Review

Soil Organic Carbon in Alley Cropping Systems: A Meta-Analysis

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Abstract: Population growth and an increasing demand for food cause the intensification of agriculture leading to soil degradation and a decrease in the soil organic carbon (SOC) stock. Agroforestry systems such as alley cropping are gaining more and more attention as a practice to maintain and/or increase SOC in agroecosystems. The aim of this study was to add to the knowledge on SOC in alley cropping systems and to evaluate the contribution of introducing trees into agricultural landscapes by conducting a meta-analysis of the available data. The soil carbon (C) input will increase with time. Our findings suggest that a beneficial effect on SOC occurs after approximately a decade of alley cropping practice adoption. Furthermore, the effect of alley cropping is more beneficial in regions with lower initial SOC concentration compared to that in regions rich in SOC. Higher relative SOC is observed in the tropical region compared to that in the temperate climate zone. The establishment of alley cropping systems on agricultural land needs to consider several parameters such as alley width and tree species when designing such systems to achieve the highest possible tree and crop productivity while increasing SOC.

Keywords: alley cropping; soil organic carbon concentration; soil organic carbon stock; tree age

1. Introduction

Population growth, changes in consumption patterns, and intensive industrialization have led to the increase of carbon dioxide (CO_2) emissions into the atmosphere. At the same time, deforestation and intensification of agriculture, as well as urbanization and land-use change, resulted in soil degradation and reduction of plant cover, which had a positive role in sequestering atmospheric CO_2 and increasing its turnover time [1]. The soil organic carbon (SOC) pool contains more than twice as much carbon (C) as there is C in the atmosphere [2], and as such, soil represents the largest reservoir of SOC in the terrestrial biosphere. Therefore, the soil has a vital role in C cycling and mitigating greenhouse gas (GHG) emissions through SOC sequestration [2]. Forest ecosystems account for approximately 73% of the SOC pool [3], and, thus, deforestation and intensive agriculture can slow down the C flow between the atmosphere and pedosphere. There is a need for increasing afforestation and establishing agricultural systems that store more C. It is important to identify agricultural practices that will intensify the C flow between the atmosphere and the pedosphere [4,5]. Efficient management of agricultural systems, such as alley cropping systems, in which trees are introduced into the agricultural land with crops grown between tree rows, can increase C sequestration and positively reduce anthropogenic CO_2 emissions [6–9]. Alley cropping entails the mixing of crops with trees and/or shrubs on the same land area. It combines the production of tree and crop outputs with the provisioning of ecosystem services, such as nutrient cycling [10,11], maintenance of soil quality [12], and microclimate and erosion control [13–15].

Although alley cropping was a common agricultural practice, with the intensification of agriculture, farms' commercial characteristics have changed; a lack of immediate financial benefit and soil preservation policies has led to the abandonment of alley cropping systems. One of the first alley cropping systems in recent times was established in 1982 where maize (*Zea mays* L.), beans (*Phaseolus* sp.), and cassava (*Manihot esculenta* L.) were integrated with trees such as *Erythrina poeppigiana* in order to evaluate crop productivity and the ability to maintain soil fertility [16].

Nair et al., 2010 [17], reported that agroforestry systems could store between 30 and 300 Mg C/ha in up to 1 m of soil depth. Introducing trees into agricultural land and creating an alley cropping system is also an agroforestry approach that positively affects C sequestration [6,9]. Thus, management practices that include incorporating trees into the agricultural land are considered an efficient strategy for soil C sequestration and mitigation of GHGs within agroecosystems [17]. However, the long-term influence of the incorporation of trees on soil C sequestration potential and stabilization of SOC, along with its storage and accumulation, needs to be evaluated. The stability of SOC is affected by the presence of trees and the quantity and quality of litter inputs [18]. Management practices have little effect on stable C forms due to their long turnover time in soil. However, labile soil C pools are more responsive to management changes, and, although labile SOC pools are a relatively small fraction, they can serve as an indicator of changes in SOC [19].

Shi et al. [20] report positive differences in SOC in alley cropping stands compared to that in agricultural fields. However, in their meta-analysis, they used a large number of publications that investigated alley cropping stands that were converted from natural forests to alley cropping. The decay of organic matter (OM) can take up to several decades [21], so it is expected that SOC in such alley cropping systems, converted from natural forests, is higher than that in long-term agricultural fields under monocultures. However, what about the land-use conversion in the other direction? What is the trend of SOC when converting agricultural monoculture fields to alley cropping stands? Will the trees have a positive effect? How long will it take them to increase SOC concentrations? Will there be differences among different tree families? Will there be differences between climate zones? Laganière et al., 2010 [22], conducted a meta-analysis on afforestation of agricultural fields, i.e., converting agricultural fields to tree plantations, and found a positive effect of trees on SOC. Tree plantations are similar to alley cropping systems, the difference is the intercrop in between tree rows. However, such intercropped alley cropping systems can have much wider tree alleys, compared to tree plantations, in order for the crop to grow in between tree rows. Will the same beneficial effect on SOC be observed in such systems similar to that observed by Laganière et al. [22] and Shi et al. [20]?

