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Research article

Do poplar plantations enhance organic carbon stocks in arable soils? A comprehensive study from Northern Italy

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ABSTRACT

Soil organic carbon (SOC) depletion, primarily driven by land use change, is a global challenge influenced by factors such as climate, plant cultivation, and adopted management practices. Poplar plantations (PP), predominantly used for plywood and bioenergy production in the Mediterranean, have shown carbon (C) potential capture as biomass. However, their contribution to SOC and climate change mitigation remains understudied. Thus, this study evaluates the potential of PP in enhancing SOC stocks in arable soils in Northern Italy covering fifteen sites within six farms. SOC stocks under land use change were analyzed, at 0–10 and 10–30 cm soil depths, using the time-for-space substitution method (paired comparison), comparing cropland (CR) to PP, and spatial survey approach evaluating SOC after thirty years of PP. Additionally, conventional PP was also compared with c plantations (PC), which integrate diverse tree species supporting biodiversity and fostering sustainability. Results showed that PP maintains higher SOC stock than CR management, with significant variations observed in fifty percent of the cases. Relative SOC sequestration rates were 0.09 and 0.32 Mg C ha^{-1} year^{-1} at 0–10 and 10–30 depth, respectively. The mean SOC rate for PP was 0.75 Mg C ha^{-1} year^{-1} under stock differential methods, with the initial C loss observed in the early stages (1–5 years). PC demonstrated greater SOC stocks and sequestration rates, indicating its potential for climate change mitigation through European policies. Overall, this study shows PP has potential for C sequestration varies by sites. Further investigation into fertilization and deep-soil tillage is needed to understand their impact on SOC stocks. Moreover, direct engagement with PP farmers revealed supply chain issues, highlighting the need for sustainability improvement.

1. Introduction

Soils are regarded as the predominant reservoir for terrestrial carbon (C), comprising approximately two-thirds of the entire terrestrial C (Scharlemann et al., 2014), and depending on land management activities, they can act as a source or a sink (Lal, 2004; Scharlemann et al., 2014; Silva Neto et al., 2023). Across Europe, soils under grasslands, forests, and natural vegetation store C and serve as C sinks. In contrast, soils under agricultural land usually emit C due to higher mineralization rates in tilled soils and the reduced amount of organic materials retained or reintroduced to the fields as compost (European Commission, 2011). Land use and management strategies significantly influence C sequestration, with varying efficiency based on vegetation type and practices: C losses from terrestrial systems over the past 200 years were primarily due to converting grasslands and forests into agricultural land (IPCC, 2000).

Moreover, soils are essential for sustaining ecosystem productivity, biodiversity, and environmental services, thus addressing critical global issues including food security, sustainability, and climate change mitigation (Certini and Scalenghe, 2023; Vanino et al., 2023). The potential for soil organic C (SOC) sequestration is estimated at 23.8 Gt of CO_2 equivalent per year globally, with the potential to contribute 25% towards climate change mitigation efforts (Bossio et al., 2020). However, intensive conventional farming practices characterized by substantial use of synthetic agro-chemicals, tillage, and monoculture, have increased agricultural yields but have significantly detrimental effects

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on soil health and functionality over the long term (Liu et al., 2022; Ghiglieno et al., 2023; Ibáñez et al., 2024). Specifically, intensive tillage practices in conventional agriculture reduce SOC and involve the removal of crop residues, which leads to increased soil erosion and degradation (Hussain et al., 2021). Additionally, the use of agro-chemicals can harm soil microorganisms essential for nutrient cycling, such as phosphorus solubilization and nitrogen (N) fixation, potentially leading to shifts in microbial communities and negative effects like antimicrobial resistance (Mandal et al., 2020). Overall these practices result in significant reductions in SOC, and substantially contribute to global climate change (Valkama et al., 2020; Kumar et al., 2024), with SOC losses accounting for 30–60% of total soil C stock (Kopittke et al., 2019). To reduce SOC emissions, sustainable agricultural management practices are essential strategies (Longo et al., 2023). These practices not only ensure food security but also enhance soil C storage and mitigates greenhouse gas (GHG) emissions from agricultural activities (Kumar et al., 2024). In this context, European policies actively encourage the adoption of sustainable practices within the framework of the C farming initiative (European-Commission et al., 2021), to promote atmospheric CO_2 sequestration and boosting SOC reserves in agricultural soils. The C farming policies are specifically implemented through the C farming credits systems which allows farmers to earn C-credits for implementing practices that sequester C or reduce the emissions (e.g., agroforestry, silvopasture, afforestation, minimum tillage, crop rotation, composting, and the use of cover crops, etc). These credits can be used in the voluntary C market, providing farmers with additional economic, social, and environmental co-benefits (Harrison et al., 2021).

Land cover changes within the same category (e.g., transitioning from annual to perennial crops) or land use changes (e.g., converting grassland to perennial crops) significantly impact the C cycle and SOC stocks, potentially enhancing climate change mitigation efforts (Guo and Gifford, 2002; Arevalo et al., 2009; McClean et al., 2015; Deng et al., 2016). In the agricultural sector, the impact of land cover/land use changes on SOC has been investigated, particularly concerning the replacement of cropland (CR) or grassland with short rotation coppices (SRC) (Arevalo et al., 2009; Harris et al., 2017; Rösch et al., 2013). SRC crops, including fast-growing plantations like poplars or willows, are characterized by high-density tree planting and follow rotation cycles ranging from two to eight years (Berhongaray et al., 2017). This wood material is commonly used for bioenergy purposes. These types of land cover/land use changes have a contrasting impact on SOC stocks, with SOC stock increasing when SRC are established on croplands but decreasing when practiced on grasslands (Don et al., 2012), with SOC sequestration rates of 0.44 and −1.3 Mg C ha^{-1} yr^{-1}, respectively.

In Italy, more than fifty percent of plywood, packaging, pulp, paper, and wood-based panel enterprises source industrial hardwoods from poplar plantations (Puletti et al., 2019). Poplar is primarily cultivated in the Northern part of the Italian peninsula, covering a total area of 46, 125 ha (Corona et al., 2018), occupying about 1.3% of the entire national forest area at the country level (Vaglio Laurin et al., 2022). In comparison to annual crops, poplar plantation (PP) reduces adverse environmental impacts, decreases C emissions, and slightly enhances biodiversity (Cantamessa et al., 2022), despite natural forests exhibit significantly higher biodiversity (Porro et al., 2021).

In the Italian context, wood plantations are characterized by a varying rotation length: a) a very fast rotation cycle (2–5 years), for energy production, b) a fast rotation cycle (10-12 years, see Castro et al. (2014)), primarily for plywood production, and c) medium to long rotation cycles (20–40 years) aimed at producing high-quality wood in combination with other species (e.g., cherry, ash, walnut, oak).

The existing literature on the effects of poplar cultivation on SOC is limited, particularly regarding plantations designated for plywood production and longer rotation cycles (e.g., polycyclic plantations) that involve mixing poplar with other species. Our study is one of the few that explores these specific types of data. Polycyclic plantations (PC) consist of various tree crops with differing growth rates, such as walnuts in combination with different poplar varieties, enabling the production of diverse assortment from the same stand. Compared to traditional poplar stand cultivation, mixed plantations are regarded as more sustainable, as they enable output diversification and ensure consistent wood yields over time (Plutino et al., 2022).

Thus, the objective of this study is to bridge the knowledge gap in understanding SOC dynamics within the PP cultivated for the plywood industry, particularly in Mediterranean environments. The evaluation encompasses the following specific objectives: i) evaluate the land cover/land use change from cropland and grassland to PP in terms of SOC variation; ii) evaluate the impact of continuous PP on SOC stock resampling the same points in PP after 29 years, iii) evaluate the performance of PC in sequestering SOC after conversion from agriculture in comparison with conventional PP.

2. Materials and methods

The soil survey was conducted in the Lombardy region of Italy, specifically in the provinces of Mantova and Pavia. The selected sites are located in the Padano-Veneta floodplain along the Po Valley. All the areas are located in the Italian ecoregions 1-temperate division, 1B Po Plain Province (Blasi et al., 2014), with a mean annual temperature of 13.9 °C, and a mean annual precipitation of 930 mm (Torresani et al., 2022). The soils are mainly classified as Cambisol, Luvisol, and Fluvisol, according to the georeferenced database of the soil regions of Italy (Righini et al., 2002).

2.1. Sites description

The selected PP are conventionally managed featuring approximately 278 trees per hectare (ha^{-1}). After each harvesting of poplar, all the branch residues and tree stumps are either removed or shredded into the soil. The soil preparation for establishing new plantations involves deep ploughing (40–60 cm) followed by disc harrowing. The following operation is performed seasonally to remove weeds.

