtures of species belonging to different botanical families (legumes, brassicas, grasses), followed by mono-species legumes, with an even lower sequestration rate for mono-species grasses. Regardless of the conflicting results on the effects on SOC reported by various authors, in relation to the botanical composition of cover crops, green manures undoubtedly represent an effective carbon-farming practice for transferring the CO_2 sequestered by plant biomass to the soil, and we therefore believe that the selection criteria of botanical species should be guided by the agronomic effects/agro-ecological functions that push the entrepreneur to make use of cover crops. These include the nitrogen-fixing function of legumes, the biofumigant function of brassicas, the anti-erosion function of fast-growing species with a high plant cover index, as well as the function of stable humus formation of grasses. Instead, the effect of double crops, the biomass of which is removed, according to our review remains doubtful (data not shown), thus requiring further studies.

3.2.2 Land-use change: transition from arable cropland to forage grassland or pastureland

The transition from annual arable cropland to secondary multiannual hay meadows or pastures (G/P vs CRO) is recognized by many authors as one of the most effective practices for increasing soil carbon stock (Freibauer *et al.*, 2004; Maris et al., 2021). Our review has found a delta of 0.85 t C ha^{-1} yr^{-1} for the conversion of cropland to pastures or multiannual meadows supplemented with inorganic fertilizer. Although these production systems are able to stock large quantities of organic carbon, the expansion of pastures and meadows cannot be considered a sustainable intervention not only because it subtracts soil from arable land that may be used for the production of human food, but also because animal husbandry, and in particular the production of meat and bovine, ovine and caprine derivatives, represents the agricultural sector with the highest impact on climate change, land use, the use of water resources and the loss of biodiversity. Furthermore, this review provides many examples of how proper cropland management can lead to the same, if not greater, carbon stock increases observed for pastures and grasslands.

3.2.3 Switching from conventional to organic or conservation agriculture

The annual difference in carbon stock we estimate for conservation and organic agricultural management compared to conventional agriculture is around 0.7 and 0.92 t C ha^{-1} yr^{-1}, respectively. In the presence of ΔSOC_{ABS} values, it is preferable to use the latter as estimates of net increases in carbon stocks (see section 3.1 of the present report).

3.2.4 Fertilizers and crop residues

The annual carbon difference per hectare observed in the 0-30 cm topsoil induced by the application of organic amendment relative to its non-application (OA vs -OA) is 0.41 tons; such difference increases to 0.52 tC ha^{-1} yr^{-1} when organic amendment is compared to inorganic soil fertilization (OA vs CF). Comparing the ΔSOC_{REL} (OA vs CF) with the ΔSOC_{ABS} (OA vs SOC STOCK) associated with the application of compost/manure it is possible to hypothesize that inorganic fertilization of the soil leads to a progressive loss of organic carbon, which Francaviglia *et al.* (2017) estimate at 0.17 tons per year per hectare. The maintenance of agricultural residues in the field (R), such as straw and stubble, after the cultivation of a cereal crop shows a small soil carbon retention potential (0.15 tC ha^{-1} yr^{-1}) compared to burning or the sale to third parties (-R), however, when combined with minimal/reduced tillage or no-tillage, the carbon loss mitigation potential in the 0-30 cm topsoil rises to 0.53 t C ha^{-1} yr^{-1} due to synergistic effect of the latter technique, which, by decreasing the disturbance of the soil, inhibits the rate of mineralization of the organic matter (RSD + R vs CT-R).

3.2.5. Reduction of soil disturbance

Techniques adopted in conservation agriculture for reducing soil disturbance (RSD) without inversion of the surface layers, which include non-tillage, minimum tillage and reduced tillage, demonstrate a mild ability to limit soil organic carbon losses compared to deep plowing (estimated at 0.21 t C ha^{-1} yr^{-1} in topsoil) as a consequence of a reduced mineralization of organic matter. Our review has not identified studies that evaluate the effects of stock increases (SOC STOCK difference method) for this technique as the latter is not an actual carbon-farming technique that sequestrates new organic carbon into the soil. Based on what can be learned from the analysis of extra-European studies (Powlson *et al.*, 2011 ; Powlson *et al.*, 2014), no-till or minimum-till cause an apparent increase in organic carbon on the soil surface versus deep plowing by virtue of three mechanisms:

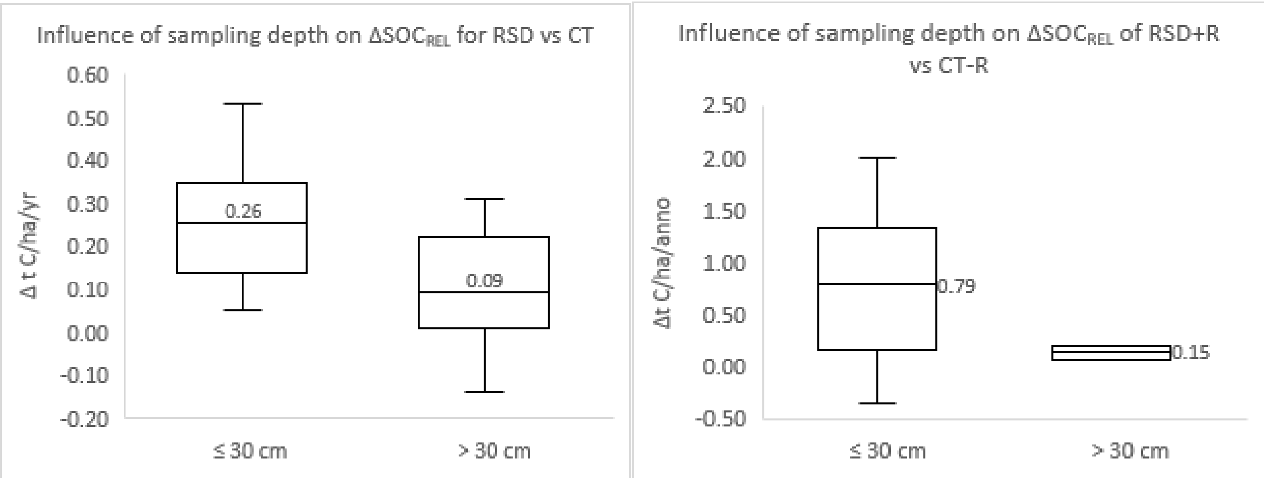
1) redistribution of organic matter in the first 20-25 centimeters of soil;

2) deceleration in the mineralization rate of organic matter due to a lower oxygen supply, and preservation of stable soil aggregates;

3) mitigation of soil erosion especially in the presence of moderate to steep slope plots.

Plowing, on the other hand, distributes and buries organic substance in deep soil layers -generally in the 30-60 cm layer, where the microbial activity is naturally low - by means of the mechanical operation of inverting soil layers. At the same time, plowed surfaces are highly prone to topsoil organic matter mineralization and losses through wind and water erosion in the presence of moderate to steep slope plots.

Taking note of the hypothesis that the carbon retention potential of no-till or minimum tillage compared to plowing has been overestimated, we proceeded to a further analysis of our data points, dividing the dataset into two based on the sampling depth of the associated studies.



Figures 3a, 3b. ΔSOC_{REL} associated to different sampling depths (≤ 30 cm vs. >30 cm) for reduced tillage compared to deep plowing (figure 3a), and for the combined action of reducing soil disturbance and maintenance of crop residues compared to deep plowing with removal of crop residues (figure 3b).

In the left part of each boxplot hereinabove (Figures 3a, 3b) we have grouped the ΔSOC_{REL} values for those studies that include only measurements taken at depths less than or equal to 30 cm (≤ 30 cm); in the right part of the boxplots are shown the data obtained from all and only the studies examined which include measurements taken at a depth greater than 30 cm (> 30 cm). As can be seen, the values for each practice differ considerably and depend on the soil profile investigated. In accordance with many reviews of the scientific literature and several experimental studies (Plaza-Bonilla *et al.*, 2010; Troccoli *et al.*, 2022; Sun *et al.*, 2011; Álvaro-Fuentes *et al.*, 2007; Álvaro-Fuentes *et al* 2008; Alcantara *et al.*, 2017), the sole techniques of no-till, minimum till or reduced-till, if not coupled with an input of organic matter (e.g., crop residues, biomass from cover crops, organic amendment), do not lead to an increase of carbon in the soil compared to plowing, but rather may possibly help to slow down carbon loss due to a deceleration in the mineralization activity of the organic matter.