Dhillon and Van Rees [21] reported that assessments of SOC pools could help determine the effects of land management practices on soil C sequestration potential as well as its quality and fertility. In this research, we were interested in the impact of trees on SOC when trees are introduced into agricultural fields and not alley cropping stands established on previously natural forest sites. This study discusses SOC concentrations in alley cropping systems and evaluates the importance of introducing trees into arable land and its effect on SOC concentrations. We hypothesized that introducing trees into agricultural land will have a beneficial impact on SOC, especially on degraded soils. The additional objective of this article was to add to the knowledge on SOC in alley cropping systems and to evaluate the effect of tree age and tree taxonomic family on SOC in different climate zones by conducting a meta-analysis of the available data. Filling this knowledge gap contributes to the improvement of decision-making regarding growing trees in agricultural landscapes.

2. Materials and Methods

2.1. Data Collection

For the purpose of meta-analysis, an extensive literature search of published papers was conducted during November 2021 using the Web of Science Core Collection (WoS

CC) database. Search terms used in the first search were "alley cropping" AND "soil" AND "carbon"; in the second, they were "alley cropping" AND "soil" AND "organic" AND "matter"; and in the third, "alley cropping" OR "silvoarable" AND "soil organic carbon". These three searches identified 940 papers that were searched for data on SOC or SOM in alley cropping systems and sole crop systems. We excluded manuscripts where agroforestry sites were established from natural forests and then compared with agricultural fields without trees. We focused our review only on research in which trees were introduced into agricultural fields and whether any change was reported compared to SOC in agricultural fields. We excluded manuscripts reporting total C and focused on studies reporting only SOC or SOM as we were interested in the C input from biomass (tree and crop). A total of 43 articles were identified with such data (Figure 1). For these 43 articles, using these two data sets (SOC in alley cropping and SOC in sole crop system), relative soil organic carbon values (RSOC) of SOC were calculated in alley cropping (alley cropping SOC/agricultural SOC). The collected data on relative soil organic carbon (RSOC) in alley cropping systems were used to conduct a meta-analysis from the reviewed literature. Such an approach is commonly applied in the meta-analysis, where experimental treatment values and control treatment values are used to calculate the relative values for each study [23]. This procedure was deemed necessary to harmonize the data and minimize the influence of diverse approaches in the data. These procedures created a total of 377 data sets that were used in further analysis (Table 1).
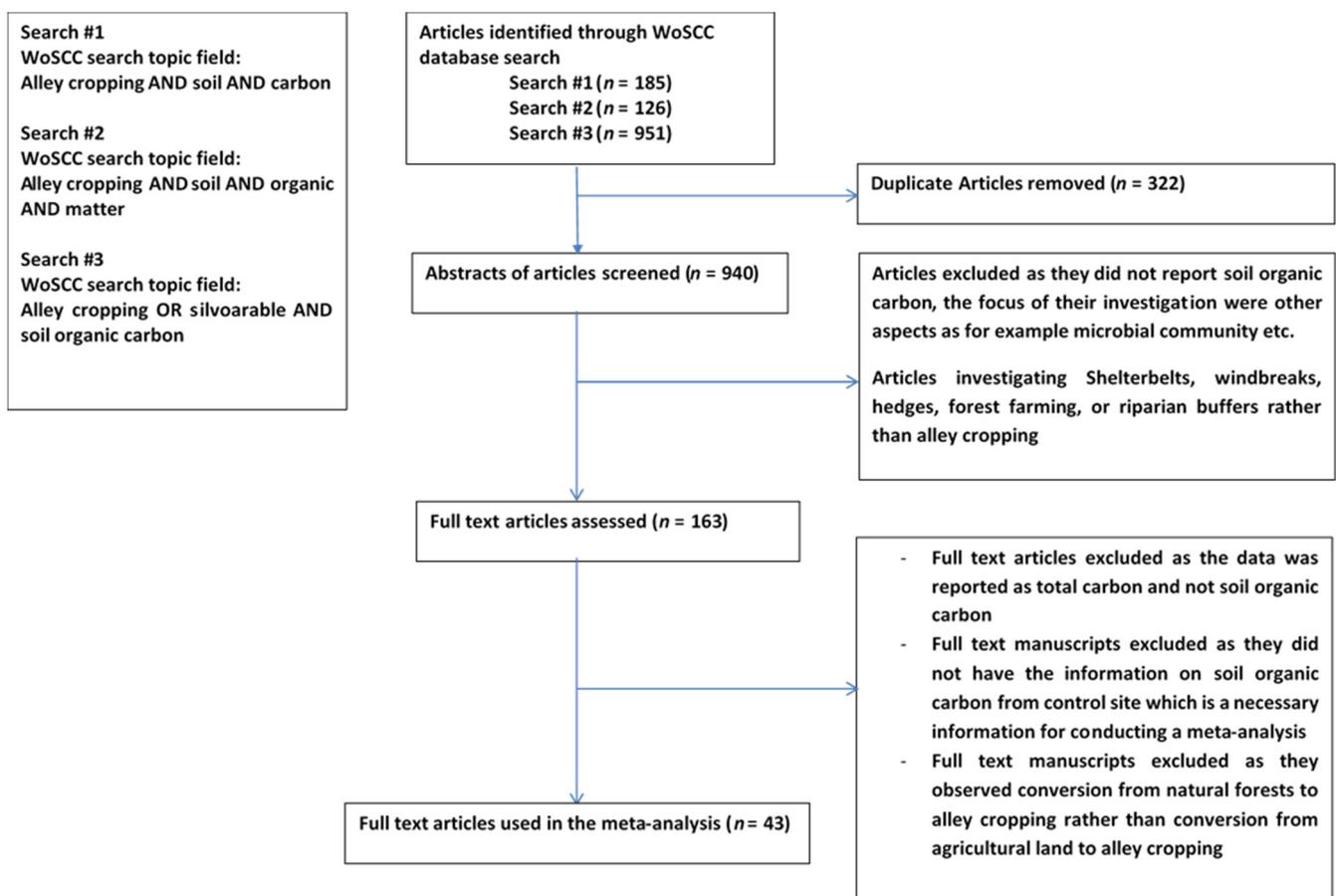