An exception in the management of the plantations was recorded for the site called 1-P19. In this latter site, PC were cultivated using poplars for plywood production (*Clone Populus xcanadensis* 'I-214') with 91 plants per hectare, mixed with numerous other tree varieties contributed to the overall planting density of 994 plants ha^{-1}. Additionally other plants, including walnuts (*Juglans regia* L.) and hybrid walnuts with 45 plants ha^{-1}, ash tree (*Fraxinus* spp) with 52 plants ha^{-1}, the English oak (*Quercus robur* L., *1753*) with 39 trees ha^{-1}, the black alder (*Alnus glutinosa* (L.) Gaertn.) with 331 trees ha^{-1}, the common elderberry or black elderberry (*Sambucus nigra* L.) with 130 trees ha^{-1}, the wild service tree (*Sorbus torminalis* L.) with 52 trees ha^{-1}, the pear tree (*Pyrus communis* L.) with 39 trees ha^{-1} and common hazel (*Corylus avellana* L.) with a density of 130 plants ha^{-1} were also planted. The PC rotation cycle was 10 years for the poplar and 20 years for all the other species.

Furthermore, the CR sites involved in this research were managed using conventional farming practices, which included mechanical tillage to prepare the soil for planting, as well as the application the application of synthetic fertilizers and pesticides to enhance yields and control pests and weeds. Minimal rotation alternating soybeans, wheat, and maize was implemented over consecutive years.

2.2. Experimental design

The experimental design to address the first specific objective involved selecting six farms across different locations in the Northern Italy, encompassing a total of eleven PP sites and four CR sites. Four of the six farms, including both PP and CR, facilitated the comparisons through the method of space-for-time substitution, as described by Georgiadis et al. (2017). This method involves, comparing the SOC stock of two experimental plots, that share identical site characteristics (e.g.

soil and climate type, slope, etc), at a single point in time. One site serves as the control, while the other site, referred to as the treatment, share the same type of land use/land cover and management as the control site. This treatment site has been converted to its current land use/land cover and management practices over a specified period. This method assumes that the C stock in the control plot represents the pre-treatment SOC stock of the treatment plot (Petersson et al., 2024). This method is among the most used in recent literature (Walter et al., 2015; Georgiadis et al., 2017; Rowe et al., 2016) for evaluating SOC differences between cropland and poplar plantations.

The selection of farms were determined based on the availability of SOC data on these farms from 1990, which served as our baseline for understanding the SOC accumulation over the 32-year of poplar cultivation, using the SOC stock difference method. Detailed information on the historical land use of individual sites is provided in Table 1. However, only farms including both PP and CR were selected for this analysis i.e. a total of three farms that cumulatively showed five PP at various ages and four agricultural fields considered as the base (0) year.

For the second specific objective, a subset of the eleven sites was selected, where SOC was measured over a period ranging from 16 to 28 years prior to our sampling. This test relies on the experimental difference from actual SOC sampled in 2022 with respect to the baseline represented from the old soil C measurements carried out in the same sites during 1996 and 2006. This allows a direct SOC comparison between the same areas at different times, such as the method used by (Rytter and Rytter, 2020). The acronyms for the site name in this study indicate specific information: the first number denotes the location, the letter 'P' signifies a poplar plantation, and the subsequent number indicates the age of the plantation. If two poplar stands within the same farm had the same age, an additional sequential number was added to differentiate the sites.

The third research objective was based on the existence of the polycyclic wood system between the sites selected for the current investigation. Notably, the latter site was sampled in the nineties, enabling the contemporary evaluation of its impact on SOC and highlighting a comparison with conventionally managed PP. Additionally, adjacent to the polycyclic site there was a cropland, allowing for the assessment of the impact of land cover change on SOC.

2.3. Soil sampling

The soil sampling was performed in November 2022 using a soil auger 7.0 cm in diameter. The sampling design is a modification of the protocol proposed by the Joint Research Center of the European Commission (Stolbovoy et al., 2007). Three square cells were chosen in each site using a pseudo-random sampling technique, supplying the requirement for non-contiguity of the cells. Soil samples ($n = 18$) were collected at two different depths, 0–10 cm and 10–30 cm in each plot. The sampling depth was determined according to the principles outlined by the Intergovernmental Panel on Climate Change (IPCC) standard sampling depth (Aalde et al., 2006). This depth is particularly significant as it typically represents the top soil layer where changes in SOC stock resulting from land-use changes or management practices are most pronounced and identifiable.

In the center of the plot, a small soil profile down to 50 cm depth was opened for the collection of the bulk density (BD) following the core method (Blake, 1965) at the same depth as the soil samples using a metal cylinder with a known volume (diameter = 5.0 cm, height = 5.0 cm, volume = 34.3 cm^3). In total 270 samples were collected, with 72 for the croplands, 180 for the poplar plantations, and 18 for the polycyclic plantations.

2.4. Sample preparation and analysis

The soil samples were then taken to the laboratory, oven dried at 60 °C until constant mass, and then sieved at 2 mm to separate the fine earth (i.e., the less than 2 mm soil fraction) from the possible presence of rock fragments, which were not detected. Bulk density samples were oven dried at 105 °C until constant mass and then weighed. The 2 mm samples were further grinded to fine powdered and used for SOC and N

Table 1
Specific site dependent information. Coordinates are expressed in decimal degrees while the following site characteristics are identical for each site: rotation length equal to 10 years, tree density of 278 plants per hectare, poplar clone Populus xcanadensis 'I-214'. Information about the previous land use is dated back to 1980 due to the specific land cover maps of Lombardy region (DUSAF) (Lombardia, ERSAF, 2010) and to photo interpretation made with Google Earth Imagery (© 2022 Google).

Site code	Site number	Age (year)	Latitude (°)	Longitude (°)	Current land use	Previous land use
1-CR	1	–	45.026	10.625	CR	CR since 1980
1-P19[b]		19	45.024	10.624	Polycyclic	CR from 1980 to 2003 Polycyclic plantation from 2004 to 2022
2-P3	2	3	45.138	9.285	Poplar	PP from 1980
2-CR		–	45.140	9.279	CR	PP from 1980 to 1990 CR from 1990 to 1999 PP from 1999 to 2009 CR from 2009 to 2022
2-P10		10	45.133	9.285	Poplar	PP since 1980
2-P7		7	45.129	9.285	Poplar	PP since 1980
3-CR	3	–	45.073	10.350	CR	Data Not available from 1980 to 1999 CR from 1999 to 2022
3-P9		9	45.073	10.351	Poplar	PP since 1980
4-P9[a]	4	9	44.964	10.646	Poplar	PP in 1980 CR from 1980 to 1994 PP from 1994 to 2022
4-P4[a]		4	44.964	10.644	Poplar	PP from 1980 to 1994 CR from 1994 to 2010 PP from 2010 to 2022
4-CR[a]		–	45.956	10.647	CR	PP from 1980 to 2021 CR in 2022
5-P1-1[a]	5	1	45.018	10.649	Poplar	PP since 1980
5-P1-2[a]		1	45.023	10.655	Poplar	PP since 1980
6-P1[a]	6	1	45.036	10.645	Poplar	PP since 1980
6-P10[a]		10	45.031	10.656	Poplar	PP since 1980

[a] Indicate that those PP are not included in the land use change investigation since they lack the CR field needed for comparison with poplar and the case of the site n° 4, where the land was designated as cropland just a year before the measurements, making it no longer appropriate to classify it as genuine cropland.
[b] indicates that this plantation is managed following polycyclic arboriculture principles (Plutino et al., 2022).

analyses through a CHN-Elemental Analyser (Thermo-Finnigan Flash EA112 CHN). Before the analyses, the inorganic C from the soil was eliminated by adding a 10% HCl solution. The SOC stock was calculated as follows (Boone et al., 1999):

$$SOC\ stock\ \left(Mg\ ha^{-1}\right) = \Sigma \left[SOC\ x\ BD\ x\ Depth\ x\ \left(1 - \left(\frac{Frag}{100}\right)\right)\right] \quad (1)$$

Where *SOC stock* is the SOC pool in megagram per hectare (Mg ha^{-1}), *SOC* is the concentration in a soil sample (kilograms of C per kilogram soil), *BD* is the soil density of the fine earth (Mg m^{-3}), *depth* is the thickness of the layer within the considered soil section (cm) while *Frag* indicates the percent of rock fragments.