Such slowdown is evident and significant only in studies investigating the superficial soil layers (up to 30 cm depth). In the few studies investigating the effect at greater depths (up to 60 cm depth), the effect is not statistically significant. This is due to the combination of burying organic matter in deep soil (>30 cm) by plowing and the low microbial activity that occurs in the subsoil. We believe that the data we have analyzed are not sufficient to classify no-till or minimum till as a carbon-farming practice, i.e., we have no evidence considering the entire soil profile (ideally, 0-100 cm) according to which no-till is a more virtuous practice than plowing in retaining organic soil carbon. However, when studies investigating the full soil profile detect a positive ΔSOC_{REL}

compared to conventional tillage, it is likely to be attributed to a mitigation of carbon emissions/or losses provoked by a combination of reduced mineralization and erosion rates. Given the current state of the art, the massive diffusion of this practice could lead, when compared to conventional tillage, to economic repercussions for producers (lower yields), soil compaction problems (and consequently increased greenhouse gas emissions generated in anaerobic conditions), as well as a greater impact on the health of ecosystems and humans due to an increase in the use of synthetic herbicides for weed control. Notwithstanding, it should be remembered that many environmental benefits are associated with conservative soil management techniques, including inhibition of erosive phenomena, increase in the hydraulic capacity of the soils, reversal of desertification, reduction in the use of fossil fuels, and preservation of the soil microbiome's habitat including of natural mycorrhizae.

3.3 Perennial crops - effect of agricultural practices on soil organic carbon

Orchards are agroecosystems capable of sequestering large quantities of CO_2 from the atmosphere, storing it both in soil and in woody biomass, when compared to annual crops, whose maximum soil sequestration potential is around 1 tC ha^{-1} yr^{-1} in the best-case scenario we have identified. The ability to accumulate carbon in the soil depends mainly on weed management along the row and in the inter-row space, debris management (e.g., burnt, left of the soil surface, converted into compost or biochar), and on the type of fertilizer applied. Permanent soil cover in the inter-row space terminated by means of green manuring, mowing and mulching in the phase of maximum growth (generally May) or, better still, by foraging of grazing cattle (CC (GM/GR)), leads to a ΔSOC_{REL} of 1 tC ha^{-1} yr^{-1} compared to bare soil (BS). If permanent vegetation cover is also associated with no-tillage or minimum tillage (CC (Mu) + RSD vs CT + BS), the increase compared to bare soil and frequent till rises up to 1.34 tC ha^{-1} yr^{-1}. This value is almost identical to the ΔSOC_{ABS} of 1.36 tC ha^{-1} yr^{-1} calculated though the SOC STOCK method for CC (MU) + RSD vs SOC STOCK, suggesting an equilibrium state for SOC STOCK even under conventional management of perennial crops.

