Review

Reversion of Perennial Biomass Crops to Conserve C and N: A Meta-Analysis

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Abstract: Perennial crops have been proposed as a solution to couple the production of sustainable biomass for multiple uses with several environmental benefits such as soil C storage. Concerns exist that the C sequestered in soil could be lost in a few years after the perennial crops are reverted to arable land. In this study, the current knowledge on the effects of perennial crop reversion on soil C and N was summarized by performing a meta-analysis. One year after the reversion a significant increase of soil C and N stocks (+15% and +12% respectively) were found in the 0–30 cm layer, while in the time interval between the second to fifth year after the reversion, there were no significant increases or decreases of soil C and N. The incorporation of the belowground biomass (BGB) into the soil at reversion plays a key role in the fate of soil C and N stocks after the reversion. In fact, when reverting a multiannual biomass crop there are significant losses of soil C and N. In contrast, when reverting a perennial biomass crop (PBCs) such as rhizomatous herbaceous or SRC woody crops there are no losses of soil C and N. The BGB of perennial grass is mainly composed of root systems and not of a huge amount of belowground organs as in the case of PBCs. The shredding of the BGB and its transformation as particulate organic matter (POM) represent the major pulse C input at the reversion that can undergo further stabilization into a mineral-associated organic matter (MAOM) fraction. Introducing PBCs into crop rotation resulted in an effective carbon farming solution with a potential positive legacy for food crops in terms of achievement of both climate and soil fertility goals.

Keywords: perennial biomass crops; perennial crops; plant reversion; willow; poplar; miscanthus; soil carbon; soil nitrogen

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1. Introduction

The 21st century will challenge agriculture to produce more food, energy, and goods for a growing human population while respecting the environment [1]. This necessitates approaches to mitigate the impact of agriculture on climate and reduce greenhouse gas (GHG) emissions to keep the increase in global mean temperature well below 2 °C, and especially for the ambitious target of below 1.5 °C [2]. In the agricultural sector, strategies for carbon dioxide (CO₂) removal by carbon (C) sequestration in soil, relies on plant photosynthesis to carry out the initial step of C “removal” from the atmosphere into the plants’ biomass [3]. Soil is one of the most important C sinks on the planet [4] and the agricultural management of cropland, which governs the balance between the rate of C input from plant residues and the rate of C lost from the soil (mainly as CO₂ from decomposition processes), can lead to a substantial loss of soil organic C (SOC) and GHG emissions [5]. Anthropogenic perturbations that increase the decline of SOC are mainly ploughing, residue removal, monoculture, or the conversion of natural ecosystems to agricultural production [4,6]. For these reasons, in 2015, the “4 per mille” initiative (<https://www.4p1000.org>, accessed on 28 December 2021) was launched at the COP21 in Paris, to increase SOC by 0.4% every year to compensate for the C emissions of humankind [7].

Several studies have proven that the cultivation of perennial crops (PCs) is an effective method to increase SOC [8,9] thanks to the plant C input (fine roots C, litter-leaf C, harvest residue C) and minimal soil disturbance [10–13]. Examples of PCs, which are defined as: “crops that are planted but not replanted and/or fully harvested annually to obtain goods” [8] are woody plants (fruits trees), beverage crops (e.g., coffee, tea, cocoa), oil crops (e.g., palms), short rotation coppices (SRC, e.g., poplar, willow or black locust), perennial rhizomatous crops like switchgrass, miscanthus, giant reed [14,15] and multiannual biomass crops (MBC) [16,17]. PCs can produce high biomass yields in a wide range of climatic and soil conditions with low inputs [18–21] which can be used for a multitude of products, from food and fiber to bioenergy production [15]. In addition, PCs can sustain the provision of multiple ecosystem services (ES) [22–24] directly and indirectly connected to the increase of soil organic matter (SOM) [25] as nutrient cycling [26,27], the reduction of heavy metal concentration in soil [28] or the increase of biodiversity [14,29]. Besides C sequestration in soil, PCs can sequester huge amounts of C in the belowground organs [13]. Despite the huge effort that has been made recently to summarize the knowledge on the effect of PC cultivation on SOC [8,30], limited information is available on the fate of SOC after the perennial crops are terminated and the soil is reverted to arable crops. There are concerns that the benefit brought about by PCs would soon be lost with the reversion to arable crops [13,31]. However, some authors suggested that a positive effect of reversion on the soil C and N pool is possible, due to the high C and N inputs from the incorporation of belowground biomass (BGB) [13] and harvest residues [32]. Consequently, we hypothesized that a positive soil C storage trajectory is possible when PCs with high BGB are reverted to arable land.

