Chapter 4
Soil Organic Carbon and Nitrogen in Agroforestry Systems in Sub-Saharan Africa: A Review

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Abstract Effective nutrient management is a key to sustainable agroforestry systems, chiefly in the current context of changing and variable climate along with increasing uncertainties of production systems to meet the needs for food security. The diversity of agroforestry systems throughout Sub-Saharan Africa results in a diverse nutrient management models with specific underlying mechanisms. Over the past decades several studies have been conducted on nutrient dynamics in agroforestry practices in various farming systems across a large range of agro-ecological conditions. We conducted a meta-analysis of the published data of four of these practices (alley cropping, improved fallow, mulching and parkland) for sub-Saharan region to examine their contribution to soil organic carbon and nitrogen content. The results of this analysis revealed an increase in both SOC and N contents of these practices over their corresponding treeless control plots. C to N ratios showed the higher values in the mulching and parkland practice as opposed to the alley cropping, which is nitrogen fixing species-based agroforestry technology. It has therefore been hypothesized that increase SOC may contribute to the provision of important supporting ecosystem services (nutrient inputs, the enhancement of internal flows, the decrease of nutrient losses, etc.). Therefore, agroforestry as a science hold promising solutions for alleviating soil fertility problems and achieving sustainable land management provided (1) resources sharing between components are better understood and (2) pathways for sustainable nutrient management are context-oriented and made available for users and policy makers.

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Contents

4.1 Introduction

Human pressure on natural resources has led to their degradation with a drastic reduction in vegetation cover in Sub-Saharan Africa. The associated consequences of such pressure are decrease in soil organic carbon and increases in runoff and soil erosion that ultimately lead to reduced crop yields and increase human malnutrition in this region (Vågen et al. 2005; Moebius-Clune et al. 2011; Le et al. 2012). To revert the current trends, part of the solution lies in some forms of agricultural production that maintain a certain threshold of vegetation cover by integrating more trees on farmlands or in other words in some forms of agroforestry practices which are in general low external inputs technologies (Graves et al. 2004; Sileshi et al. 2008, 2010; Jerneck and Olsson 2013; Carsan et al. 2014). Agroforestry is basically defined as the inclusion of trees in farming systems and their management in rural landscapes to enhance productivity, profitability, diversity and ecosystem sustainability (ICRAF 2013).

Trees in farming systems play a range of ecological functions among which soil fertility improvement seems be the most accepted role, particularly through the increase in soil carbon and nitrogen (Bayala et al. 2014; Carsan et al. 2014). Through CO_2 fixation by photosynthesis and nitrogen by nitrogen-fixing, trees can increase soil fertility and by incorporating more biomass into soils enable more efficient use of inorganic fertilizers (Kater et al. 1992; Bationo et al. 2007). Indeed, it is known that CEC lower than 4–5 meq. per 100 g makes the use of fertilizer non economical (Kater et al. 1992). Soil fertility can also be improved through nutrient cycling where trees extract nutrients from the lower levels of the soil profile and return them to the surface through leaf litter and fine root decay (Bayala and Ouédraogo 2008; Nair and Nair 2014). All these processes will increase soil carbon content which is one of the key factors to consider when assessing the sustainability of cropping systems and their effect on the environment. This is particularly valid in Sub-Saharan, where kaolinite is the main type of clay in the soils (Andriulo et al. 1999; Bationo and Buerkert 2001; Bayala et al. 2006; Bationo et al. 2007). In many places of this region, Cation Exchange Capacity (CEC) strongly depends on the presence of organic carbon, which of course has an impact on soil fertility, and trees have been reported to have a significant impact on CEC (Kater et al. 1992). Thus, trees, and particularly agroforestry systems, are nowadays widely acknowledged as valuable land management options within various concepts including “climate smart” agriculture, ever-green agriculture, ecological or agro-ecological intensification (Garrity et al. 2010; Neufeldt et al. 2013; Tittonell and Giller 2013).