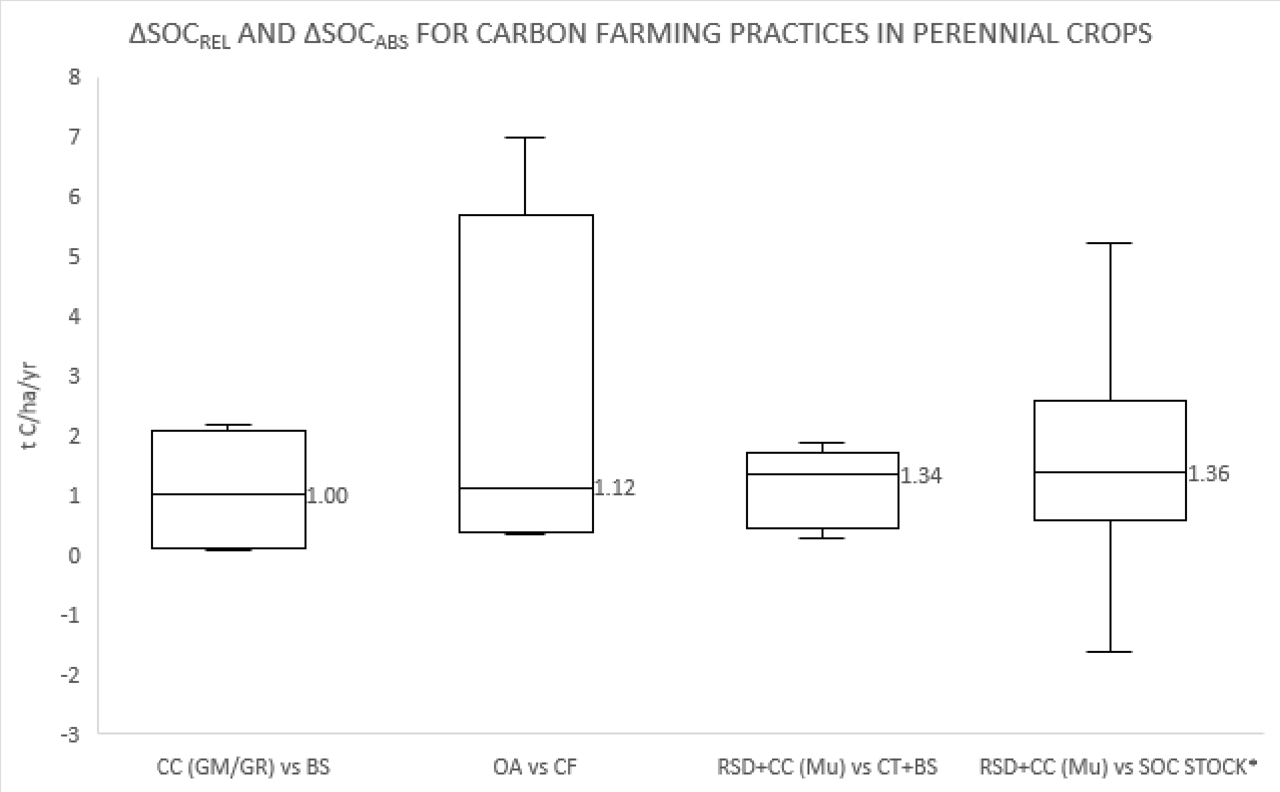


Figure 4. Median annual variations of organic carbon in the soil of perennial crops associated with single agronomic practices and combinations of practices.
* Note: For RSD + CC (Mu) vs SOC STOCK these are ΔSOC_{ABS} values referred to the European database: net increase rate of organic carbon compared to the baseline content.

As already reported for annual crops, replacing inorganic nitrogen fertilizer with organic amendment represents one of the most effective options in order to increase organic matter in the soil, meet crop nutritional requirements, and foster the chemical, biological and physical fertility of cultivated soils. The dataset that includes the ΔSOC_{REL} values selected for Lombardy incorporates only the effect of compost and olive pomace, and results in a median estimate of 1.12 tC ha^{-1} yr^{-1} compared to mineral fertilizer. In particular, Regni *et al.* (2017) report, following the application for eight consecutive years of 50 t ha^{-1} yr^{-1} of composted olive pomace together with pruning residues, an increase of almost 56 tons of carbon per hectare of olive grove. On the other hand, the application of an amount of fresh olive pomace equaling the carbon content of composted pomace, has been shown to lead to an annual increase of only 2.65 tC ha^{-1} yr^{-1}. This result supports the notion that it is the content of humic and recalcitrant substances that determines the effect on SOC of biomass incorporated in the soil.

3.4 Carbon storage in the woody biomass of orchards

Woody crops help to sequester atmospheric CO_2 by storing carbon in woody biomass through the process of photosynthesis; however, scientific studies aimed at measuring the carbon stock in orchards or agroforestry systems are poorly represented. Therefore, in order to quantify the contribution to carbon stock of arboreal orchard biomass - both aboveground biomass (AGB) and belowground biomass (BGB), we searched for recent systematic reviews or meta-analyzes on perennial crops in Europe.

We extracted from a systematic review, conducted in the Mediterranean basin and implemented during the LIFE MEDINET project (Chiti *et al.*, 2018b; 2018c), an average value of CARBON STOCK in AGB and BGB of 9.7 tC/ha for mature vineyards and 11.7 tC/ha for mature olive groves, excluding the contribution of pruning - which can have different destinations depending on the management technique – estimated at around 0.9 tC ha^{-1} yr^{-1} for vineyards and 2 tC ha^{-1} yr^{-1} for olive groves, regardless of the age group. For the remaining fruit tree species, carbon stock rises to 13 tC / ha in AGB and BGB, and 1.6 tC ha^{-1} yr^{-1} in mature pruning.

Considering an average production cycle of 20 years and applying the *STOCK difference method* to the results obtained from the aforementioned review, we obtained a ΔSOC_{ABS} of 0.58 tC ha^{-1} yr^{-1} for olive groves, 0.48 tC ha^{-1} yr^{-1} for vineyards and 0.65 tC ha^{-1} yr^{-1} for other fruit trees.

The results of our research for permanent crops highlight a potential for carbon sequestration from the entire agroecosystem (soil and biomass) of almost 3 tons per hectare per year in the presence of permanent soil cover managed with no- or minimum till combined with the application of organic amendment.