In this study, the current knowledge on the effect of PC reversion on soil C and N was summarized by performing a meta-analysis. In particular, the work focused on, firstly, the changes occurring in soil C and N as a function of the soil layer considered (above or below the average reversion depth); secondly, the changes in soil C and N were investigated as a function of the time since reversion was performed. Finally, the changes in soil C and N were evaluated across different predictor factors (i.e., soil characteristics, climatic and experimental conditions).

2. Materials and Methods

2.1. Data Collection

A literature survey of peer-reviewed English-written scientific papers was carried out from October 2020 to October 2021 using major databases and library services as Google Scholar (<https://scholar.google.com>, accessed on 29 December 2021) or Scopus (www.scopus.com/, accessed on 3 January 2022). The combinations of keywords to search on titles, abstracts and keywords used as a primary step to collect literature are given in Appendix A. Bibliographies of the papers included in the meta-analysis were screened for other potentially relevant papers that may have been missed by the primary searches. When the data were presented in figures, mean values, standard error (SE) or standard deviation (SD) were extracted using *WebPlotDigitizer* (<https://automeris.io/WebPlotDigitizer/>, accessed on 1 November 2021). Authors were contacted for unpublished data and missing information. PCs considered in this study include all the perennial plants for which the above-ground biomass is annually harvested for agricultural purposes but excluding the reversion of PCs from native ecosystems, pastures, or natural forests. In this study, “Reversion” is intended as the operation of PC removal, with or without the spraying of herbicides and performed using ploughs, forestry mulchers or, more in general, the use of machinery that incorporates into soil the belowground biomass of PCs.

2.1.1. Soil

The following information on the soil was extracted from the papers: mean, SD and sample size (n) of C and N stock (in Mg ha^{-1}) and soil C/N ratio when provided. In addition, texture class (or percentage of clay, silt and sand,) soil bulk density (BD in g cm^{-3})

and sampling depths (cm) were extracted. If C and N were reported as concentrations (% or g kg⁻¹), data were transformed to stocks using soil BD. In the case that N data were not reported, N stock or concentration was calculated from C data using the C/N ratio. If SD of soil C and N data were not reported, they were calculated from SE and sample size (n):

$$SD = SE \times \sqrt{n} \quad (1)$$

If SD, SE, and n were not provided, SD was calculated as 1/10 of the mean as proposed by Luo et al. [33]. Considering that, in the literature, measurements of C and N in soil are relative to sampling depth ranging from 5 to 100 cm, and assuming that during the reversion process the first 30 cm of soil are mixed, soil data were grouped in two layers: 0–30 and 30–100 cm. Soil C stock before the reversion was divided into three different categorical groups randomly selected to be of equal sample size as described in Terrer et al. [34] using the *equal_freq* function of the *funModeling* R package [35]. Soil texture was divided into three subgroups: loam, silty-loam, and sandy-loam. Regarding fertilization, only two categorical groups were formed: fertilized (yes) or not fertilized (no).

2.1.2. Crops

Information on crops cultivated before and after the reversion was extracted. PCs, in this study, were split into subgroups according to the end-use of biomass or the species, in particular: willow (*Salix* spp.), poplar (*Populus* spp.), miscanthus (*Miscanthus x giganteus*) were classified as perennial biomass crops (PBCs), while alfalfa (*Medicago sativa*) and the mixture of perennial herbaceous species such as the false wheatgrass (*Leymus chinensis*) or the feather grass (*Stipa* spp.), (hereinafter referred as “Mixture”) used as forages were classified as multiannual biomass crops (MBC).

2.1.3. Time

Information about the experiment’s lifetime before and after the reversion were extracted from the literature. This was done because soil samplings after the reversion were performed at different time intervals between papers. The time interval between reversion and sampling was divided into five subgroups: 1st year, 2–5, 5–10, 10–30 and >30th year. The minimum period between reversion and the first soil sampling was set as 1 year.

2.1.4. Climate

The following climatic information were extracted from the papers: latitude, longitude, mean annual temperature (MAT) and mean annual precipitation (MAP). MAT was divided into three subgroups into <5 °C, 5–10 °C and >10 °C, while MAP was divided into two subgroups < 500 mm and 500–900 mm

2.2. Effect Size and Meta-Analysis

The effect size (ES), selected to measure the effect of reversion on soil C and N stocks, was the response ratio (RR) between prereversion C or N stock mean (X_1) and postreversion C or N stock mean (X_2) for each observation:

$$RR = \frac{X_1}{X_2} \quad (2)$$

RR computations were carried out on a log scale [36]. The RR was calculated as follow:

$$\ln R = \ln(R) = \ln\left(\frac{X_1}{X_2}\right) = \ln(X_1) - \ln(X_2) \quad (3)$$

A transformation from average RR to percentage of change was conducted to directly evaluate the effect using the equation below:

$$\text{Percentage change} = \left[\exp^{(RR)} - 1 \right] * 100 \quad (4)$$

The variance of the ES (V_{es}) was calculated as below:

$$V_{es} = S_{pooled}^2 \left(\frac{1}{n_1(X_1)^2} + \frac{1}{n_2(X_2)^2} \right) \quad (5)$$

where S_{pooled} is the pooled SD. S_{pooled} is calculated as:

$$S_{pooled} = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}} \quad (6)$$

where n_1 and n_2 are the sample size of the two groups, and S_1 and S_2 are the standard deviations of the two groups.