Figure 1. PRISMA diagram for selection of articles procedure.

Table 1. Studies and data included in the analysis (Climate zone, Region, Tree family, AC age—age of the alley cropping system, Alley width, SOC—soil organic carbon, C STOCK and RSOC—relative soil organic carbon).

MS nr.	MS	nr. Sites	Climate Zone	Region	Tree Family	*n*	AC Age	Alley Width	SOC	C STOCK	RSOC
							Year	m	%	t/ha	AVG
1	Andrianarisoa et al., 2016	1	Temperate	S. Europe	*Juglandaceae*	5	14	13	N/A	242.00	1.03
2	Benbi et al., 2012	1	Tropical	Asia	*Salicaceae*	1	6	5.3	0.83	N/A	1.04
3	Cardinael et al., 2015	1	Temperate	S. Europe	*Juglandaceae*	10	18	13	0.67	N/A	1.02
4	Cardinael et al., 2017	5	Temperate	S. Europe	*Juglandaceae*	19	6, 18, 41	11, 13, 14, 26, 29	1.38	N/A	1.11
5	Cardinael et al., 2019	10	Temperate	S. Europe	*Salicaceae, Juglandaceae*, Mix. Sp.	10	6, 7, 8, 9, 18, 41	9, 11, 12, 24, 27, 28	N/A	64.90	1.14
6	Dalland et al., 1994	1	Tropical	Africa	*Fabaceae*	2	7	3	0.78	N/A	1.05
7	Gao et al., 2013	1	Temperate	Asia	*Rosaceae*	6	4	5	0.51	N/A	0.75
8	Guo et al., 2009	1	Tropical	Asia	*Salicaceae*	4	2	4	0.57	N/A	1.12
9	Gupta et al., 2009	1	Tropical	Asia	*Salicaceae*	6	1, 3, 6	6.5	N/A	13.03	1.49
10	Henriksen et al., 2002	1	Tropical	C. America	*Fabaceae*	24	7	6	10.39	N/A	1.02
11	Hulugalle et al., 1993	1	Tropical	Africa	*Fabaceae*	1	1	6	1.12	N/A	0.78
12	Hulugalle et al., 1994	1	Tropical	Africa	*Chrysobalanaceae, Fabaceae*	3	1	6	1.64	N/A	0.88
13	Isaac et al., 2003	1	Tropical	C. America	*Fabaceae*	27	3, 5	8	2.41	N/A	1.09
14	Jackobsen and Jordan, 2009	1	Temperate	N. America	*Fabaceae*	3	2, 3, 4	5	N/A	12.77	1.18
15	Kang et al., 1998	1	Tropical	Africa	*Euphorbiaceae, Chrysobalanaceae, Fabaceae*	8	11	4	0.94	N/A	1.11
16	Korwar and Radder, 1997	1	Tropical	Asia	*Fabaceae*	8	2, 3, 4	6.6	0.62	N/A	1.15
17	Kremer and Kussman, 2011	1	Temperate	N.America	*Juglandaceae*	20	7, 8, 9, 10, 13	15	2.22	N/A	1.20
18	Lal, 1996	1	Tropical	Africa	*Fabaceae*	8	4, 5, 6, 7	4	1.41	N/A	1.12
19	Lee and Jose, 2003	1	Tropical	N. America	*Juglandaceae*	2	3, 47	18.5	1.42	N/A	1.17
20	Lu et al., 2015	1	Temperate	Asia	*Juglandaceae*	3	7	8	1.05	N/A	0.92
21	Lulu and Insam, 2000	1	Tropical	Africa	*Fabaceae*	3	7	5	2.07	N/A	1.37
22	Makumba et al., 2006	1	Tropical	Africa	*Fabaceae*	5	11	1.5	0.54	N/A	2.07
23	Mao et al., 2012	1	Temperate	Asia	*Salicaceae*	4	4	4	0.43	N/A	1.07
24	Mao et al., 2013	1	Temperate	Asia	*Salicaceae*	2	5	4	0.43	N/A	1.08
25	Mapa and Gunasena, 1995	1	Tropical	Asia	*Fabaceae*	8	3	4	1.90	N/A	1.60
26	Medinski et al., 2014	3	Temperate	N. Europe	*Salicaceae, Fabaceae*	24	1, 3, 4	48	N/A	1.54	1.08