If trees have positive impact on soil fertility (C and N), such effects will depend on a number of factors including but not restricted to the tree species and their management, the ecological conditions, the soil and its management, etc. A number of practices have been deployed and tested with respect to soil fertility improvement. The present review aims at capitalizing the existing information about soil carbon and nitrogen improvement of four key agroforestry practices which are alley cropping, improved fallow, mulching and parkland.

4.2 Methods

4.2.1 Definitions of the Geographic Area and Practices Studied

This analysis focuses on sub-Saharan Africa covering an area from humid to semi-arid zones. The agroforestry practices were then grouped into the following four categories for the purpose of the meta-analysis: alley cropping, fallow, mulching and parkland.

1. Alley cropping: Alley cropping, a system in which food crops are grown between hedges of trees which are regularly cut back to minimise tree-crop competition for light, water and nutrients (Kang 1993; Tossah et al. 1999). In this practice, the application of tree prunings to the soil surface is reported to generate a number of benefits including the reduction external inputs, the improvement of mineral fertilizer use efficiency, the enhancement of biological activity, the recovery N supplied with the prunings in absence of crop growth (Vanlauwe et al. 1998). The woody component of this technology is generally a nitrogen species like *Acacia auriculiformis* A. Cunn. ex Benth., *Acacia mangium* Willd., *Acacia colei* Maslin & L.Thomson, *Acacia tumida* Benth., *Albizia lebbeck* (L.) Benth., *Gliricidia sepium* (Jacq.) Walp., *Leucaena leucocephala* (Lam.) de Wit, *Prosospis africana* (Guill. et Perr.) Taub., etc.
2. Fallow: Improved fallows consist of deliberately planted species – usually legumes – with the primary purpose of fixing N_2 as part of a crop-fallow rotation (Sanchez 1999). Improved fallows with herbaceous legumes are commonly called green manures or sometimes cover crops and are not included in the present review. Improved fallows with woody legumes are usually called by the tree used, for example ‘*Gliricidia* fallows’ (Sanchez 1999).

3. Mulching: Mulching consists of covering the ground with a layer of plant materials in order to conserve soil water, to stimulate the activity of soil biota (e.g. termites) and to reclaim a degraded soil for crop production. This involves use of a range of plant materials (wild grass, crop residues or tree biomass, either leguminous or not) in the semi-arid area and sometimes in association with soil and water conservation techniques using crop residues or prunings from trees and shrubs or a mixture (Bayala et al. 2012).
4. Parklands: Parklands are anthropogenic vegetation assemblages derived from savannas ecosystems (Maranz 2009). Farmers usually protect naturally regenerating trees during tillage operations, keeping tree density low so that canopy cover is not continuous. Farmer managed natural regeneration (FMNR), which consists of selecting and thinning stems which sprout from indigenous tree and shrub stumps or appear as seedlings, has been actively used to obtain significant re-growth of trees on crop fields and fallow fields (Gijsbers et al. 1994; Reij et al. 2009). Therefore, parklands are a reflection of a slow process of species selection and density management of indigenous trees by farmers (Mortimore and Turner 2005). Key parkland species are *Acacia spp., Adansonia digitata* L.*, Borassus aethiopum* Mart.*, Faidherbia albida* (Del.) Chev.*, Ficus spp., Hyphaene thebaica* (L.) Mart.*, Lannea microcarpa* Engl. et K. Krause*, Parkia biglobosa* (Jacq.) R. Br. ex G. Don*, Pterocarpus erinaceus* Poir.*, Pterocarpus lucens* Guill. et Perr.*, Sclerocarya birrea* (A. Rich.) Hochst.*, Tamarindus indica* L.*, Vitellaria paradoxa* C. F Gaertn, *Ziziphus mauritiana* Lam., etc. (Bayala et al. 2012).