ES was calculated with the *escalc* function from the *metafor* [37] R package. Effects were calculated in a weighted, random-effects model using the *rma.uni* function in *metafor*. The weight assigned to each study was calculated by the inverse of its variance [36,38]. The heterogeneity (τ^2) was estimated using the restricted maximum likelihood (REML) model [39,40]. The 95% Wald-type confidence intervals (CI) were calculated to test whether RR differed significantly from zero. When a 95% CI value of the RR did not overlap with 0, we considered the effect of reversion to affect significantly soil C and N stocks. The *rma.uni* function was used to conduct the omnibus test to investigate differences between the levels of the different factors. When significant differences were found, Tukey's test for post hoc analysis under the general linear model (GLM) with Holm's adjustment was conducted with the *multcomp* package [37,40,41]. A stepwise multiple linear regressions analysis was applied, with the *leaps* package [42], to discriminate and rank the most important variables in explaining the change in soil C after the reversion. The following group of environmental variables were explored as predictors: MAP, MAT, time interval between reversion and sampling (YFR, years from reversion), the lifetime of the perennial crop (duration), clay content and the initial C stock. Best AIC models were selected and the relative importance of the chosen predictors in the linear model (% of total R^2 of the model) was estimated with the *relaimpo* [43]. The breakdown of the model R^2 into the relative importance metrics was performed with the *lmg* method, while the significance of the differences between the predictors' relative importance (Bonferroni $p < 0.05$) was calculated with the *bootstrap* function (1000 samples). All statistical analysis was conducted with R [44].

3. Results

3.1. Reversion of Perennial Crops

The database covers five countries: the United States of America, Germany, United Kingdom, France, and China (Figure 1 and Table S1) with a wide range of soil and climatic conditions (Table 1). Soil texture varied from sandy loams to clay loam soils. The duration of the studies varied from 1 to 70 years after the reversion. The average depth of reversion and soil cultivation after the reversion was 30 cm (Table 1). A detailed presentation of the studies included in this meta-analysis is reported in Table 2. In the following section, the change of soil C and N stock is presented as a function of soil depth layers or time passed since the reversion occurred. No significant effect of the reversion on soil C ($RR\% = -5.03$, $SE = 3.34$, $p = 0.13$) and N ($RR\% = 2.56$, $SE = 3.67$, $p = 0.48$) (fi) was found both using pooled data or by dividing the dataset according to the 0–30 and 30–100 cm layers (Table 3). Considering that no significant effects of the reversion were found in the 30–100 cm layer and that this layer was not involved directly in the reversion, the subsequent analyses were limited to data obtained from the 0–30 cm layer. Considering that there were no observations between the 5th to 10th year and just few in the 10th to 30th year and >30th year, the subsequent analyses were limited to data from the 1st and 2nd to 5th year. One year after the reversion, a significant increase of soil C and N stocks (+15% and +12% respectively, Table 3) was found in the 0–30 cm layer, while in the time interval

between the second to fifth year after the reversion, there was no significant increase or decrease of soil C and N (Table 3).

Figure 1. Location and type of perennial crops in the studies included in this meta-analysis.

Table 1. Environmental and soil characteristics of studies assessing the effect of perennial crops reversion.

Variable	Mean	Minimum	Maximum
Latitude	48.24	41.88	53.82
Longitude	49.35	−100.63	124.31
Elevation * (m)	310	22	1350
Mean annual temperature (°C)	6.29	−1	12
Mean annual precipitation (mm)	565	350	815
Duration (years)	14	5	>75
Years from reversion	13	1	70
SOC stock (0–30 cm, Mg ha ^{−1})	61.9	24.0	92.1
STN stock (0–30 cm, Mg ha ^{−1})	4.6	1.9	8.2
Depth of reversion (cm)	30	15	40

* Above mean sea level (a.m.s.l.). Abbreviations: SOC (soil organic carbon), STN (soil total nitrogen).

Table 2. Summary of data for the studies in the meta-analysis on the effect of perennial crop reversion on soil C and N stocks.

