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Soil Organic Carbon Sequestration in Finger Millet Production in Sub-Saharan Africa: A Review of Concepts and Practices

Joseph Ekwangu[1, 2, 4, *], Susan Tumwebaze Balaba[2], Twaha Ali Basamba Ateenyi[2], John Steven Tenywa[2], Helen Opie[1], Deborah Lillian Nabirye[2], Charles Andiku[3], Owere Lawrence[4]

[1]African Center of Excellence in Agro Ecology and Livelihood Systems, Faculty of Agriculture, Uganda Martyrs University, Nkozi, Uganda

[2]College of Agricultural and Environmental Sciences, Makerere University, Kampala, Uganda

[3]Faculty of Agriculture and Animal Sciences, Busiteme University, Tororo Uganda

[4]Buginyanya Zonal Agricultural and Development Research Institute (BugiZARDI), Mbale, Uganda

Email address:

jekwangu@gmail.com (Joseph Ekwangu)

[*]Corresponding author

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Abstract: Soil has the capacity to sequester about 50-66% of the 42-78 Giga tons of carbon lost per year. However, the capacity of the soil to sequester carbon is dependent on soil texture and structure, rainfall, temperature, farming systems, and soil management practices. Management practices to enhance soil carbon sequestration include; cover cropping, nutrient management, woodland regeneration, no-till farming, manure, and sludge application, water conservation, and harvesting, efficient irrigation, and agroforestry, among others. These practices have however been applied in un-integrated manner, this has led to continuous loss of soil carbon; consequently, there has been a decline in crop yield especially cereals due to climate-change, soil degradation, pest, and disease burden, among other factors. Yet an increase in soil carbon by one in a degraded soil could increase cereal yield by up to 40 kg ha^{-1}, for example, increase wheat yield by up to 20-40 kg ha^{-1} and Maize up to 10-20 kg ha^{-1} as well as reducing fossil fuel emission by 0.4-1.2 Giga tons of carbon per year. This review paper, therefore, looks at current ways of sequestering carbon and how these approaches can be improved and integrated to enhance soil carbon sequestration in cereal-legume cropping systems. There is a need to increase the production of cereals due to the increasing demand for cereals in sub-Saharan Africa and it is projected that, by 2050, the demand is expected to triple due to global population increase which is expected to outmatch production due to low soil carbon sequestration and soil fertility.

Keywords: Soil Carbon Sequestration, Carbon Sink, Farming Systems, Finger-Millet, Soil Fertility and Crop Yield

1. Introduction

Soil fertility is the inherent capacity of the soil to provide plant nutrients in adequate amounts and in suitable proportions [1]. It can also be referred to as the ability of the soil to continuously provide nutrients necessary for plant growth in their available form [2, 3]. While plant nutrition is a process by which a plant extracts chemical elements and compounds from the soil/ growth media to support its metabolism, growth, and reproduction [3].

Given the diverse contribution of soil fertility to natural ecosystem function, it is therefore, imperative to discuss the role of soil fertility in crop production for human utilization. However, soil fertility cannot be discussed in isolation of plant nutrition, which in recent studies have been described as the management of chemical elements and compounds necessary for the plant to attain its full growth potential (life cycle) [4, 5]. These chemical elements are both essential and non-essential; the essential elements are necessary for metabolic processes within the plant and are also responsible for the completion of the plant's life cycle. While none essential elements/nutrients are those whose non availability does not affect the completion of a plant's growth cycle [6, 7]. Nutrients that are essential to the plants have been identified to be seventeen (17) and are further subdivided into macro and microelements (Table 1). The categorization is premised on the nutrient in plant tissues as opposed to their requirement for growth of the plant. Macronutrients are available in plant tissue at concentrations above 0.2%, while micronutrients are present at concentrations below 0.01% usually measured on a dry weight basis. In addition to the seventeen essential elements, there are also, Carbon (C), hydrogen (H), and oxygen (O) which are derived from carbon dioxide (CO_2) and water (H_2O), and through the process of photosynthesis, they form carbohydrates. These chemical elements (C, H, and O) are present in the highest concentrations of any element in plant tissue. They are, however, not considered mineral elements and are almost always available in amounts necessary for their direct use in complete plant metabolism [1].

Furthermore, macronutrients are subdivided into; primary macronutrients, which include nitrogen (N), potassium (K), and phosphorus (P), and secondary macronutrients (calcium (Ca), magnesium (Mg), and sulfur (S)). The micronutrients are mainly Copper (Cu), manganese (Mn), iron (Fe), boron (B), nickel (Ni), molybdenum (Mo), chlorine (Cl) and zinc (Zn). In addition to the eight micronutrients above, there is also cobalt (Co), sodium (Na), silicon (Si), selenium (Se), and vanadium (V), these elements improve the crops' growth and quality and are referred to as 'beneficial elements'.