SOC sequestration rates within the land use change analysis are calculated by dividing the mean difference in SOC stock between PP and CR by the number of years from the poplar establishment. We used the sample function in RStudio (RStudio Team, 2023) to obtain a state of random mating between the SOC data sampled in the CR and the PP: the pairs of raw values that have been compared considering the two-land use are randomly established within the row data. Regarding the sampling conducted during the 1990s, the data pertained to soil horizons with different thickness across different sites. Therefore, the data were harmonized to 30 cm depth to facilitate comparison with contemporary sampling. In some cases of the samplings conducted in the 1990s, data were available only for soil organic matter (SOM), which was converted to SOC using a factor of 1.72 (Nelson and Sommers, 1996). The SOC sequestration rate, expressed as megagram C per hectare per year (Mg C ha^{-1} yr^{-1}), was calculated by dividing the difference in total SOC stock at a depth of 30 cm (Mg ha^{-1}) of PP by the years they have been cultivated.

2.5. Statistics

Statistical analyses were conducted for each soil depth. The normality of the data was assessed using the Shapiro–Wilk Test. Given the non-normal distribution of the data, a Mann–Whitney *U* test was employed, considering all raw data, to compare SOC stock differences between PP and among PP and CR. Statistical significance was determined at $p < 0.05$. All statistical analyses, as well as descriptive data statistics, were performed using the R statistical program (R Core Team, 2020) version 4.0.0 2020-04-24- "Arbor Day" and RStudio 2023.03.1 + 446 "Cherry Blossom" release (RStudio Team, 2023).

C rates calculated in the land use change analysis with the method of time for space substitution are expressed in Mg C ha^{-1} yr^{-1}, with the relative uncertainty. Notably, no statistical analysis was applied to the estimation of SOC rates due to continuous PP, because the 1990s data provided only a single value measured per site, making the statistical analysis inapplicable.

3. Results and discussions

The analysis of the results related to SOC dynamics, evaluated through the SOC stock change method and the paired plot method, adheres to the definitions provided by (Peralta et al., 2022; Petersson et al., 2024). The former articles provides guidance on when it is appropriate to use terms such as SOC sequestration, soil CO_2 emission reduction, SOC retention, and SOC accumulation, while referring to "absolute SOC stock change" (ΔSOC_{ABS}) when applying the "stock difference method" and as "relative SOC stock change" (ΔSOC_{REL}), when employing the paired comparison method in soil analysis. Detailed information about all data collected from the various sites, including bulk density, SOC stock values, C concentrations, and all relevant statistics, are provided in Table 2.

Table 2
SOC stock (Mg ha^{-1}) for the investigated soil depths at the different sites. Bulk density is averaged on a total of 9 samples for each site at each soil depth. The terminology used indicates the following: BD (bulk density), BD_{sd} (bulk density standard deviation), C (carbon concentration), Csd (carbon concentration standard deviation), SOC_{sd} (SOC stock standard deviation).

Site	Soil depth	BD	BD_{sd}	C	C_{sd}	SOC stock	SOC_{sd}
	cm	Mg m^{-3}		%		Mg ha^{-1}	
1-CR	0–10	1.25	0.04	1.48	0.13	18.38	1.5
1-CR	10–30	1.35	0.14	1.45	0.23	39.83	9.1
1-P19	0–10	0.98	0.08	2.10	0.34	20.66	4.3
1-P19	10–30	1.19	0.11	2.32	0.36	55.19	11.0
2-CR	0–10	1.08	0.11	1.22	0.44	13.30	5.4
2-CR	10–30	1.12	0.11	1.10	0.16	24.67	4.6
2-P10	0–10	1.02	0.08	1.43	0.49	14.82	5.8
2-P10	10–30	1.11	0.08	1.33	0.33	29.46	6.7
2-P3	0–10	0.96	0.04	1.40	0.17	13.46	1.5
2-P3	10–30	1.10	0.05	1.26	0.22	27.82	5.1
2-P7	0–10	0.88	0.17	2.68	0.63	23.11	5.4
2-P7	10–30	0.99	0.09	2.40	0.71	46.95	12.2
3-CR	0–10	1.21	0.16	1.29	0.24	15.11	1.9
3-CR	10–30	1.40	0.11	1.37	0.43	37.81	9.5
3-P9	0–10	1.29	0.16	1.66	0.21	21.26	3.4
3-P9	10–30	1.37	0.21	1.68	0.50	45.71	14.9
4-CR	0–10	0.82	0.06	1.02	0.24	8.33	2.2
4-CR	10–30	1.31	0.03	0.96	0.29	25.32	7.6
4-P4	0–10	1.43	0.16	1.26	0.29	18.30	5.9
4-P4	10–30	1.52	0.03	1.09	0.16	33.21	5.5
4-P9	0–10	1.15	0.13	1.13	0.30	12.62	2.1
4-P9	10–30	1.25	0.07	0.82	0.11	20.34	2.0
5-P1-1	0–10	1.18	0.02	0.90	0.11	10.63	1.4
5-P1-1	10–30	1.19	0.06	1.02	0.18	24.04	3.5
5-P1-2	0–10	1.18	0.07	1.01	0.07	11.96	1.4
5-P1-2	10–30	1.30	0.07	1.07	0.27	27.79	7.3
6-P1	0–10	1.16	0.07	1.58	0.78	18.44	9.8
6-P1	10–30	1.37	0.04	1.41	0.50	38.24	13.4
6-P10	0–10	0.87	0.14	1.75	0.29	15.03	4.3
6-P10	10–30	1.05	0.01	1.86	0.55	38.95	11.5

3.1. Land use change

3.1.1. From cropland to poplar plantations

The results of the transition from CR to PP (Fig. 1) indicate statistically significant differences in SOC stocks. Notably, in farm 2 at the 0–10 cm depth, where site 2-P7 exhibited statistically higher values compared to all other sites, including the PP ($0.01 < p > 0.001$). Similarly, in farm 3 at the 0–10 cm depth, site 3-P9 demonstrated significantly higher levels of SOC compared to its respective CR reference ($p = 0.002$). In contrast, for farm 1, there is no statistical significance between CR and PP regarding SOC at the 0–10 cm depth. However, at the 10–30 cm depth, the PC shows a 38% increase in C compared to the CR ($p < 0.01$). The sites sampled in farm two continue to exhibit the same trend even at the 10–30 cm depth, with site 2-P7 significantly differs in SOC when compared with the other poplar and CR sampled within the same farm. Finally, in farm 3 at the 10–30 cm depth, the SOC stocks are comparable to those of the CR with no statistically significant differences observed.

Considering the SOC rates, farm 1 confirms the trend observed for the SOC stocks. At a depth of 0–10 cm the SOC rate of the PC compared to the CR is relatively low at 0.10 Mg C ha^{-1} yr^{-1}. However, at the 10–30 cm depth, this rate increases to 0.80 Mg C ha^{-1} yr^{-1}. In farm 2, nearly all poplar sites show C rates close to zero at both depths, with the exception of site 2-P7, which exhibit rates 0.26 and 0.48 Mg C ha^{-1} yr^{-1} at the two investigated soil depths. The poplar plantation analyzed in farm 3, exhibits SOC rates of 0.13 and 0.22 Mg C ha^{-1} yr^{-1} at 0–10 and 10–30 cm soil depths, respectively.

Overall, the transition from CR to PP yielded an average increase in SOC stock of 3.07 and 6.92 Mg C ha^{-1} at 0–10 and 10–30 cm soil depths, respectively. The ΔSOC_{REL} exhibits values within a range of 0.01–0.23 Mg C ha^{-1} yr^{-1} at 0–10 cm soil depth, while a range that extends from