Reference	Country	Location	Climate	Depth (cm)	MAT (°C)	MAP (mm)	Elevation (a.m.s.l)	Crop	Perennial Crop Type	Main Crop	Duration	YFR	Texture Class
Toenshoff et al. (2013) [31]	Germany	Georgenhof	Continental	0–30	8	740	322	Poplar	Perennial biomass crop	Corn	20	1	silty loam
Toenshoff et al. (2013) [31]	Germany	Georgenhof	Continental	0–30	8	740	322	Poplar	Perennial biomass crop	Lolium perenne	20	1	silty loam
Toenshoff et al. (2013) [31]	Germany	Watchum	Continental	0–30	9	815	22	Poplar	Perennial biomass crop	Corn	20	1	sandy loam
Toenshoff et al. (2013) [31]	Germany	Watchum	Continental	0–30	9	815	22	Poplar	Perennial biomass crop	Lolium perenne	20	1	sandy loam
Toenshoff et al. (2013) [31]	Germany	Georgenhof	Continental	0–30	8	740	322	Willow	Perennial biomass crop	Corn	20	1	silty loam
Toenshoff et al. (2013) [31]	Germany	Georgenhof	Continental	0–30	8	740	322	Willow	Perennial biomass crop	Lolium perenne	20	1	silty loam
Wachendorf et al. (2017) [45]	Germany	Georgenhof	Continental	0–30	8	740	322	Poplar	Perennial biomass crop	Corn	20	4	silty loam
Wachendorf et al. (2017) [45]	Germany	Georgenhof	Continental	0–30	8	740	322	Poplar	Perennial biomass crop	Lolium perenne	20	4	silty loam
Wachendorf et al. (2017) [45]	Germany	Watchum	Continental	0–30	9	815	22	Poplar	Perennial biomass crop	Corn	20	4	sandy loam
Wachendorf et al. (2017) [45]	Germany	Watchum	Continental	0–30	9	815	22	Poplar	Perennial biomass crop	Lolium perenne	20	4	sandy loam
Wachendorf et al. (2017) [45]	Germany	Georgenhof	Continental	0–30	8	740	322	Willow	Perennial biomass crop	Corn	20	4	silty loam
Wachendorf et al. (2017) [45]	Germany	Georgenhof	Continental	0–30	8	740	322	Willow	Perennial biomass crop	Lolium perenne	20	4	silty loam
Qi et al. (2012) [46]	China	Xilin River Basin	Semi-Arid	0–100	−1	450	1350	Mixture	Multiannual biomass crops	Wheat	>75	36	NA
Dufossé et al. (2014) [47]	France	Paris	Oceanic	0–45	12	557	NA	Miscanthus	Perennial biomass crop	Wheat	20	1	silty loam
Dufossé et al. (2014) [47]	France	Paris	Oceanic	0–45	12	557	NA	Miscanthus	Perennial biomass crop	Bare soil	20	1	silty loam
Ding et al. (2013) [48]	China	Duerbote 1	Continental	0–100	4	407	150	Mixture	Multiannual biomass crops	Corn	>75	30	silty loam
Ding et al. (2013) [48]	China	Duerbote 2	Continental	0–100	4	407	150	Mixture	Multiannual biomass crops	Corn	>75	70	silty loam
Ding et al. (2013) [48]	China	Changling 1	Continental	0–100	5	470	150	Mixture	Multiannual biomass crops	Sunflower	>75	2	silty loam
Ding et al. (2013) [48]	China	Changling 2	Continental	0–100	5	470	150	Mixture	Multiannual biomass crops	Sunflower	>75	15	silty loam
Ding et al. (2013) [48]	China	Kezuohouqi 1	Continental	0–100	6	450	260	Alfalfa	Multiannual biomass crops	Corn	3	15	sandy loam
Ding et al. (2013) [48]	China	Kezuohouqi 2	Continental	0–100	6	450	260	Mixture	Multiannual biomass crops	Corn	>75	4	loam
Wienhold & Tanaka (2001) [49]	USA	North Dakota	Continental	0–15	4	410	549	Alfalfa	Multiannual biomass crops	Wheat	6	2	loam
Wang et al. (2008) [50]	China	Site 1	Semi-Arid	0–100	1	350	NA	Mixture	Multiannual biomass crops	Wheat	>75	35	sandy loam
Wang et al. (2008) [50]	China	Site 2	Semi-Arid	0–100	1	350	NA	Mixture	Multiannual biomass crops	Corn	>75	20	sandy loam

Table 2. Cont.