Although Silicon is considered a beneficial element, it has been reported to aid some metabolic processes responsible for the completion of the life cycle of many plants outside the family of Equisetaceae [8, 9]. More studies are therefore required to establish the role of Silicon in plant nutrition. Table 1 below gives a summary of the essential and beneficial elements and their roles in plant growth and development.

Table 1. *Essential nutrient and beneficial elements and their roles in plant growth and development.*

Nutrient type	Element (s)	Form taken up by plants	Role in a plant
Non-mineral macro nutrients	Carbon (C)	CO_2	Mediates the process of photosynthesis.
	Hydrogen (H)	H^+, OH^- and H_2O	Directly plays a role in photosynthesis.
	Oxygen (O_2)		Aids respiration process.
Mineral Macro nutrients	Nitrogen (N)	NH_4^+ and NO_3^-	Mediates enzyme controlled activities and is a major component of chlorophyll, amino acids and proteins
	Phosphorus (P)	HPO_4^{2-} and $H_2PO_4^-$	Component of adenosine di- and triphosphate (ADP and ATP) which is essential for energy storage and transfer. Is also an important component of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Responsible for the growth and development of plant tissues and seeds.
	Potassium (K)	K^+	Mediates metabolic processes such as photosynthesis, enhances plant water use efficiency and drought tolerance. Aids disease resistance and stem strength.
	Calcium (Ca)	Ca^{2+}	Responsible for the growth of tissues, cell division and elongation and activation of enzymes
	Magnesium (Mg)	Mg^{2+}	Major component of chlorophyll and is responsible for photosynthesis. Aids protein synthesis as well as phosphate metabolism, respiration and enzyme activity.
	Sulfur (S)	SO_4^{2-}	Component of amino acids and is necessary for protein synthesis. Responsible for nodule formation in legumes and in the development of enzymes, seeds and chlorophyll.
Mineral Micro nutrients	Copper (Cu)	Cu^{2+}	Components of chlorophyll and contributes in enzyme activation.
	Manganese (Mn)	Mn^{2+} and Mn^{4+}	Activate enzymes and mediate photosynthesis synthesis
	Iron (Fe)	Fe^{2+} and Fe^{3+}	Responsible for chlorophyll synthesis and mediates respiration and photosynthesis processes.
	Boron (B)	H_3BO_3, BO_3^- and $B_4O_7^{2-}$	Responsible for germination, growth, development of female and male parts of the plant, and grain. Has been reported to aid the translocation of sugars, starches, N and P.
	Nickel (Ni)	Ni^{2+}	Components of some enzymes such as urease responsible in N metabolism.
	Molybdenum (Mo)	MoO_4^{2-}	Mediates enzyme aided reactions and metabolic processes that reduces NO_3^- to NH_4^+ in plants (nitrate reductase) and N fixation by rhizobia.
	Chlorine (Cl)	Cl^-	Responsible for energy generation in the plant and enzyme controlled functions in the plant
	Zinc (Zn)	Zn^{2+}	Mediates the processes leading to formation of pant growth compounds (hormones), chlorophyll, carbohydrates and enzyme systems.
Beneficial elements	Cobalt (Co)	Co^{2+}	Responsible in formation of N complexes and synthesis of vitamin B_{12}.
	Sodium (Na)	Na^{2+}	Contributes to the functioning of halophytic plants in the absence/limitation of K^+.
	Silicon (Si)	H_4SiO_4	Mediates activities of photosynthesis regulating enzymes.
	Selenium (Se)	SeO_3^{2-} and SeO_4^{2-}	Essential in animal nutrition.
	Vanadium (V)	VO_3^-	Responsible for N fixation by rhizobia and in some cases biological oxidation and reduction reactions.