4.2.2 Data Collection

Data for the meta-analysis were compiled from publications and reports. The foci of the present analyses were carbon and nitrogen of the plot under the various agroforestry practises described above. The following criteria were used for a publication to be included in the analysis: (1) The data are from sub-Saharan Africa; (2) The publication contains reported carbon and nitrogen data of the four agroforestry practices and a corresponding control plot where the practice was not applied, with mean values reported numerically; (3) Data were from well designed and replicated experiments or observational studies either on a research station or on farmers' fields.

The studies included were located by searching through computer library databases (ICRAF, FAO, and Google Scholar). A search using the terms Agroforestry and soil fertility and any of the four practices and soil fertility yield a maximum of 1745 references. When restricted to sub-Saharan Africa 393 references where found. Finally, only 34 references fulfilled all the criteria listed above. These publications covered the semi-arid to humid agro-ecological zones (347 to 2500 mm) with the altitude of the study sites ranging from 200 to 1800 m and the rainfall from 347 to 2500 mm with both uni-modal and bi-modal rainfall patterns. In cases where the same data has been presented by the same author in two or more different publications, only one was included in this analysis. When data on more than one practice was available in the same publication or when data from different seasons and sites were reported, all were included. This yielded a total of 223 separate pairs of means (treatment and control) for carbon and 194 pairs of means for nitrogen. Some 62% of the studies came from on-farm trials and observational studies while 38% were from on-station experiments. Over 63% of study designs were laid out as randomized complete blocks, 27% as completely randomized designs and the rest 10% was split between Latina square and split plot designs.

4.2.3 Data Analysis

Data were converted to mean difference in soil carbon and nitrogen contents (D) which was defined as the difference in carbon or nitrogen between plot using a given agroforestry practice and the control of no such practice from the same study ($D = Me - Mc$). When both C and N data has been reported, C:N ratios were calculated and the difference between the treatment and control was also calculated using the same formula. Mean difference in carbon, nitrogen and C:N data were analysed by simple summary statistics. Data on D were further analysed using mixed models fitted using Restricted Maximum Likelihood (REML). Besides null hypothesis testing, statistical inference was based on the predicted means and their 95% confidence intervals (CI). One of the advantages of 95% CI over traditional hypothesis testing is the additional information they convey. The interpretation of the CIs is that if the same experiment was repeated many times, 95% of the time the D estimate would fall within the upper and lower confidence limits associated with the mean (Gelman et al. 1995). The upper and lower bounds of the CI give information on how big or small the true effect might plausibly be. Mean D for a given agroforestry practice treatment was considered different from 0 if the 95% CI did not include 0. If there is no difference between treatment and control the expected increase will be 0.0.

4.3 Results and Discussions

The results in Table 4.1 reveal that all of the technologies increase soil organic carbon (SOC) over the control. The 95% confidence intervals (lower upper) do not include 0. For example, alley cropping increased SOC by 20.57% (95 CI: 6.76–34.39), meaning the true value of SOC increase by treatment will fall between 6.76% and 34.39%; which is way above 0 (Table 4.1). Similarly to carbon, all of the technologies except improved fallows significantly increased nitrogen over the control. Improved fallows had variable response (Table 4.1). Negative values of the nitrogen difference in fallows may be due to the fact the species used do not fix

Table 4.1 Percentage increase in soil organic carbon (SOC) and nitrogen (N) due to various tree-based technologies over a corresponding tree less control for four agroforestry practices tested in Sub-Saharan Africa