Reference	Country	Location	Climate	Depth (cm)	MAT (°C)	MAP (mm)	Elevation (a.m.s.l)	Crop	Perennial Crop Type	Main Crop	Duration	YFR	Texture Class
Wang et al. (2008) [50]	China	Site 3	Semi-Arid	0–100	1	350	NA	Mixture	Multiannual biomass crops	Wheat	>75	33	sandy loam
Wang et al. (2008) [50]	China	Site 4	Semi-Arid	0–100	1	350	NA	Mixture	Multiannual biomass crops	Wheat	>75	36	sandy loam
Kahle et al. (2013) [51]	Germany	Gülzow	Continental	0–90	9	578	NA	Poplar	Perennial biomass crop	Barley	17	1	sandy loam
Rowe et al. (2020) [52]	UK	Nottingham	Continental	0–100	10	741	NA	Miscanthus	Perennial biomass crop	Wheat	6	3	sandy loam
Rowe et al. (2020) [52]	UK	Taunton A	Continental	0–100	11	734	NA	Miscanthus	Perennial biomass crop	Wheat	6	4	silty loam
Rowe et al. (2020) [52]	UK	Taunton A	Continental	0–100	11	734	NA	Miscanthus	Perennial biomass crop	Wheat	7	3	silty loam
Rowe et al. (2020) [52]	UK	Taunton B	Continental	0–100	11	734	NA	Miscanthus	Perennial biomass crop	Alfalfa	5	4	silty loam

Abbreviations: mean annual temperature (MAT); mean annual precipitation (MAP); elevation is measured in meters above mean sea level (a.s.m.l); years from reversion (YFR); Not applicable (NA).

Table 3. Effect of reversion of perennial crops on soil C and N stocks according to soil depth and time factors.

Overall	Element	Effect (%)	Lower CI (%)	Upper CI (%)	p-Value
	Carbon	−5.03	−11.58	+1.53	ns
	Nitrogen	+2.56	−4.62	+9.75	ns
Depth (cm)	Element	Effect (%)	Lower CI (%)	Upper CI (%)	p-Value
0–30	Carbon	−4.79	−13.59	+4.02	ns
30–100	Carbon	−5.74	−15.49	+4.00	ns
0–30	Nitrogen	2.35	−6.90	+11.59	ns
30–100	Nitrogen	3.94	−6.81	+14.69	ns
Time	Element	Effect (%)	Lower CI	Upper CI (%)	p-Value
1st	Carbon	+15.24	+3.48	+27.00	0.01
2–5th	Carbon	−10.69	−27.14	+5.74	ns
1st	Nitrogen	+12.28	+1.59	+22.96	0.002
2–5th	Nitrogen	+3.46	−18.91	+25.83	ns

3.2. Effect of Crop Type

After the reversion of a perennial biomass crop (PBC), no significant changes of soil C (Figure 2) were found, but a significant increase of soil N (RR% = +15%, SE = 5.06, $p = 0.003$, Figure 3) was found. In contrast, when the reversion was performed on a multi annual biomass crops (MBC), significant losses of both C (RR% = −20%, SE = 6.46, $p = 0.002$, Figure 2) and N (RR% = −16%, SE = 5.92, $p = 0.008$, Figure 3) were found. Among the PBCs considered in this study, the reversion of willow increased both soil C (RR% = +26%, SE = 11.71, $p = 0.02$, Figure 2) and N (RR% = +43%, SE = 9.30, $p = 0.001$, Figure 3), while no significant increase or decrease of soil C and N were found after the reversion of poplar or miscanthus (Figures 2 and 3).

Figure 2. Percentage change of soil organic carbon (Mg SOC ha^{−1}) after the reversion of perennial crops according to perennial crop type (PBCs and MBCs), crop species or soil carbon stock in the 0–30 cm layer (Mg C ha^{−1}). Error bars represent the 95% confidence intervals. Parenthesis indicates the number of observations used to calculate the effect size.

Figure 3. Percentage change of nitrogen stocks (Mg N ha^{-1}) after the reversion of perennial crops according to perennial crops type (PBCs and MBC) and crop species. Error bars represent the 95% Confidence Intervals. Parenthesis indicates the number of observations used to calculate the effect size.

In agreement with what was reported for MBC, after the reversion of alfalfa or a mixture of perennial grasses species, no significant losses of soil C and N were found (Figures 2 and 3).