Table 1. *Cont.*

MS nr.	MS	nr. Sites	Climate Zone	Region	Tree Family	*n*	AC Age	Alley Width	SOC	C STOCK	RSOC
							Year	m	%	t/ha	AVG
27	Moura et al., 2010	1	Tropical	S. America	*Fabaceae*	15	5	4	1.06	N/A	1.25
28	Oelbermann et al., 2004	3	Tropical	Africa, Asia, C. America	*Fabaceae*	10	5, 6, 10, 13, 19	6	2.14	48.79	1.25
29	Oelbermann et al., 2006a	1	Temperate	N. America	*Salicaceae*	2	13	12.5	N/A	113.50	1.04
30	Oelbermann et al., 2006b	1	Tropical	C. America	*Fabaceae*	8	10, 19	6	N/A	131.66	1.17
31	Park et al., 1994	1	Temperate	N. Europe	*Salicaceae*	6	4	12.5	3.38	N/A	1.06
32	Ramesh et al., 2015	1	Tropical	Asia	*Magnoliaceae, Fabaceae, Betulaceae, Pinaceae*	20	26	5	3.2	N/A	1.24
33	Rhoades et al., 1998	1	Temperate	N. America	*Fabaceae*	2	3	4	N/A	9.95	1.08
34	Rivest et al., 2013	1	Temperate	N. America	Mixed sp.	1	8	12	2.25	N/A	1.14
35	Schmidt et al., 2021	3	Temperate	N. Europe	*Salicaceae*	3	6, 8, 9	48	N/A	52.97	1.12
36	Seiter et al., 1999	1	Temperate	N. America	Mixed sp.	12	3	0.8, 4.5	2.25	N/A	1.06
37	Spacicini et al., 2002	1	Tropical	Africa	*Fabaceae*	2	5	N/A	1.53	N/A	0.86
38	Tian et al., 2005	1	Tropical	Africa	*Fabaceae*	8	11	4	1.07	N/A	0.94
39	Upson and Burgess, 2013	1	Temperate	N. Europe	*Salicaceae*	5	19	10	1.75	N/A	1.03
40	Vanlauwe et al., 2000	8	Tropical	Africa	*Fabaceae*	8	3, 5, 6, 9	4.5	0.79	N/A	1.16
41	Vanlauwe et al., 2005	1	Tropical	Africa	*Fabaceae*	8	16	4.5	0.79	N/A	1.57
42	Wang and Cao, 2011	1	Tropical	Asia	*Ginkgoaceae*	3	4	8	0.99	N/A	1.09
43	Winans et al., 2014	2	Temperate	N. America	*Salicaceae*, mix sp.	48	9	10, 12	N/A	42.49	0.81
		70				**377**					

N/A—no data.

2.2. Standardization and Calculation of the Carbon Data

The identified 43 studies for the analysis varied widely in the way of presenting the results by using different units, soil depths, or methods for determining SOC or SOM. Some reported percentages SOC or SOM concentrations and some SOC stocks (Mg/ha) taking into consideration soil depth and bulk density (BD). However, all 377 had the data on alley cropping SOC as well as sole cropping SOC and, thus, it was possible to analyze all 377 data points. Some studies sampled soils within the alleys while others sampled within rows as well. Only the data within the alleys were considered in this analysis. Most of the research monitored alley cropping stands of age between 0 and 20 years, one study investigated an alley cropping stand of 26 years [24], and three studies had data points for alley cropping stands over 40 years of age [6,25,26]. Data points over 40 years of age were considered outliers and not used in this analysis, retaining 373 data points. Since most of the data originated from relatively young alley cropping systems, we applied the same models on data from 10 cm depth, 40 cm depth, and using the whole data set. The models were developed only by using relative values as these data showed the highest heterogeneity of the data compared to the observed values. The following observed parameters influencing SOC in alley cropping systems were considered by the analysis: tree age (age of the alley cropping system), climate zone, and tree family. Variables were tested for interaction, and no interaction was found. The regression models were developed using "tree age" as a continuous variable and "climate zone" and "tree family" as categorical variables. The models were developed for the data up to 10 cm depth (110 data points), 40 cm depth (200 data points), and all data (373 data points). Models using data up to 10 and 40 cm depth showed no significant effect of any of the observed variables; so, we focused our discussion on model outcomes and findings from the models using the whole data set of 373 data points. In the regression analysis, a study was considered as a random effect while all other parameters were fixed effects, so this was a mixed-effect model. Study as a random factor was more supported (judged by ΔAIC) compared to when using location or study and location as a random factor. Using study as a random factor accounts for the correlation between data originating from the same research or experiment, thus accounting for an imbalance in the number of observations between different experiments and ensuring that each experiment gets an appropriate weight in the analysis in relation to the number of observation records and the correlation between measurements from the same study [23,27].