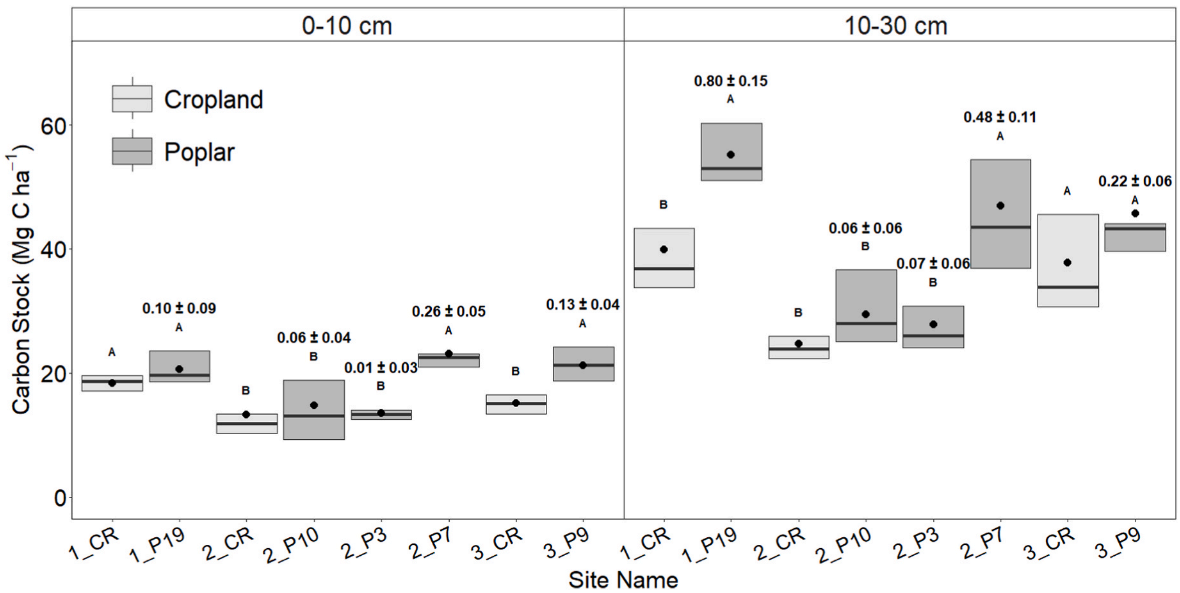

Fig. 1. The x axis defines the sites sorted by site number, the y-axis shows the C stock in Mg ha^{-1}, the upper limit of the boxplot shows the 75th percentile, the lower limit shows the 25th percentile while the black bar in the middle indicates the median values. The light boxplots indicate CR while grey boxplots indicate PP. The site name below as given in Chapter 2.2 indicates the farm number, the age of the plantations and whether it is a CR or a PP. The numbers above the boxplots indicate the C rates in Mg ha^{-1} yr^{-1}, approximately the standard deviations, calculated between each poplar plantation and its respective cropland. Black bullets indicate the mean.

0.07 to 0.80 Mg C ha^{-1} yr^{-1} at 10–30 cm soil depth. Despite the C rates consistently being positive, the mean ΔSOC_{REL} is low and equal to 0.09 Mg C ha^{-1} yr^{-1} at 0–10 cm soil depth and to 0.32 Mg C ha^{-1} yr^{-1} at 10–30 cm soil depth with high variability between the selected sites. Nevertheless, our results reveal a clear pattern, indicating that PP maintains larger SOC stock than CR sites across all considered soil depths, with statistical significance observed in approximately half of the cases. This lack of significance in about fifty percent of the comparisons between CR and PP may result from repetitive management practices influencing SOC dynamics in PP. Increased tillage could have accelerated soil C mineralization and potentially reduced shrub vegetation and relative biomass, thereby affecting SOC levels. Moreover, SOC variability may depend on the investigated soil depth, as the heterogeneity of soil physical properties, such as clay content, can influence SOC accumulation (Perdomo Echenique and Hesser, 2023). Directly comparing the current results with other studies assessing SOC and accumulation rates between PP and CR is challenging, as several factors may influence the SOC rate accumulation following the CR conversion to PP. These factors include the influence of the initial level of SOC stock (Rowe et al., 2016), fertilization practices (Hellebrand et al., 2010), time since conversion (Paul et al., 2023) differences in soil properties (De Vos et al., 2015), and climatic conditions (Berg and Meentemeyer, 2011). In addition, the wide spatial and temporal variability of SOC (Goidts et al., 2009) and other site-specific factors may have a great influence on C accumulation (Garten, 2002). Short rotation cultures of PP (*P. alba*, *P. nigra*, and *P. euramericana*) in Central Italy showed a greater C sequestration potential when exposed to elevated CO_2 levels (550 ppm) using the free-air CO_2 enrichment technique (Miglietta et al., 2001; Calfapietra et al., 2003). After three growing seasons, elevated CO_2 increased aboveground biomass by 15–27% and belowground biomass by 22–38% compared to poplar growing under ambient CO_2. *P. nigra* was the most productive, with total biomass increasing from 62 to 72 Mg ha^{-1} under elevated CO_2 (Calfapietra et al., 2003).

Drawing a comparison, our findings align slightly with those reported by Sierra et al. (2013) indicating a greater SOC in PP than CR of corn crops with a much higher mean ΔSOC_{REL} equal to 1.16 Mg C ha^{-1} yr^{-1}, and from Hansen (1993) that observed how PP between 12 and 18 years old exhibited a SOC rate exceeding that of nearby CR by 1.63 Mg C ha^{-1} yr^{-1}. In general, our SOC rates are in agreement with those from Zhang et al. (2011), examining PP afforestation on former arable land and reporting a ΔSOC_{REL} of 0.13 Mg C ha^{-1} yr^{-1}, those of Hellebrand et al. (2010) indicating a SOC accumulation rate of 0.3 Mg C ha^{-1} yr^{-1}, and finally with those from Walter et al. (2015), using the paired plot approach across 21 sites in Central Europe, which observed no overall SOC sequestration. Our findings are also reasonably consistent with the estimated potential SOC sequestration rates in willow plantations, which range from 0.4 to 0.5 Mg C ha^{-1} yr^{-1} (Don et al., 2012; Rytter, 2012). This is further supported by Rytter et al. (2015), who calculated SOC rates of 0.15–0.45 Mg C ha^{-1} yr^{-1} at a soil depth of 30 cm. Applying non-parametric statistics to the raw data used in this analysis revealed significant differences in SOC between PP and CR exclusively at a soil depth of 0–10 cm ($p < 0.05$). The primary factor driving the greater SOC storage of PP compared to CR within the 0–10 cm soil depth is likely the presence of perennial vegetation, resulting in higher C inputs through leaf and root decomposition (Blanco-Canqui and Lal, 2004). In this context, previous studies have shown that leaf litter within PP in the Mediterranean areas can release substantial amounts of primary macronutrients to the environment (Pérez et al., 2021; González et al., 2022) providing a significant source of SOC (Sayer, 2006). High variability was also observed in the poplar SOC stock. Specifically, in farms 4, 5, and 6, SOC values within the PP ranged between 8 and 38.6 Mg C ha^{-1} at 0–10 cm soil depth and from 16.4 to 82.5 Mg C ha^{-1} at 10–30 cm soil depth. The variance in SOC stock changes resulting from the conversion of CR to PP was attributed to site-specific factors (Garten et al., 2011). However, with the currently available data, it was not possible to identify the key drivers of this variability. This analysis suggests that the contribution of PP to SOC rates, when compared to CR, is highly variable and site-dependent. In the potential context of C farming certification credits, the C stored in poplar woody biomass should be considered. Indeed, PP showed a high capacity for storing C within the woody biomass. Nevertheless, different yields are found at the end of the ten years rotation cycle according to the selected species. In the same sites, Chiarabaglio et al. (2020) found an above ground biomass equal to 158 m^3 ha^{-1} for the 'I-214' poplar clone stands and 197 m^3 ha^{-1} for the stand with other clones offering greater environmental sustainability (MSA clones). A more recent dataset provided by Rizza et al. (2023) reveals compelling evidence suggesting that when PP reaches a decade in age, production yields can exceed 300 m^3 ha^{-1}. In addition, when considering the potential utilization of the C farming credit generated by SOC within PP, it is essential to account for the potential reversibility of SOC, as emphasized by Jacobs et al. (2020). In conclusion, as noted by Paul et al. (2023) the permanence of SOC cannot be guaranteed. Hence, C farming policies should incorporate and support the long-term participation of poplar farmers to maintain and enhance C sequestration efforts.

3.2. C stock within age groups

The data provided in the text below represents the mean ± S.D. of cumulative C stock values collected from various sites falling within a common age group (Fig. 2). In this analysis, all sites were included except site 4-CR, which became CR only in the last two years. The CR exhibits slightly higher mean SOC stocks than PP within the class of 1–5 years old at both investigated depths, with statistical significance observed only at 0–10 cm soil depth ($p = 0.03$). At 0–10 cm soil depth respectively, the CR showed mean SOC stocks equal to 15.6 ± 3.9 Mg C ha^{-1} while the 1–5 years poplar 14.4 ± 5.8 Mg C ha^{-1}. Conversely, at 10–30 cm soil depth the CR and the 1–5 years of poplar showed a mean SOC stock equal to 34.2 ± 10.3 and to 30 ± 8.7 Mg C ha^{-1}. Considering the distribution of all row data, the differences between the CR and PP are statistically significant only at the surface soil depth of 0–10 cm ($p = 0.03$).