3.3. Effect of Environmental Conditions

The reversion of PCs significantly reduced soil C in the first 30 cm, only when the soil C stock before the reversion was below $58.5 \text{ Mg C ha}^{-1}$ (Figure 2). In contrast, there was no significant losses of C when soil C stock before the reversion was higher than $58.5 \text{ Mg C ha}^{-1}$ (Figure 2). In the first 30 cm, reversion decreased soil C significantly only in soil with loam texture ($\text{RR}\% = -40\%$, $\text{SE} = 15.70$, $p = 0.01$, Figure 4), otherwise, reversion had no significant effect on soil C or N (Figures 4 and 5). The reversion of PCs (Figures 4 and 5) decreased soil C when MAT was lower than 5°C ($\text{RR}\% = -15\%$, $\text{SE} = 7.08\%$, $p = 0.03$) or MAP was lower than 500 mm per year for both C ($\text{RR}\% = -20\%$, $\text{SE} = 7.05\%$, $p = 0.005$) and N ($\text{RR}\% = -15\%$, $\text{SE} = 5.92\%$, $p = 0.007$). No significant effect of fertilization on soil C and N were found after the (Figures 4 and 5). The linear relationships between the soil C stock after reversion was investigated with a series of linear regression analyses. Single linear regression models were built considering one variable at a time as the dependent variable and the soil C stock after the reversion as the independent variables. The only significant predictor that had a significant effect on soil C after the reversion was the duration of PC reversion experiments (42% of variance explained, Table 4).

Figure 4. Percentage change of soil carbon (Mg C ha^{-1}) after the reversion of perennial crops according to soil texture, mean annual temperature ($^{\circ}\text{C}$), mean annual precipitation (mm), fertilization. Error bars represent the 95% confidence intervals. Parenthesis indicates the number of observations used to calculate the effect size.

Figure 5. Percentage change of nitrogen stocks (Mg N ha^{-1}) after the reversion of perennial crops according to soil texture, mean annual temperature ($^{\circ}\text{C}$), mean annual precipitation (mm), fertilization. Error bars represent the 95% confidence intervals. Parenthesis indicates the number of observations used to calculate the effect size.

Table 4. Summary statistics of the regression model.

Variable	Residual Standard Error	Multiple R ²	Adjusted R ²	f-Statistic	p-Value	Significant Predictors (% Relative Importance) *
Change of SOC stock (Mg ha ⁻¹)	0.279	0.48	0.35	3.681	0.015	Duration (42%)
						Other predictors (% relative importance)
						MAP (28%), YFR (12%), MAT (9%), Initial C stock (6%),

Abbreviations: mean annual precipitation (MAP), mean annual temperature (MAT), years from reversion (YFR), duration of perennial crop experiments (Duration). * Metrics are normalized to sum to 100% of adjusted R². Significant differences among predictors ($p < 0.05$ Bonferroni test) were assessed by bootstrap ($n = 1000$) measures of relative importance

4. Discussion

This study collates data from papers on the reversion of perennial to arable crops. In total, 17 papers were found according to the combinations of keywords listed in Appendix A.

Nine of these seventeen were used in the meta-analysis. The other eight papers were excluded since data on soil C and N were not provided. However, they dealt with the topic of reversion focusing on other aspects such as the nutrient cycling [53], the C and N emissions from soil [54–56], the weed incidence or the soil quality after the reversion [32,57]. Another study, Toenshoff et al. [58], was excluded from the analysis because the time interval between reversion and sampling was shorter than 1 year, even though data on soil C and N were provided. In total, 49 observations for C (Table S2) and 39 observations for N (Table S3) were extracted from the nine papers included in this meta-analysis (Tables S4 and S5). Ledo et al. [8,30] evaluated the effect of different land-use conversion into PCs on soil C, compiling a dataset of 180 studies: potentially, 112 of them are suitable for being included in our meta-analysis once reverted. This difference between the number of studies in the database of Ledo et al. [8,30] with respect to this study is a clear indication of the lack of information on the reversion from perennial to annual crops. Most of the PC experimental trials reviewed in Ledo et al. [8,30] are continuing or maybe are undergoing the process of reversion but data on C dynamics are still not published. Despite this fact, our meta-analysis provided the first evidence in response to the concerns of several authors about the potential threats of reversion on losing the SOC sequestered by PCs during their crop lifespan [11,13,31]: this hypothesis is rejected. The reversion of PCs has no significant effect on soil C and N stocks (Table 3), either on the reversion layer (0–30 cm) or on the subsoil (30–100 cm) (Table 3). The findings of this study support the conclusion of many authors who have suggested that storing C in a deeper soil layer, as SOC or in the below-ground biomass, is a suitable solution to stock C in the long term since, in that layer, there are less favorable conditions for C degradation [59] and the soil is not directly involved in the reversion [10,13]. Since no significant changes of soil C and N were found in the reversion layer (0–30 cm) when using pooled data, the analysis was limited to this layer to analyze the effect of time factors on the change of soil C and N after the reversion. The observed increase of soil C and N one year after the reversion of PCs is a consequence of the initial incorporation of crop residues and BGB [60] which is considered one of the most important C sources for SOC accumulation even before reversion [25,61]. This initial increase of soil C and N is likely affected by the type of PC that is reverted as shown by crop type subgroup analysis in Figures 2 and 3. Miscanthus, poplar and willow, that are PBCs storing a high amount of C in belowground organs (such as rhizome and stumps) [13] when reverted do not affect soil C and N or significantly increase them. In contrast, when reverting an MBC richer in fine root biomass (i.e., *Medica sativa*, *Leymus chinensis* or *Stipa* spp.) significant losses of C and N were observed, likely due to a strong priming effect induced by labile C on native SOC [62]. The difference in the amount of C stored in the

BGB between PBCs and MBC is likely the factor that determines a significant C loss after MBC reversion.