Tree Biomass Carbon Stock				
	AGB tC ha^{-1}	BGB tC ha^{-1}	AGB+BGB tC ha^{-1}	tC ha^{-1} yr^{-1} for 20 yrs
Olive groves	9.1	2.62	11.7	0.58
Vineyards	5.5	4.4	9.7	0.48
Fruit trees	8.39	4.62	13	0.65

Table 5. Carbon stock in Mediterranean perennial woody crops at maturity
From Chiti et al., (2018 b, 2018c)
Note: tC ha^{-1} yr^{-1} for 20 yrs (ΔSOC_{ABS}) derives from our elaboration for a 20-year orchard

4. CONCLUSIONS

Carbon sequestration in European cropland is an ambitious challenge, since conventional management seems to be leading to a progressive depletion of soil organic carbon pools. We are most likely decarbonizing the soil and carbonizing the atmosphere, as things currently stand. Reversing this trend is likely to occur only through a paradigm shift in agricultural management, which requires carbon-farming to become the new conventional management. The results of our research show how the synergic combination of organic and conservation practices, often referred to as 'Organic Regenerative Agriculture', represents a viable strategy in order to sequester CO_2 while ensuring current and future food supply needs.

In light of the evidence of high carbon sequestration rates by woody perennial systems and pastures, and in agreement with numerous authors (Montagnini & Nair, 2004; Ramachandran Nair *et al*, 2009; Lorenz & Lal 2014; De Stefano & Jacobson; 2018), we point to agroforestry systems, such as silvoarable and silvopastoral systems, as well as Organic Regenerative Agriculture (Newton *et al*, 2020) as the research frontier of carbon-farming in Europe.

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ANNEX 1

Selection of C-farming practices for Lombardy pedo-climatic strata

climate	soil code	control	treatment	n	mean	median	min	max	sd
MDM	2	BS	-BS	3	0.34	0.41	0.17	0.43	0.12
MDM	3	BS	-BS	4	0.73	0.85	0.12	1.11	0.38
MDM	3	SOC STOCK	CONS	5	0.73	0.84	0.15	1.26	0.45
MDM	3	SOC STOCK	RSD+CC (Mu)+R+CF+IR	4	0.88	0.99	0.27	1.26	0.38
MDN	2	-OA	OA	3	0.22	0.40	-0.54	0.79	0.56
MDN	4	-OA	OA	4	0.61	0.34	0.20	1.55	0.55
MDN	3	-R	R	5	0.16	0.15	0.12	0.20	0.03
MDN	2	BS	-BS	3	0.37	0.49	0.10	0.52	0.19
MDN	4	BS	GM/Mu+OA	4	0.98	0.97	0.71	1.25	0.19
MDN	4	BS	-BS	3	0.28	0.32	0.18	0.33	0.07
MDN	1	CONV	CONS	5	0.68	0.70	0.45	1.02	0.21
MDN	4	CONV	ORG	5	0.90	0.92	0.62	1.25	0.22
MDN	1	CRO	LUC/SET-A-SIDE	4	1.04	1.01	0.45	1.71	0.48
MDN	3	CRO	LUC/SET-A-SIDE	5	0.47	0.47	-0.77	1.31	0.70
MDN	1	CT	RSD	4	0.83	0.83	0.14	1.52	0.66
MDN	4	CT	RSD	16	0.21	0.23	0.03	0.53	0.13
MDN	2	CT-R	RSD+R	4	0.15	0.14	0.08	0.25	0.06
MDN	3	CT-R	RSD+R	11	1.00	1.14	0.21	1.53	0.41
MDN	4	CT-R	RSD+R	6	0.24	0.11	-0.36	1.54	0.61
MDN	2	G	OA+CF	4	0.23	-0.03	-0.54	1.52	0.83
MDN	2	SOC STOCK	OA	4	0.50	0.36	0.10	1.20	0.42
MDN	4	SOC STOCK	ORG	4	0.85	0.91	0.37	1.19	0.30
MDN	4	SOC STOCK	GM/Mu+OA	3	1.00	0.96	0.86	1.19	0.14

Where is it:

n: data entries

mean, median, min, max, sd are expressed as: $tC\ ha^{-1}\ yr^{-1}$

MDM: Mediterranean Mountain; MDN: Mediterranean North

* **1** texture class which includes Sandy Loam – Sand - Loamy Sand soils

* **2** texture class which includes Loam soils
* **3** texture class which includes Clay Loam – Clay - Sandy Clay Loam - Sandy Clay soils
* **4** texture class which includes Silt Loam - Silty Clay Loam - Silty