Variable	Technology	Percentage increase	95% confidence intervals	
			Lower	Upper
SOC	Alley cropping	20.6	6.8	34.4
	Fallow	22.8	8.6	37.1
	Mulching	39.5	20.7	8.2
	Parkland	35.5	25.1	45.9
Nitrogen	Alley cropping	32.1	8.6	55.5
	Fallow	15.3	−12.1	42.7
	Mulching	32.4	4.8	60.0
	Parkland	35.5	17.2	53.8

nitrogen or the trees were still too young to displaying other processes of accumulating nitrogen which include deposit from animal (birds, livestock) and wind, the redistribution through the root systems, fine roots decay, litter decomposition, deep nitrate capture, etc. (Bayala and Ouédraogo 2008). The increases in both SOC and N revealed by the meta-analysis corroborate previous reports. Indeed, mature trees have always been associated with island of high fertility in the parkland systems in one hand (Bayala et al. 2006; Lufafa et al. 2008; Takimoto et al. 2009). On another hand, the three other practices studied (alley cropping, fallow, and mulching) are meant by nature to increase soil fertility particularly C and N (Kang 1993; Vanlauwe et al. 1998; Tossah et al. 1999). Indeed, the use of prunings and litter for soil fertility improvement is one of the earliest benefits claimed in agroforestry-based cropping systems especially in addressing soil N deficiency. However, the extent of soil improvement is related to the soil, the ecological conditions, the quality of the organic materials used because the nutrient content (especially N and P), lignin and polyphenol concentrations of litter strongly influence its rate of decomposition and nutrient release to the soil (Palm and Sanchez 1990). There is a general consensus that net N mineralisation occurs if the N concentration is above 2% and immobilisation occurs below that concentration (Palm and Sanchez 1990, 1991; Bayala et al. 2005). Fast release of N may be linked with high microbial activity inducing N deficit. Therefore, immobilization is likely to occur during the decomposing process of the leaves of some species and that may explained why in some cases the control N content was higher than that of the agroforestry practice (Bayala et al. 2005). Furthermore, if legume tree-based farming systems are able to increase soil nitrogen (N) availability and therefore improve soil fertility and crop yields sustainably, they can also induce the release of nitrous oxide (N_2O) in the surrounding environment. Such potential hazard should be taken into consideration (Rosenstock et al. 2014).

C:N ratios varied with technology with all of the technologies that increased the values of this parameter but alley cropping had significantly lower values compared to mulching and parklands (Table 4.2). Pruning is the main management tool in

Table 4.2 Percentage increase in C to N ratios in various tree-based technologies tested in Sub-Saharan Africa

			95% confidence intervals	
Variable	Technology	C:N	Lower	Upper
C:N ratio	Alley cropping	8.7	3.8	13.9
	Mulching	23.2	18.2	28.2
	Parkland	17.3	15.4	19.2