The poplar stands in the 5–10 years age class appear to increase SOC stock compared to the 0–5 years age class, with statistically significant differences at both investigated soil depths. Despite the increase in SOC stock, no statistically significant differences are observed at either depths when compareing the 5–10 years age class to the CR. Considering the class of 5–10 years old PP, SOC stocks were equal to 17.3 ± 5.9 and 36.8 ± 14.3 Mg C ha^{-1} at 0–10 cm and 10–30 cm soil depth respectively. Interesting to highlight how the 10–20 years old PC showed the highest SOC stock, becoming particularly significant when compared to the CR ($p = 0.004$) and to the 1–5 years old class ($p = 0.0003$). Indeed, PC showed a SOC stock equal to 20.8 ± 4.5 and 55.1 ± 10.9 Mg C ha^{-1} at 0–10 and 10–30 cm soil depths, respectively. The statistical data for the C stock within age groups are presented in Table 3.

In summary, when considering each site individually, we did not detect an increase in SOC stocks with time since conversion, as also observed by Georgiadis et al. (2017). In contrast, various studies have indicated a rising accumulation of C over time since conversion (Gupta et al., 2009), attributing this increase to the input of litter exceeding decomposition rates (Tolbert et al., 2002; Harris et al., 2015).

Although no clear pattern emerged when analyzing the age of poplar stands and their SOC stock individually, a consistent trend observed when the sites were grouped by age as a determinant of C stock at both investigated soil depths. Regardless of the considered soil depth when CR is used as the baseline, an initial C loss is evident in the early stages of PP, as previously confirmed by (Hansen, 1993) and Arevalo et al. (2011) who found a decrease of 4.0 Mg C ha^{-1} yr^{-1} in the first 2 years after conversion to poplar short rotation coppice in Canada. The SOC loss highlighted within the early stages of PP could potentially be a consequence of depth tillage and stump removal effectuated when a new plantation is established. Effectively, tillage operations made on a previous short rotation forestry impact directly soil aggregates and can imply a SOC redistribution along the profile as observed by (Kahle et al., 2013).

However, with time PP shows an increase in SOC stock, as observed for the older poplar age classes. Assuming linearity in SOC stock changes over time, it appears that soil C is restored to pre-plantation levels within the 5–10 years' timeframe. The PC showed the highest SOC stocks confirming that increased biodiversity using multiple species in extensive culture and forest improves soil quality and SOC (Forrester et al., 2013; Li et al., 2021; Fanin et al., 2022). Adopting a strategy to store C in the early stages of poplar farming, such as lowering the degree of soil tillage would contribute to enhancing C sequestration while reducing energy demand and C dioxide emissions (Holland, 2004), and soil compaction, defined as the process in which soil undergoes mechanical stress, leading to increased density (Sutarno and Mohamad, 2023). In addition, mulching of tree stumps, rather than their removal, could potentially contribute positively to the increase or conservation of SOC (Sun et al., 2021), increasing at the same time economic and environmental production sustainability (Iqbal et al., 2020).

3.3. Effect of poplar plantations on SOC

The effect of PP on SOC is described by the annual rates reported in Table 4. Almost all monitored sites showed positive SOC rates with the exclusion of sites 4-P10 which showed neither C sequestration nor reduction with ΔSOC_{ABS} close to zero (−0.04 Mg C ha^{-1} yr^{-1}). On the contrary, the polycyclic site showed the highest ΔSOC_{ABS}, about 2 Mg C ha^{-1} yr^{-1}, while PP showed a mean ΔSOC_{ABS} equal to 0.75 Mg C ha^{-1} yr^{-1}.

Encouraging the cultivation of PC is crucial, not only for enhancing SOC accumulation but also for fostering biodiversity. These plantations exhibit minimal ecological and landscape impacts, particularly when compared with conventional poplar cultivation, which entails substantial farmer inputs and exerts a notable environmental footprint (Pra

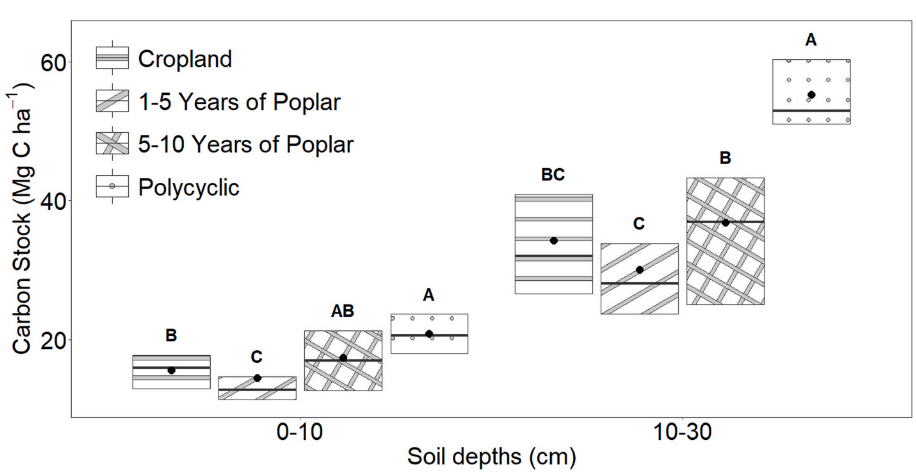

Fig. 2. Comparing cumulative C stocks in PP versus CR: C stock trends within PP are categorised in the x axis into 0–5, 5–10, and 10–20 years old, measured at soil depths of 0–10 cm and 10–30 cm. The upper limit of the boxplot shows the 75th percentile, the lower limit shows the 25th percentile while the black bar in the middle indicates the median values. Black bullets indicate the mean.

Table 3
Detailed information on the variability of the mean SOC stocks within the selected age classes. The terminology used indicates the following: the cycle identifies cropland, poplar plantations grouped by age, or polycyclic systems, C (%) indicates the mean percentage of C for each selected group while C_{sd} is the respective standard deviation.

Soil depth	Cycle	C	C_{sd}	Mean SOC stock	SOC_{sd}	Median SOC stock	25^{th}percentile	75^{th} percentile
cm		%		Mg C ha^{-1}				
0–10	Cropland	1.33	0.31	15.62	3.97	15.9	12.9	17.7
10–30	Cropland	1.31	0.33	34.25	10.30	32.0	26.6	40.8
0–10	1–5 Years of Poplar	1.22	0.43	14.47	5.81	12.7	11.4	14.7
10–30	1–5 Years of Poplar	1.16	0.31	30.04	8.73	28.0	23.7	33.8
0–10	5–10 Years of Poplar	1.73	0.68	17.38	5.91	17.0	12.7	21.3
10–30	5–10 Years of Poplar	1.64	0.71	36.84	14.37	36.9	25.0	43.3
0–10	Polycyclic	2.13	0.35	20.84	4.59	20.6	18.0	23.6
10–30	Polycyclic	2.32	0.36	55.19	10.96	52.9	51.0	60.3

Table 4
Differences in SOC stock due to continuous poplar cultivation at the same site. The SOC stock t_0 indicates the baseline carbon stock measured before the experiment in the treatment plot and rescaled at 30 cm soil depth, expressed in Mg C ha^{-1}. The SOC stock t_1 is the stock measured, at 30 cm soil depth, after the experiment in the treatment plot, expressed in Mg C ha^{-1}. The time indicates the years of the treatments. The asterisk (*) indicates that the site is managed in polycyclic arboriculture.

Site name	SOC Stock t_0 (Mg C ha^{-1})	SOC Stock t_1 (Mg C ha^{-1})	Time (Years)	SOC Rate (Mg C ha^{-1} year^{-1})
1-P19*	40	75	17	2.06
2-P3	21	41	28	0.71
2-P10	33	44	28	0.39
2-P7	32	69	28	1.32
4-P9	33	32	28	−0.04
5-P1-2	28	39	28	0.39
6-P1	38	56	27	0.67
6-P10	25	54	16	1.81

et al., 2019). Besides, from an economic standpoint, Pra et al. (2019) conducted research in the Po Valley, revealing that PC can potentially provide more compelling economic prospects when compared to monospecific plantations. Additionally, as suggested by Chen et al. (2023), encouraging species diversification within forests emerges as an effective strategy for fostering soil quality, boosting the fertility of the soil's N content and C sink capability.