Understanding the contribution of BGB residues to SOC sequestration during PC cultivation and after reversion is crucial to quantify the belowground climate mitigation potential of PBCs. As shown by Ferrarini et al. [60], in addition to quantitative BGB yield data, data on C mineralization of BGB residues are essential to refine the crop–soil model to predict long-term soil C changes associated to PC cultivation. For these reasons, new data on the BGB of PCs are needed. However, to date, only two studies have precisely quantified the belowground organs of PCs [13,63]. In the available literature, the most used approach is to measure the belowground biomass from soil coring with augers before [64,65] or after the reversion [31,55]. The coring method is time- and cost-effective and does not involve the use of heavy machinery [13,66]. Although the coring approach has been widely used for the estimation of fine root biomass in PCs [10,13,67], it has two major limitations for the estimation of the belowground organs in PBCs (i.e., stumps in woody PBCs and rhizomes in herbaceous PBCs): (1) a low reliability for measuring the amount of belowground organs on a hectare basis from the core area of few cm², (2) soil coring is not applicable to BGB of woody PBCs. As suggested by Klimešová and Martíková [66], there is an urgent need in the belowground sciences to embrace the “all belowground organs” viewpoint in the study of biomass and C allocation in PCs. For example, MBC can allocate more C in the belowground biomass with respect to the annual crops [68] but less than PBCs [69] since the former is mainly composed of the root systems and not by huge belowground organs [13,66].

Managing PCs in long-term crop rotation as shown by our meta-analysis is an effective carbon farming solution. The contribution of the BGB of PCs to SOC depends mainly on its turnover, that is influenced by the stand age and the source of input. According to data of Agostini et al. [70], the C input to soil from miscanthus rhizomes turnover, for example, is higher than the one from fine roots, while in crops such as switchgrass the main C input to soil is fine root biomass. As a result of a different turnover of BGB components, the C input under PBCs contribute to SOC in a significant amount as particulate organic matter (POM) not only before the reversion [11,71,72] but also after, if the BGB is incorporated and shredded into the soil. Toenshoff et al. [31] found that SOC in bulk soil was not affected by the reversion of willow or poplar plantations one year after reversion, but there was a significant increase of microbial biomass C and POM after the reversion. The shredding of the BGB and its transformation as POM depend strictly on the shredding efficiency of the machine performing the reversion, as, by definition, POM is largely made up of lightweight fragments from plants debris that are relatively undecomposed [73]. Immediately after the reversion of PBCs, arable soil can be considered as a POM-dominated system by three pools of different origin: the major POM pool derived from the belowground biomass shredding which enters the soil at the reversion, a second POM pool is the legacy of PBC cultivation that is composed by plant-derived free-light POM [11,71,72], a third pool is the POM released during tillage operations at the reversion that was previously stored as occluded POM into macro-aggregates [74]. The pulse C that enters the soil mainly as POM in large quantities at the reversion (i.e., POM from BGB shredding is on average of 15 Mg C ha^{−1}, Martani et al. [13]), can have two different fates: respired as CO₂ or sequestered in stabilized SOM fractions into the soil after microbial degradation (mineral-associated organic matter—MAOM). It is desirable to expect an initial huge peak of GHG emissions in the first days after the reversion due to the increase of SOM mineralization and priming effect caused by the pulse input of labile C sources from residues incorporation [75]. Dufossé et al. [47] and Drewer et al. [54] for example found an increase of CO₂ emission from the soil directly after the reversion of miscanthus, while McCalmont et al. [55] found an increase of GHG emissions, especially N₂O, following the reversion of willow and miscanthus plantations. After this initial period of C losses, the soil system likely enters a phase of C sink, owing to rapid and constant humification of the POM into a stable MAOM fraction. Indeed, 1 year after reversion, already a significant increase of C and N stocks

was observed. However, this meta-analysis suggested that soil C and N storage trajectories become stabilized between the second and fifth years after the reversion with no significant stock increases.