2.3. Statistical Analysis

Three mixed-effects models were fitted to the data (Table 2). Differences in relative SOC in alley cropping between different climate zones is described by model 1. In this model, β_1 describes the difference in relative SOC between temperate and tropical climate zone. Model 2 estimates the effect of tree age on mean relative SOC in alley cropping. The effect of tree species was described in model 3. In all the models, the random variation in relative SOC between experiments is described by a_i. This term is normally distributed with mean zero and a variance, which describes the variation in relative SOC between experiments. Residual variation is described by ε_{ij}, where i denotes the experiment and j denotes an observation in an experiment (Table 2).

Descriptive statistics and mixed-effect models were conducted in R [28], using the R function lme from the R package nlme [29]. The assumption of equal variance was checked by model plots of residuals against fitted values [27]. No violations of model assumptions were found.

Table 2. Specification of models fitted to the data.

Model	Model Equation	Data	Effects Studied
1	$RSOC_{ij} = \beta_0 + \beta_1 \times Climate\ zone_{ij} + a_i + \varepsilon_{ij}$	373 records	Climate zones: tropical and temperate (categorical)
2	$RSOC_{ij} = \beta_0 + \beta_1 \times Tree\ Age_{ij} + a_i + \varepsilon_{ij}$	373 records	Tree age (continuous)
3	$RSOC_{ij} = \beta_0 + \beta_1 \times Tree\ family_{ij} + a_i + \varepsilon_i$	373 records	Tree family: Juglandaceae, Fabaceae, Chrysobalanaceae, Betulaceae, Salicaceae, Euphorbiaceae, and mixed species (categorical)

The indices i and j represent experiment ID and treatment ID within an experiment, respectively. a_i is a random experiment effect, assumed to be normally distributed with constant variance. ε_{ij} is a residual random error, assumed to be normally distributed with constant variance. a_i and ε_{ij} were assumed to be independent. The number of records analyzed varied depending on the number of records with available data.

3. Results and Discussion

The correlation analysis shows the correlation of RSOC with alley width and tree age (Table 3). Such correlation indicates that older tree stands had higher RSOC values, suggesting accumulation of SOC with time. In addition, alley width and RSOC concentrations were negatively correlated, i.e., the wider the alley, the lower the RSOC concentrations, i.e., higher tree density was associated with higher SOC concentrations [30]. It is assumed that narrower alleys will have more trees and, therefore, more biomass and higher input of biomass C from tree litter and roots.

Table 3. Correlation of tree age and alley width with SOC (%), SOC stock (Mg/ha), and relative SOC.

	Tree Age	Alley Width	Relative SOC	SOC%
Alley width (m)	−0.199 0.0001			
Relative SOC	0.108 0.037	−0.125 0.016		
SOC%	−0.010 0.864	−0.059 0.343	−0.116 0.061	
SOC Mg/ha	−0.028 0.716	0.224 0.003	0.236 0.002	0.047 0.724

Relative SOC—the ratio between SOC in alley cropping system and agricultural field.