Overall, the high SOC rates observed in this investigation could be partially attributed to the consistent application of N-phosphorus-potassium (NPK) fertilizers commonly utilized in PP practices. Not specific studies on NPK fertilization and SOC increase are available in PP management, while some studies indicate a SOC increase due to NPK application in CR. Kaur et al. (2008) showed how SOC accumulation dynamics are influenced by NPK fertilizers under maize-wheat cropping systems while Zhang et al. (2010) observed a clear linear correlation between soil C sequestration and C input across the studied sites and revealed how long-term applications of NPK fertilizers lead to a notable increase in SOC levels considering sites employing double-cropping systems. Furthermore, according to Li et al. (2024), investigating salt marsh ecosystems, revealed that also continuous N application can modify plant growth influencing SOC accumulation.

The global agricultural and food system relies on the use of synthetic N fertilizers to improve crop yields, even though employing these fertilizers is unsustainable (Menegat et al., 2022). Moreover, pesticide application impacts approximately 70% of the total agricultural land globally (Puri et al., 2023). This provides the opportunity to highlight that, within the framework of a circular economy, achieving genuine SOC sequestration should be accompanied using fertilizer produced on-site or within the region of chain production (e.g., manure application). This could minimize GHG emissions resulting from fertilizer production and relative transportation, and on-site utilization (Walling and Vaneeckhaute, 2020). Previous studies suggest how under organic management, consistent application of organic inputs can effectively displace C losses occurring during tillage operations. As a result, SOC may increase for a certain time (Gattinger et al., 2012; Messmer et al., 2012). We therefore recommend the promotion of a short and local manure supply chain, given that Martínez-Suller et al., 2008 demonstrated how the Lombardy region alone encompasses over 26% of Italy's cattle and more than 44% of its pig's production, capable of producing an estimated annual volume of 85 million cubic meters of manure.

4. Conclusions

SOC rates calculated using the spatial survey approach showed how PP can enhance SOC accumulation. Relative SOC rates showed positive values although SOC stock differences between poplar and CR were statistically significant in a few cases. To enhance the evaluation of the SOC contribution of PP, we recommend conducting long-term studies that integrate both the paired method and the SOC stock difference methods. This approach should involve examining deeper soil layers and considering all factors affecting SOC storage, including a thorough assessment of agronomic practices with detailed attention to fertilization, irrigation plans, and soil tillage operations.

Despite results indicating a good correlation between SOC and grouped age classes, this correlation is essentially fragile due to the few plantations older than ten years old and the variance in SOC stock in the selected age classes. Regardless, the latter analysis confirmed how the first five years of growing PP may bring a loss of SOC compared to CR as the soil is periodically disk-arrowed to eliminate competition with weeds. The conversion of the PP back to CR certainly leads to a loss of SOC, a phenomenon that requires further clarification and extensive study. The PC showed the best ΔSOC_{ABS}, possibly due to its high biodiversity and the less impacting soil operations such as tillage. We recommend that this approach of arboriculture be supported by the European C Farming certification schemes to promote a compatible supplier chain. The wide variability of SOC among different poplar sites suggests that multiple factors may influence soil C sequestration. Furthermore, we believe that several sustainable farming techniques remain underutilized, including the use of minimal tillage after the poplar stand has been cleared and replanted, the establishment of polycyclic systems for cultivation, mulching rather than seasonal ploughing, the use of cover crops and manure, and the burial of pruning residues to enhance the sustainability of the poplar cultivation chain. The implementation of the aforementioned practices can enhance carbon inputs into the soil, yielding social, environmental and economic co-benefits. This approach can enhance SOC levels, potentially reduce soil compaction through minimum tillage, positively impact soil micro-fauna, and ultimately decrease the need for fertilizer application.

In conclusion, PP utilized for plywood production, when compared to CR using the paired method, do not exhibit a significant impact on SOC although they unequivocally enhance biodiversity and C accumulation at an ecosystem level. Moreover, the impact of PP on SOC investigated through the SOC stock change method over three decades of uninterrupted cultivation reveals positive SOC rates, which become notably high when focusing on PC, suggesting the need of further investigations.

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CRediT authorship contribution statement

Gabriele Antoniella: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abhay Kumar:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pier Mario Chiarabaglio:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Giuseppe Scarascia Mugnozza:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Tommaso Chiti:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Aalde, H., Gonzalez, P., Gytarsky, M., Krug, T., Kurz, W.A., Lasco, R.D., Martino, D.L., McConkey, B.G., Ogle, S., Paustian, K., et al., 2006. In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Agriculture, Forestry and Other Land Use, 4. IGES, Kanagawa, Japan.

Arevalo, C.B.M., Bhatti, J.S., Chang, S.X., Sidders, D., 2009. Ecosystem carbon stocks and distribution under different land-uses in north central Alberta, Canada. Forest Ecol. Manag. 257, 1776–1785.

Arevalo, C.B.M., Bhatti, J.S., Chang, S.X., Sidders, D., 2011. Land use change effects on ecosystem carbon balance: from agricultural to hybrid poplar plantation. Agricul. Ecosys. Environ. 141, 342–349.

Berg, B., Meentemeyer, V., 2011. Litter fall in some European coniferous forests as dependent on climate: a synthesis. Can. J. For. Res. 31, 292–301.

Berhongaray, G., Verlinden, M.S., Broeckx, L.S., Janssens, I.A., Ceulemans, R., 2017. Soil carbon and belowground carbon balance of a short-rotation coppice: assessments from three different approaches. GCB Bioenergy 9, 299–313.

Blake, G.R., 1965. Bulk Density. Methods of Soil Analysis, pp. 374–390.

Blanco-Canqui, H., Lal, R., 2004. Mechanisms of carbon sequestration in Ssoil aggregates. Crit. Rev. Plant Sci. 23, 481–504.

Blasi, C., Capotorti, G., Copiz, R., Guida, D., Mollo, B., Smiraglia, D., Zavattero, L., 2014. Classification and mapping of the ecoregions of Italy. Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology 148, 1255–1345.

Boone, R.D., Grigal, D.F., Sollins, P., Ahrens, R.J., Armstrong, D.E., 1999. Soil sampling, preparation, archiving, and quality control. In: Robertson, G.P., Coleman, D.C., Bledsoe, C.S., Sollins, P. (Eds.), Standard Soil Methods for Long-Term Ecological Research. Oxford University Press, p. 1.

Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., Smith, P., et al., 2020. The role of soil carbon in natural climate solutions. Nat. Sustain. 3, 391–398.

Calfapietra, C., Gielen, B., Galema, A.N., Lukac, M., De Angelis, P., Moscatelli, M.C., et al., 2003. Free-air CO2 enrichment (FACE) enhances biomass production in a short-rotation poplar plantation. Tree Physiol. 23, 805–814.

Cantamessa, S., Rosso, L., Giorcelli, A., Chiarabaglio, P.M., 2022. The environmental impact of poplar stand management: a life cycle assessment study of different scenarios. Forests 13, 464.

Castro, G., Fragnelli, G., Zanuttini, R., 2014. La pioppicoltura e il compensato di Pioppo dell'industria Italiana. Edizioni Lampi di Stampa, Milano, Italy, p. 9.

Certini, G., Scalenghe, R., 2023. The crucial interactions between climate and soil. Sci. Total Environ. 856, 159169.

Chen, X., Taylor, A.R., Reich, P.B., Hisano, M., Chen, H.Y.H., Chang, S.X., 2023. Tree diversity increases decadal forest soil carbon and nitrogen accrual. Nature 618, 94–101. https://doi.org/10.1038/s41586-023-05941-9.

Chiarabaglio, P.M., Deidda, A., Bergante, S., Castro, G., Faciotto, G., Giorcelli, A., et al., 2020. Life Cycle Assessment (LCA): new poplar clones allow an environmentally sustainable cultivation. Ann. Silvicul. Res. 45.

Corona, P., Bergante, S., Castro, G., Chiarabaglio, P.M., Coaloa, D., Facciotto, G., Gennaro, M., Giorcelli, A., Rosso, L., Vietto, L., Nervo, G., 2018. Linee di indirizzo per una pioppicoltura sostenibile. Rete Rurale Nazionale, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria. Rom. 1–63.

De Vos, B., Cools, N., Ilvesniemi, H., Vesterdal, L., Vanguelova, E., Carnicelli, S., 2015. Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey. Geoderma 251–252, 33–46. https://doi.org/10.1016/j.geoderma.2015.03.008.

Deng, L., Zhu, G.-y., Tang, Z.-s., Shangguan, Z.-p., 2016. Global patterns of the effects of land-use changes on soil carbon stocks. Global Ecol. Conserv. 5, 127–138.

Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M.S., Drewer, J., et al., 2012. Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. GCB Bioenergy 4, 372–391.

European Commission, 2011. Soil: the Hidden Part of the Climate Cycle. Publications Office of the European Union, Luxembourg.