Soil reverted from PBCs to arable cropping may further increase in SOC content until a new equilibrium level is reached but suitable agronomic practices must be adopted. From an agronomic and environmental viewpoint, it is desirable to keep the legacy of SOC storage trajectories of the previous cropping system as high as possible as this is beneficial for the whole range of SOM functions. SOM formation and decomposition are determinants of C persistence and soil functions under PBCs. Targeting MAOM for SOM sequestration is logical for persistence, but not always feasible, as MAOM can saturate [76] while POM cannot. The POM vs. MAOM framework has been recently proposed to support recommendations on SOM management to practitioners and policy makers [73]. This framework is particularly helpful to study the reversion of PBC plantations and how these pools contribute to two important management goals of arable cropping systems: fertility goal (high nutrient cycling rate) and climate goal (long-term soil C sequestration). After reversion to arable land, targeting POM or MAOM may reflect two distinct strategies for managing C and nutrients in soil: targeting POM might be useful for achieving soil fertility goals while targeting MAOM might be useful for climate goals. This suggests that understanding the effect of soil, crop, and fertilizer management strategies on the decomposition dynamics of the C input after reversion is crucial to meet these dual goals. For example, Ferrarini et al. [60] in a lab-incubation experiment with six PBC residues found that the C/N ratio is not the main controlling factor of decomposition when residue N is not a limiting factor, while the availability of easily decomposable substrates and cell-wall composition decomposition is a strong predictor of C and N mineralization. At reversion, the high and pulse input of labile C from BGB residues might become the main precursor of MAOM “potentially” generated after reversion of PBCs. The issue of how to manage C-rich BGB residues at reversion calls for an integrated residue:nutrient management strategy able to boost the so-called microbial C pump (MCP) [77,78]. MCP emphasizes the active role of soil microbes in SOC storage by integrating the continual microbial transformation of organic C from labile to stable C fractions. Several recent findings showed how it feasible to assist microbially-mediated crop residue humification by integrating minimum tillage and crop fertilization strategies [79] with supplementary stoichiometrically balanced fertilization of crop residues [80–82]. The first years following PC reversion, the available C residues for humification stand at values higher than the critical threshold of $2.0 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ identified by Wang et al. [83] to maintain current SOC stocks in common wheat systems. For these reasons, supplemental fertilization of crop residues the first year after reversion is reasonable to sustain MCP and thus the humification of POM-C inputs into stable MAOM fractions. Another important aspect of reversion is the crop type and soil management practices adopted on the reverted soil. Crop rotation characterized by crops with high C inputs in terms of belowground C allocation and harvest residues (cover crops, temporary grassland, grain maize) and proper conservation tillage practices (minimum or no tillage) are two carbon farming practices that can strongly support SOM storage trajectories during the first years after reversion.

In this meta-analysis the response of soil C and N stocks to reversion was analyzed as a function of the environmental conditions by building single linear regression models considering one variable at a time as the dependent variable and the variation of soil C stocks after the reversion as the independent variable: the only significant predictors of the change of soil C after the reversion is the duration of the PC experiment. The initial soil C stock, clay content, MAT and MAP were expected to be the main environmental factors controlling the fate of C and N stocks in soil as previously found by other meta-analyses addressing land use change [84,85]. Higher clay or silt content may help to reduce the loss of soil C and N stocks from the reversion [85–87] as the surface charge of the organic compounds binds to silt and clay particles leading to chemical protection of soil C [88] and new aggregates are thus physically protected [89]. Nonetheless, our meta-analysis

suggested that that PC's lifespan is the key factor: the higher the duration of the PC, the higher the C input is to the soil at reversion from BGB incorporation available for decomposition and humification.

In conclusion, there are two research questions that will need to be addressed by future reversion studies to exploit the full climate-neutral potential of PBC introduction into crop rotation. First, they will have to tackle the issue of quantifying the BGB of PBCs and notably understand its contribution to C and N storage trajectories. Second, to support ecologically sustainable reversion trajectories, they will have to operationally link and identify the agricultural practices that co-target POM and MAOM meeting both C sequestration and soil fertility goals.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy12020232/s1>, Table S1: Overview of the studies used in the meta-analysis, Table S2: Overview of the studies in the carbon dataset and their treatments and results. Table S3: Overview of the studies in the nitrogen dataset and their treatments and results. Table S4: Overview of the results of the random effects model for soil carbon stock and their statistics. From column L onwards, measures of heterogeneity of the random effects model are presented, once for the entire data set and once for within groups. Table S5: Overview of the results of the random effects model for soil nitrogen stock and their statistics. From column L onwards, measures of heterogeneity of the random effects model are presented, once for the entire data set and once for within groups.

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Appendix A

Search string: (perennial biomass crop OR perennial energy crops OR perennial crops OR perennial cropping systems OR perennial agricultural systems) AND (reversion OR dismission OR reconversion OR cultivation) AND soil AND (carbon stock OR C stock OR SOC or soil organic carbon).

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