Models using only data up to 10 cm depth and 40 cm depth showed no significant effect of tree age, tree family, or climate zone. This might be due to the lower number of data points and lower variation. A significant difference was observed for RSOC among different climate zones ($p < 0.037$) (Figure 2), while tree age showed significance at the 0.1·significant level ($p < 0.056$) when using the whole data set (models 1 and 3) (Figure 3). Such low significance of tree age is probably due to a lack of data from older systems. Only one manuscript reported an alley cropping system over 20 years. The effect of the tree family was found not to be significant; however, this was probably due to the young age of the alley cropping stands as several authors reported a significant effect of tree species on SOC stocks in forest systems observed over a longer time period [31,32].
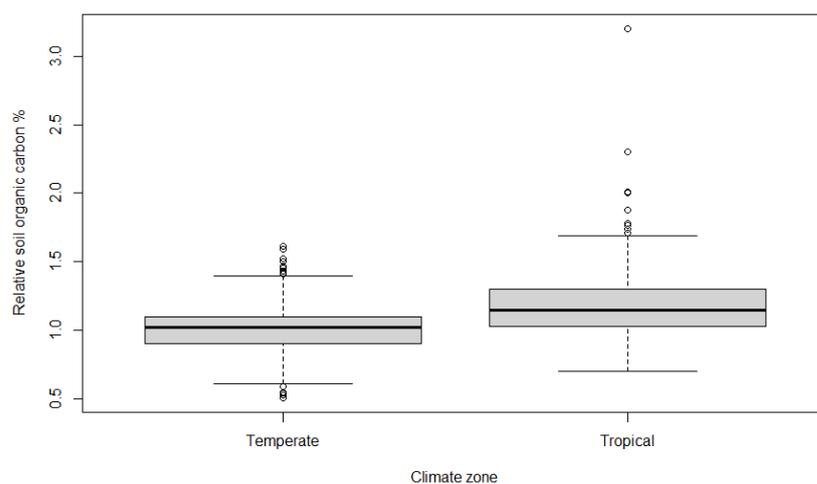
Figure 2. Relative soil organic carbon (SOC in alley cropping/SOC in agriculture) by climate zones.
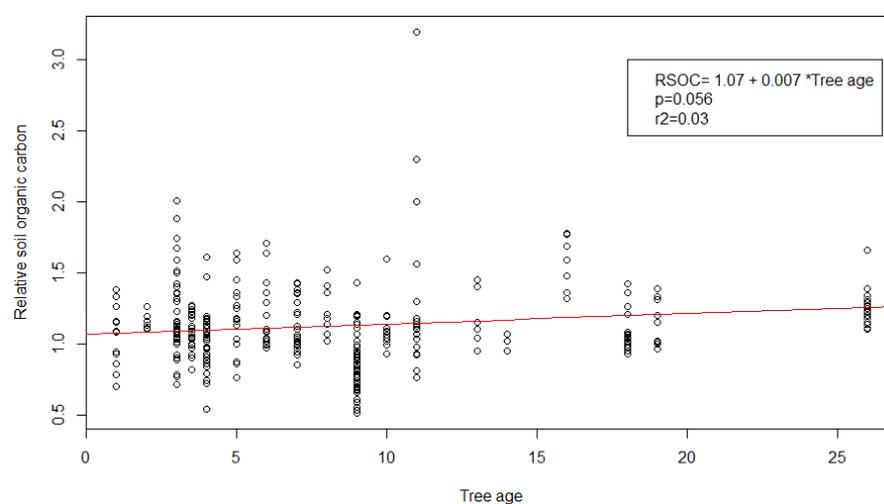

Figure 3. A plot of relative soil organic carbon (RSOC) against tree age. The regression line was fitted with model 2 (Table 1). * symbol stands for multiplication sign.

Although weak, the effect of tree age ($p < 0.056$) supports the findings of other authors who report an increase in SOC over time [6,24,26,33,34], which can be observed in Figure 3. However, not all trees mature the same, and since there was no interaction between the tree age and the tree family, we tried the model with tree age and tree family. Therefore, the model was refined by including the tree family ($RSOC_{ij} = \beta_0 + \beta_1 \times$ Tree Age$_{ij} + \beta_2 \times$ Tree family$_{ij}$ a$_i + \varepsilon_{ij}$). However, such a model was less supported (judged by ΔAIC). Since different tree species are used in different regions, we hypothesized that different tree species produce different amount of biomass and, therefore, may influence the C input into soil differently. However, model 2 shows no significant effect of the tree family on RSOC. The climate zone has been shown to have a significant effect on the RSOC, given that data from the tropical climate zone were significantly higher than RSOC values in the temperate zone ($p < 0.037$). The tropical zone includes data from degraded soils in Africa, Asia, and South America, where introducing trees had the most beneficial effect on SOC.

3.1. Soil Organic Carbon in Alley Cropping Systems in Different Regions and Climate Zones

Agroforestry systems such as alley cropping systems can directly influence atmospheric C and moderate the negative effect of climate change. However, SOC stocks may vary between the arid, semiarid, degraded sites, and tropical agroforests [35]. Moreover,

different climate zones or regions have different tree species and soil types, which influence SOC.

One of the key problems when reviewing and comparing findings from different publications is the considerable heterogeneity in the results reported. The reported data sets are mostly incomparable and inconclusive [36]. Sampling depth varies considerably among the studies, and the soil classification is often not comparable, as different authors have different approaches in determining soil class, which cannot be transferred readily from one classification system to another. The main issue with such data is the differences in soil depth among the studies, making the interpretation of results difficult. In the reviewed papers, soil depth was in a range from 5 cm depth up to 200 cm depth, which gave different SOC stock values, and it is difficult to compare such results. For example, in one study from Southern Europe [37], the SOC stock value for depth 0–100 cm was 297 Mg/ha and for depth 0–200 cm was 534 Mg/ha. In contrast, most of the other studies reported SOC values up to 40 cm depth [25,38,39], or the data were presented for deeper layers but through several sections [6], but in some cases, the SOC was presented as the average for the whole soil layer up to 150 cm [40] or even 200 cm depth [37]. Such presentation of the results as absolute values makes it difficult to discuss or compare the findings. The only way to compare the results is to observe them as the ratio between SOC in alley cropping and SOC in a sole crop in agricultural fields. With such relative values of SOC, we can assess eventual changes in SOC caused by establishing alley cropping systems.