European-Commission, 2021. Setting up and implementing result-based carbon farming mechanisms in the EU – technical guidance handbook. In: Radley, G., Keenleyside, C., Frelih-Larsen, A., McDonald, H., Pyndt Andersen, S., Qwist-Hoffmann, H., Strange Olesen, A., Bowyer, C., Russi, D. (Eds.), Directorate-General for Climate Action. Publications Office of the European Union.

Fanin, N., Maxwell, T.L., Altinalmazis-Kondylis, A., Bon, L., Meredieu, C., Jactel, H., et al., 2022. Effects of mixing tree species and water availability on soil organic carbon stocks are depth dependent in a temperate podzol. Eur. J. Soil Sci. 73, e13133.

Forrester, D.I., Pares, A., O'Hara, C., Khanna, P.K., Bauhus, J., 2013. Soil organic carbon is increased in mixed-species plantations of *Eucalyptus* and nitrogen-fixing *Acacia*. Ecosystems 16, 123–132.

Garten, C.T., 2002. Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. Biomass Bioener 23, 93–102.

Garten, C.T., Wullschleger, S.D., Classen, A.T., 2011. Review and model-based analysis of factors influencing soil carbon sequestration under hybrid poplar. Biomass Bioener 35, 214–226.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., et al., 2012. Enhanced top soil carbon stocks under organic farming. Proc. Natl. Acad. Sci. USA 109, 18226–18231.

Georgiadis, P., Vesterdal, L., Stupak, I., Raulund-Rasmussen, K., 2017. Accumulation of soil organic carbon after cropland conversion to short-rotation willow and poplar. GCB Bioener 9, 1390–1401.

Ghiglieno, I., Simonetto, A., Facciano, L., Tonni, M., Donna, P., Valenti, L., Gilioli, G., 2023. Comparing the carbon footprint of conventional and organic vineyards in northern Italy. Sustainability 15, 5252.

Goidts, E., Van Wesemael, B., Crucifix, M., 2009. Magnitude and sources of uncertainties in soil organic carbon (SOC) stock assessments at various scales. Eur. J. Soil Sci. 60, 723–739.

González, I., Sixto, H., Rodríguez-Soalleiro, R., Cañellas, I., Fuertes, A., Oliveira, N., 2022. How can leaf-litter from different species growing in short rotation coppice contribute to the soil nutrient pool? Forest Ecol. Manag. 520, 120405.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biol. 8, 345–360.

Gupta, N., Kukal, S.S., Bawa, S.S., Dhaliwal, G.S., 2009. Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. Agrofor. Sys. 76, 27–35.

Hansen, E.A., 1993. Soil carbon sequestration beneath hybrid poplar plantations in the North Central United States. Biomass Bioener 5, 431–436.

Harris, Z.M., Alberti, G., Viger, M., Jenkins, J.R., Rowe, R., McNamara, N.P., Taylor, G., 2017. Land-use change to bioenergy: grassland to short rotation coppice willow has an improved carbon balance. GCB Bioenerg. 9, 469–484. https://doi.org/10.1111/gcbb.12347.

Harris, Z.M., Spake, R., Taylor, G., 2015. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. Biomass Bioener 82, 27–39.

Harrison, M.T., Cullen, B.R., Mayberry, D.E., Cowie, A.L., Bilotto, F., Badgery, W.B., Liu, K., Davison, T., Christie, K.M., Muleke, A., et al., 2021. Carbon myopia: the urgent need for integrated social, economic and environmental action in the livestock sector. Glob. Chang. Biol. 27, 5726–5761.

Hellebrand, H.J., Strähle, M., Scholz, V., Kern, J., 2010. Soil carbon, soil nitrate, and soil emissions of nitrous oxide during cultivation of energy crops. Nutri. Cycl. Agroecosys. 87, 175–186.

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agricul. Ecosys. Environ. 103, 1–25.