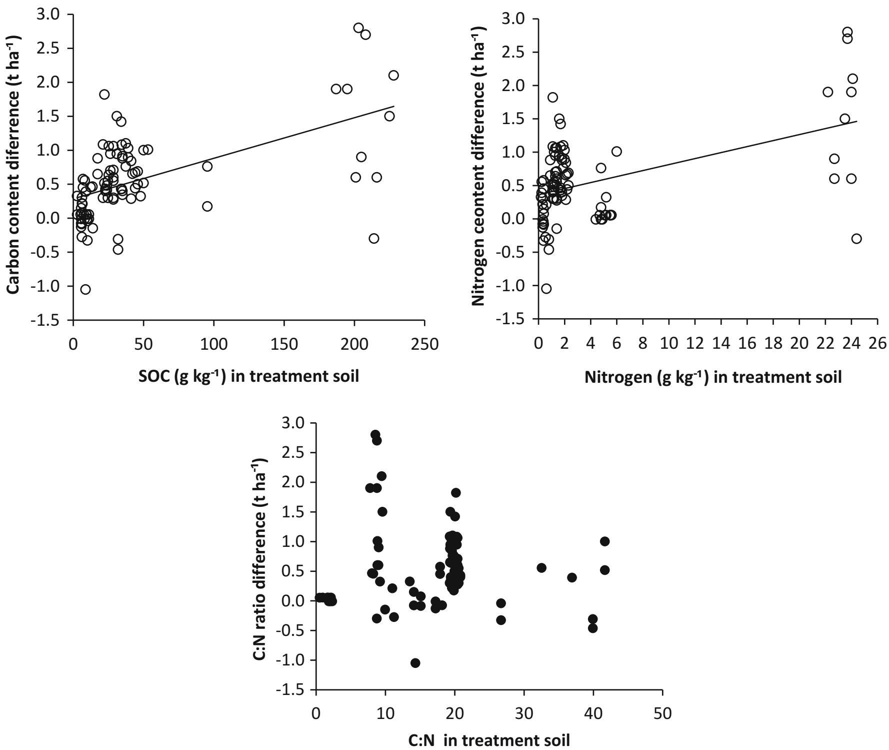

Fig. 4.1 Variation in carbon, nitrogen and C:N ratio differences with SOC, N and C:N in treatment plots for four agroforestry practices tested in Sub-Saharan Africa

alley cropping and this technique the potential to reduce the negative effects of trees in agroforestry parkland systems by reducing excessive shading and belowground competition through a reduction of fine root density (Jones et al. 1998; Bayala et al. 2008). Data points were too few for improved fallows. Therefore, fallows were not included in the analysis. The nutrient content difference (carbon and nitrogen) seems to increase with increase in nutrient content of the agroforestry plot whereas the opposite appears to be true for the C:N (Fig. 4.1). This indicates the difference that exists in the quality of the source organic matter of the studied practices. Lower C:N values in alley cropping practice is in line with the quality of the organic matter which is in principle from nitrogen fixing species. Indeed the organic matter using for mulching is generally a composite one with a mix prunings from trees that may be from leguminous species or not and crop residues. Conversely, litter from parkland species is also formed of leguminous and non-leguminous materials. In turn, by definition the species used in ally cropping are leguminous explaining the C:N is the lowest in this practice associated with higher mineralisation of the applied biomass (Palm and Sanchez 1990, 1991). All of the technologies increased the C:N ratio but alley cropping had significantly lowered values compared to mulching and parklands. As opposed to alley cropping, practices that result in high C:N may be associated with a decrease in decomposers population diversity in one hand (Wachendorf et al. 1997). On the another hand, higher SOC is associated with better soil physical properties improvement. As most of the soils in sub-Saharan have low clay activity, their Cation Exchange Capacity (CEC) becomes strongly dependent to SOC (Kater et al. 1992; Bayala and Ouédraogo 2008). In addition, vegetation clearance was reported to have detrimental effects on earthworm which are known to have an effect on soil structure (Hauser et al. 1998, 2012) and faunal diversity and biomass (Ayuke et al. 2011).

All the above mentioned results show that trees/shrubs in agroforestry practices have a direct positive contribution to SOC, justifying the need to encourage the maintenance of trees in farmed lands where the carbon content of soil appears to be the priority limiting factor for crop growth and production (Lal 2011; Bayala et al. 2014). As a consequence, agroforestry is nowadays widely acknowledged as a valuable land management option under various concepts including ever-green agriculture or climate smart agriculture or ecological intensification (Garrity et al. 2010; Doré et al. 2011; Neufeldt et al. 2013; Tittonell and Giller 2013).

4.4 Conclusion

The meta-analysis revealed that agroforestry practices including alley cropping, improved fallow, mulching and parkland increase SOC over treeless plots used as controls. Similarly, except for improved fallows, all practices significantly increased nitrogen over the control. C:N ratios showed the highest values in mulching and parklands as opposed to the alley cropping where nitrogen fixing species are incorporated. Practices that increase the SOC are contributing to re-introducing the ecological functions in the production systems because of the various supporting ecosystem services associated with trees. Therefore, such practices should be encouraged provided the processes governing the optimal utilization of growth resources among the components of the system are well understood. There is also a need to generate context-oriented pathways for sustainable nutrient management and make them available for users and policy makers.

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