The highest SOC concentrations are often reported for tropical climate zones [24,33,41] in comparison to temperate climate zones [6,42,43]. For example, the highest SOC concentration was reported in Central America by Henriksen et al. [41], where the SOC in the alley cropping system exceeded 10%, which is much higher than in all the other reviewed papers.

Different regions or climate zones have different tree species, which can influence the SOC input [33]. The most represented tree families in review papers were Fabaceae, Juglandaceae, and Salicaceae. Juglandaceae and Salicaceae are the most common species used for alley cropping in the temperate zone [44]. Fabaceae species are often used in alley cropping in a tropical zone as it is a nitrogen (N)-fixing family [45]. The Juglandaceae family is most commonly represented by walnut trees (*Juglans* spp.). Walnut trees are planted in wider alleys compared to other orchards allowing the possibility of intercropping. They have high-value timber as well as valued fruit, which makes them ideal for use in temperate alley cropping systems [46]. Salicaceae species are fast-growing tree species cultivated for biomass feedstock for bioenergy production [47]. In general, Fabaceae trees are used when the purpose of alley cropping is soil improvement and regeneration [13,48,49]. Juglandaceae trees are grown to diversify agricultural production and, at the same time, reduce further degradation of soil. Salicaceae trees are used in wide alleys on agricultural fields when bioenergy production should not affect food production [48]. Specifically, growing bioenergy plants on agricultural fields may increase food prices. Nevertheless, if bioenergy and food production occur on the same area of land, an increase in food prices might be avoided. We argue that introducing trees into agricultural land is mainly driven by these three incentives: soil improvement, food production diversification, and biomass energy production.

The lowest SOC values were reported for Asia and Africa [33,34,50–53] in comparison to other regions [6,33,40,42,54]. Such results indicate that alley cropping systems in Asia and Africa were established on soils of poor quality. Land-use change from natural forests to cropland results in faster depletion of SOC [55,56]. Quick SOM depletion on deforested land is caused by high temperature and humidity. This especially occurs in the tropical zone where conversion of natural systems to agroecosystems causes up to 75% SOC depletion, while in the temperate region, land-use change causes 60% SOC depletion [57]. The tropical zone is more sensitive as soils are affected by intense soil weathering due to soil properties, high temperature, and rainfall. However, with increasing climate change, such scenarios could happen in temperate zones as well. Trees directly contribute to the organic matter

input by litterfall, but they also have a positive effect on microclimate, i.e., trees reduce large oscillations in temperature and humidity. Therefore, alley cropping can have a positive effect on microclimate and, thus, a beneficial effect on improving carbon cycling and preventing SOC depletion [58].

When observing the relative values, it seems that, in North America, the influence of alley cropping on SOC is the smallest compared to that in other regions. High soil quality (high SOC stocks) in North American sites probably led to a relatively lower increase in SOC than that observed in sites with poorer soil quality. On the other hand, the highest increase in SOC is observed in Asia and Africa [33,34,59] (Figure 4). Such a finding confirms our hypothesis of a beneficial effect of trees on the SOC of degraded soils. For example, in only 11 years, the SOC doubled in alley cropping systems compared to sole cropping systems on poor soil in Southern Malawi [34]. Introducing alley cropping on degraded soils positively affects soil chemical and physical properties while also reducing risks of runoff and soil erosion [13,48,49]. The Fabaceae family has a beneficial effect on microbial biomass and SOC [45,60]. It is most often used in Asia and Africa as a fertilizer tree due to its positive effect on soil improvement [61]. In addition to N fixation, trees affect OM input from tree pruning and litterfall, by which trees maintain or increase the SOC stock [33].
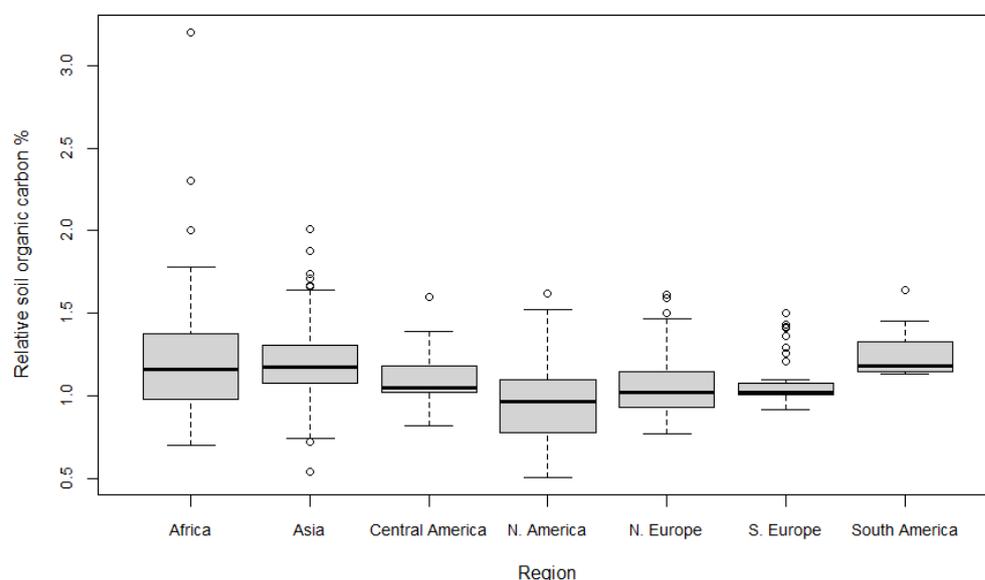