Hussain, S., Hussain, S., Guo, R., Sarwar, M., Ren, X., Krstic, D., Aslam, Z., Zulifqar, U., Rauf, A., Hano, C., El-Esawi, M.A., 2021. Carbon sequestration to avoid soil degradation: a review on the role of conservation tillage. Plants 10, 2001. https://doi.org/10.3390/plants10102001.
Ibáñez, A., Sombrero, A., Santiago-Pajón, A., Santiago-Calvo, Y., Asensio-S, Manzanera, M.C., 2024. Effect of long-term conservation tillage management on microbial diversity under Mediterranean rainfed conditions. Soil Till. Res. 236, 105923.
IPCC, 2000. In: Special report on land use, land-use change and forestry. Cambridge University Press, Cambridge.
Iqbal, R., Raza, M.A.S., Valipour, M., Saleem, M.F., Zaheer, M.S., Ahmad, S., et al., 2020. Potential agricultural and environmental benefits of mulches - a review. Bull. Natl. Res. Cent. 44, 75.
Jacobs, A., Heidecke, C., Jumshudzade, Z., Osterburg, B., Paulsen, H., Poeplau, C., 2020. Soil organic carbon certificates -potential and limitations for private and public climate action. Landbauforschung 70, 31–35.
Kahle, P., Möller, J., Baum, C., Gurgel, A., 2013. Tillage-induced changes in the distribution of soil organic matter and the soil aggregate stability under a former short rotation coppice. Soil Till. Res. 133, 49–53.
Kaur, T., Brar, B.S., Dhillon, N.S., 2008. Soil organic matter dynamics as affected by long-term use of organic and inorganic fertilizers under maize–wheat cropping system. Nutri. Cycl. Agroecosys. 81, 59–69.
Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A., Lombi, E., 2019. Soil and the intensification of agriculture for global food security. Environ. Int. 132, 105078.
Kumar, A., Antoniella, G., Blasi, E., Chiti, T., 2024. Chapter Twenty Two - agronomic practices for storing soil carbon and reducing greenhouse gas emission in the Mediterranean region. In: Vara Prasad, M.N., Erickson, L.E., Nunes, F.C., Ramadan, B.S. (Eds.), Decarbonization Strategies and Drivers to Achieve Carbon Neutrality for Sustainability. Elsevier, pp. 445–480.
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and. food security Science (New York, N.Y.) 304, 1623–1627. https://doi.org/10.1126/science.1097396.
Land use in Lombardy: Descriptive atlas, 2010. ERSAF, Lombardy Region, Milan.
Li, W.-Q., Huang, Y.-X., Chen, F.-S., Liu, Y.-Q., Lin, X.-F., Zong, Y.-Y., et al., 2021. Mixing with broad-leaved trees shapes the rhizosphere soil fungal communities of coniferous tree species in subtropical forests. Forest Ecol. Manag. 480, 118664.
Li, J., Chen, Y., Ge, T., Zhao, M., Ge, J., Han, G., 2024. Nitrogen fertilization enhances organic carbon accumulation in topsoil mainly by improving photosynthetic C assimilation in a salt marsh. J. Environ. Manag. 351, 119862. https://doi.org/10.1016/j.jenvman.2023.119862.
Liu, X., Tan, S., Song, X., Wu, X., Zhao, G., Li, S., Liang, G., 2022. Response of soil organic carbon content to crop rotation and its controls: a global synthesis. Agricul. Ecosys. Environ. Times 335, 108017.
Longo, M., Dal Ferro, N., Izaurralde, R.C., Furlan, L., Chiarini, F., Morari, F., 2023. Deep SOC stock dynamics under contrasting management systems: is the EPIC model ready for carbon farming implementation? Euro. J. Agron. 145, 126771.
Mandal, A., Sarkar, B., Mandal, S., Vithanage, M., Patra, A.K., Manna, M.C., 2020. Impact of agrochemicals on soil health Agrochemicals Detection, Treatment and Remediation: Pesticides and Chemical Fertilizers 161–187. https://doi.org/10.1016/B978-0-08-103017-2.00007-6.
Martínez-Suller, L., Azzellino, A., Provolo, G., 2008. Analysis of livestock slurries from farms across Northern Italy: relationship between indicators and nutrient content. Biosys. Eng. 99, 540–552.
McClean, G.J., Rowe, R.L., Heal, K.V., Cross, A., Bending, G.D., Sohi, S.P., 2015. An empirical model approach for assessing soil organic carbon stock changes following biomass crop establishment in Britain. Biomass Bioener 83, 141–151.
Menegat, S., Ledo, A., Tirado, R., 2022. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Sci. Rep. 12, 14490.
Messmer, M., Hildermann, I., Thorup-Kristensen, K., Rengel, Z., 2012. Nutrient management in organic farming and consequences for direct and indirect selection strategies. Organic Crop Breeding 15–38.
Miglietta, F., Peressotti, A., Vaccari, F., Zaldei, A., Angelis, P., Scarascia-Mugnozza, G., 2001. Free-air CO2 enrichment (FACE) of a poplar plantation: the PopFACE fumigation system. New Phytol. 150, 465–476.
Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. Methods of Soil Analysis 961–1010.
Paul, C., Bartkowski, B., Dönmez, C., Don, A., Mayer, S., Steffens, M., et al., 2023. Carbon farming: are soil carbon certificates a suitable tool for climate change mitigation? J. Environ. Manag. 330, 117142.
Peralta, G., Di Paolo, L., Luotto, I., Omuto, C., Mainka, M., Viatkin, K., Yigini, Y., 2022. Global soil organic carbon sequestration potential map (GSOCseq v1.1) – Technical manual. FAO, Rome. https://doi.org/10.4060/cb2642en.
Perdomo Echenique, E., Hesser, F., 2023. Understanding soil organic carbon dynamics of short rotation plantations after land use change—from establishment to recultivation. In: Hesser, F., et al. (Eds.), Progress in Life Cycle Assessment 2021. Sustainable Production, Life Cycle Engineering and Management. Springer, Cham. https://doi.org/10.1007/978-3-031-29294-1_5.
Pérez, P., Barro, R., Pérez, J., Fernández, M.J., Moyano, A., Ciria, P., 2021. Nutrient release through litterfall in short rotation poplar crops in Mediterranean marginal land. Forests 12, 1185.
Petersson, T., Antoniella, G., Chiriacò, M.V., Perugini, L., Chiti, T., 2024. The misconception of soil organic carbon sequestration notion: when do we achieve climate benefit? Soil Use Manag. 40, e13009.
Plutino, M., Bergante, S., Facciotto, G., Vitone, A., Bianchetto, E., Sansone, D., et al., 2022. Short communication: a study case on polycyclic plantations (PP) as innovative models for sustainable combined production of noble hardwood and biomass. Forest Syst. 31, eSC02.
Porro, Z., Odicino, M., Bogliani, G., Chiatante, G., 2021. Intensive forestry and biodiversity: use of poplar plantations by woodpeckers in a lowland area of Northern Italy. Forest Ecol. Manage. 497, 119490.
Pra, A., Brotto, L., Mori, P., Lattes, E., Masiero, M., Andrighetto, N., Pettenella, D., 2019. Profitability of timber plantations on agricultural land in the Po valley (northern Italy): a comparison between walnut, hybrid poplar and polycyclic plantations in the light of the European Union Rural Development Policy orientation. Eur. J. For. Res. 138.
Puletti, N., Grotti, M., Scotti, R., 2019. Evaluating the Eecentricities of poplar stem profiles with terrestrial laser scanning. Forests 10, 239.
Puri, M., Gandhi, K., Kumar, M.S., 2023. Emerging environmental contaminants: a global perspective on policies and regulations. J. Environ. Manag. 332, 117344. https://doi.org/10.1016/j.jenvman.2023.117344.
Righini, G., Costantini, E., Sulli, L., 2002. La banca dati delle regioni pedologiche Italiane. Bollettino della Società Italiana Scienza del Suolo 50.
Rizza, D., Chiarabaglio, P., Coaloa, D., Rocci, A., 2023. Ten-years dataset of poplar inventory in northern Italy. Ann. Silvicul. Res. 49.
Rösch, C., Aust, C., Jörissen, J., 2013. Envisioning the sustainability of the production of short rotation coppice on grassland. Energy Sustain. Soc. 3. https://doi.org/10.1186/2192-0567-3-7.
Rowe, R.L., Keith, A.M., Elias, D., Dondini, M., Smith, P., Oxley, J., McNamara, N.P., 2016. Initial soil C and land-use history determine soil C sequestration under perennial bioenergy crops. GCB Bioener. 8, 1046–1060.
RStudio Team, 2023. In: RStudio: Integrated development for R. Version 2023.03.1+446, "Cherry Blossom. Posit Software, PBC, Boston, MA. https://posit.co.
Rytter, R.M., 2012. The potential of willow and poplar plantations as carbon sinks in Sweden. Biomass Bioenergy 36, 86–95.
Rytter, R.-M., Rytter, L., 2020. Carbon sequestration at land use conversion – early changes in total carbon stocks for six tree species grown on former agricultural land. For. Ecol. Manag. 466, 118129.
Rytter, R.M., Rytter, L., Högbom, L., 2015. Carbon sequestration in willow (Salix spp.) plantations on former arable land estimated by repeated field sampling and C budget calculation. Biomass Bioenergy 83, 483–492.
Sayer, E.J., 2006. Using experimental manipulation to assess the roles of leaf litter in the functioning of forest ecosystems. Biol. Rev. 81, 1–31.
Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag. 5, 81–91.
Sierra, M., Martínez, F.J., Verde, R., Martín, F.J., Macías, F., 2013. Soil-carbon sequestration and soil-carbon fractions, comparison between poplar plantations and corn crops in south-eastern Spain. Soil Till. Res. 130, 1–6.
Silva Neto, E.C., Coelho-Junior, M.G., Horák-Terra, I., Gonçalves, T.S., Anjos, L.H.C., Pereira, M.G., 2023. Organic soils: formation, classification and environmental changes records in the highlands of Southeastern Brazil. Sustainability 15, 3416.
R Core Team, 2020. R: a language and environment for statistical computing (Version 4.0.0, "Arbor Day"). R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org.
Stolbovoy, V., Montanarella, L., Filippi, N., Jones, A., Gallego, J., Grassi, G., 2007. Soil Sampling Protocol to Certify the Changes of Organic Carbon Stock in Mineral Soil of the European Union. Version 2. EUR 21576 EN/2. Office for Official Publications of the European Communities,, Luxembourg, p. 56. ISBN: 978-92-79-05379-5.
Sun, X., Wang, G., Ma, Q., Liao, J., Wang, D., Guan, Q., Jones, D.L., 2021. Organic mulching promotes soil organic carbon accumulation to deep soil layer in an urban plantation forest. Forest Ecosys 8, 2.
Sutarno, M.S., Mohamad, H.M., 2023. Peat soil compaction characteristic and physicochemical changes treated with Eco-Processed Pozzolan (EPP). Civil Engineering Journal 9, 86–103. https://doi.org/10.28991/CEJ-2023-09-01-07.
Tolbert, V.R., Todd, D.E., Mann, L.K., Jawdy, C.M., Mays, D.A., Malik, R., et al., 2002. Changes in soil quality and below-ground carbon storage with conversion of traditional agricultural crop lands to bioenergy crop production. Environ. Pollut. 116, S97–S106.
Torresani, M., Masiello, G., Vendrame, N., Gerosa, G., Falocchi, M., Tomelleri, E., et al., 2022. Correlation analysis of evapotranspiration, emissivity contrast and water deficit indices: a case study in four Eddy Covariance sites in Italy with different environmental habitats. Land 11, 1903.
Vaglio Laurin, G., Mattioli, W., Innocenti, S., Lombardo, E., Valentini, R., Puletti, N., 2022. Potential of ALOS2 Polarimetric Imagery to Support Management of Poplar Plantations in Northern Italy. Remote Sens. 14, 5202. https://doi.org/10.3390/rs14205202.
Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., et al., 2020. Can conservation agriculture increase soil carbon sequestration? A modelling approach. Geoderma 369, 114298.
Vanino, S., Pirelli, T., Di Bene, C., Bøe, F., Castanheira, N., Chenu, C., et al., 2023. Barriers and opportunities of soil knowledge to address soil challenges: stakeholders' perspectives across Europe. J. Environ. Manag. 325, 116581.
Walling, E., Vaneeckhaute, C., 2020. Greenhouse gas emissions from inorganic and organic fertilizer production and use: a review of emission factors and their variability. J. Environ. Manag. 276, 111211.

Zhang, W.J., Wang, X.J., Xu, M.G., Huang, S.M., Liu, H., Peng, C., 2010. Soil organic carbon dynamics under long-term fertilizations in arable land of northern China. Biogeosciences 7, 409–425.

Walter, K., Don, A., Flessa, H., 2015. No general soil carbon sequestration under Central European short rotation coppices. GCB Bioenergy 7 (4), 727–740. https://doi.org/10.1111/gcbb.12177.

Zhang, J., Shangguan, T., Meng, Z., 2011. Changes in soil carbon flux and carbon stock over a rotation of poplar plantations in northwest China. Ecol. Res. 26, 153–161.