Figure 4. Relative soil organic carbon (SOC in alley cropping/SOC in agriculture) by regions.

3.2. Effect of Tree Age on Soil Organic Carbon in an Alley Cropping System

One of the first alley cropping systems in more recent times was established in 1982 [16]. Afterward, the number of alley cropping systems increased rapidly. However, most studies investigate systems under 20 years of age. We assume that the older alley cropping stands will have higher and longer input of OM and, thus, higher SOC stocks than younger systems. Furthermore, the alley cropping systems with narrower alley widths have higher tree density and, therefore, higher OM input than those with a wider alley width.

Several authors reported an increase in SOC stocks due to the establishment of alley cropping systems [6,24,26,34]. Gupta et al. [39] observed an increase in SOC concentration and stocks in soils of alley cropping systems with increasing system age from 1 to 6 years. In Costa Rica, field trials by Oelbermann et al. [38] found a significant increase in SOC in the 19-year-old alley cropping systems with *E. poeppigiana* and *G. sepium*. However, in the same trials, the 10-year-old system showed no such difference between the alley cropping and sole cropping without the trees [38]. Similar results were obtained in southern Canada [62] and Northeast China [63], where after nine years (Canada) and five years (Northeast China) of practicing alley cropping with poplar trees there was no significant difference in SOC stock in the 0–30 cm layer. Such results indicate that the influence of alley

cropping on SOC must be monitored for a longer time period to assess its positive effect on SOC, regardless of the climate zone or part of the world. Young [15] argues that in tropical environments, at least a 10-year-period of alley cropping is necessary before any changes may be observed. Ramesh et al. [24] studied a 26-year-old alley cropping system and reported an increase of 24% in SOC in alley cropping system compared to the sole cropping system. In even older systems over 40 years of age, the increase was over 40% [6,25,26]. Apparently, after 10 years of establishment, alley cropping systems start to increase SOC compared to sole crops and contribute to an increase in SOC sequestration. However, the full effect of alley cropping might take decades to become apparent [64]. Storage of SOC in agroforestry systems is influenced by system management, groundcovers, fallowing, system age and design (i.e., tree densities), and tree species. The SOC in these systems will be affected by tree age regardless of climate zone [33]. Such a finding is expected, as older trees would presumably have a longer period of soil C input through tree litter and roots than younger trees. However, Shi et al. [20] observed SOC change in agroforestry systems and found the highest changes for younger trees. Such findings may be explained by including alley cropping systems that were converted from natural forests. In such scenarios, it is expected that the initial SOC was high. Furthermore, the increase of C input in younger alley cropping stands may be explained by the use of fast-growing tree species, which can quickly increase litter inputs by tree pruning and accumulate SOC, especially at an early age [65].

Accumulation of SOC in alley cropping stands is also not evenly distributed, i.e., despite the deep tree rooting, SOC is mainly accumulated in the topsoil (30 cm), and much higher accumulation is within the tree rows compared to between tree rows [6]. The SOC is mainly in the form of labile organic fractions, making this C storage vulnerable to loss. However, a combination of alley cropping systems with no-till management practice may ensure an increase in SOC stocks [46]. In conclusion, introducing trees into agricultural land by establishing alley cropping systems has a positive effect on increasing SOC. However, it takes more than a decade for such an increase to be detectable.

4. Conclusions

The literature review indicated that the introduction of trees into agricultural land had gained increasing attention worldwide as a strategy to address climate change. Intercropping, such as alley cropping systems, has shown beneficial effects on SOC sequestration. The data presented suggest a more beneficial effect of alley cropping in regions with lower initial SOC concentrations compared to that in those rich in SOC. Further, the input of biomass C potentially increases with tree age. However, the increase in SOC stocks will only be observed after at least a decade of practicing alley cropping. Thus, establishing alley cropping can be beneficial on a permanent basis; it takes time for alley cropping to increase SOC, and once it is established, it needs to be maintained in order to maintain stabilized SOC levels. There were no differences among tree species used in the alleys. However, the correlation between RSOC and the alley width indicated higher SOC in denser alley cropping stands. Therefore, to establish the best possible alley cropping system, a thorough investigation and analysis of existing research are necessary to achieve the highest possible tree and crop productivity while at the same time influencing the increase in SOC concentrations and stocks.

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