Source: [1]

It is, therefore, evident that the ability of the soil to support plant growth is the backbone of crop production, however, soil fertility has been reported to be declining in sub Saharan Africa at an alarming rate due to soil erosion, unsustainable land management practices such as monoculture over use and poor application method of inorganic fertilizers, overgrazing, bush burning, continuous cultivation and poor tillage practices [10–13]. The declining soil fertility has affected crop production especially cereals [14, 15] and the problem is much felt in the semi-arid regions of sub-Saharan Africa (SSA) where climate change has become a major bottleneck affecting crop production especially among small holder farmers with limited resources and depend on traditional crops such as finger millet for nutrition and food security. These traditional crops are to a large extent tolerant to abiotic and biotic stresses have long shelf life and rich in nutrients, especially amino acid, iron, zinc, calcium and magnesium [16–18]. Finger millet has been affected by drought, weed proliferation and low soil fertility [14, 15]. Low soil fertility has been attributed to poor agronomic practices that have led to reduction in Soil Organic Carbon (SOC) which is a major indicator of soil fertility and plays a key role in soil fertility and plant nutrition [19]. It is, therefore, imperative to design strategies to manage soil degradation and enhance Soil Carbon Sequestration (SOC to attain desirable soil characteristics, production potentials and a good functional ecology [20-22] and increased finger millet productivity**.**

Given the declining levels of SOC in sub-Saharan Africa, a number of studies have recommended sustainable land management practices in soil carbon (SOC) sequestration [10-13]. One of the recommended approaches is legume integration in cereal production [23, 24], application of a combination of organic and organic fertilizer and minimum tillage [25, 26].

2. Status of Soil Organic Carbon (SOC) Stocks in Sub-Saharan Africa

The amount of carbon released to the atmosphere in form of carbondioxide emission is influenced by land utilization and management practices employed. However, the soil under good cropping and management systems has the potential of sequestering carbon ranging from 2344 gigatonne (GT) which is 1 billion tonnes of global organic carbon [27–29]. Therefore, soil has been reported to be the largest terrestrial pool of organic carbon [30, 31]. It is estimated that 300cm^3 of soil (30 cm width by100 cm depth) contains Soil Organic Carbon (SOC) in the range of 684–724 Pg and 1462–1548 Pg, respectively [32].

Therefore, the importance of soil in carbon organic carbon turn over further underscore the potential role of soil as a natural carbon sink. This is due to the fact that soil is the largest SOC pool on the land surface in addition to its ability to store carbon over long period of time [33]. Top soil (0–30 cm) is reported to store carbon in large quantities approximated to be twice the amount of carbon (C) in the atmospheric carbondioxide (CO_2) and three times that in aboveground vegetation globally [28, 32, 33]. However, global SOC levels vary from region to region, and this is affected by factors such as rainfall distribution, temperature, cropping systems, and soil management practices [27, 28]. For example, the annual release of CO_2 from deforestation as estimated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) is approximately 25% of CO_2 released from fossil fuel burning [30, 34]. These impacts negatively the carbon levels in the soil and has been reported to result in an estimated loss of 78±12 Pg C to the atmosphere annually [27, 29].

3. The Role of Soil Organic Carbon (SOC) in Soil Fertility and Plant Nutrition

Soil Organic Carbon plays a very important role in soil fertility management and plant nutrition. SOC plays a role in soil nutrient turnover and influences the physical and chemical characteristics of the soil. In the tropics, SOC is the main cause of soil fertility heterogeneity due to its variation in quantities [24, 35]. In addition, soil organic carbon plays a big role in improving soil quality through soil aggregate stabilization, reduced effect of soil erosion, improvement in cation exchange capacity, water holding capacity, biological functioning, and availability of macro and micronutrients [36]. [19, 24, 35] reported SOC levels to influence positively or negatively to soil fertility and yield, especially in sub-Saharan Africa. Soils with low SOC amounts are often low in fertility and are associated with highly weathered tropical soils, especially ferralsols which are characterized by high levels of sesquioxides, and kaolinitic clays and are inherently low in nutrient retention capacity [37, 38]. Because of the low levels of SOC, yield response to mineral N fertilizer application was reported as insignificant [35]. Thus, [39] in their study on maize response to N and P fertilizer applications under different SOC levels sought to determine the optimal SOC concentration for yield response to mineral N fertilizers. The optimal SOC level for yield response was observed at SOC > 1.2%, however, the rate at which different soil management practices/options attain the critical SOC concentration remains unknown.

4. The Role of Organic and Inorganic Fertilizer Application on Soil Carbon Sequestration

4.1. The Role of Organic Fertilizer Application on Soil Carbon Sequestration

Terrestrial ecosystems, especially soils, are an important sink of carbon [19]. However, the ability of the soils to sequester carbon is influenced by various factors such as soil fertility management practices [40] for example, long-term application of organic fertilizers sequestered carbon between 1.5 – 2.0 times higher than balanced inorganic fertilizer under rice-wheat cropping system [41]. Similarly, [42] reported an increase in soil organic carbon when Farm Yard Manure (FYM) was applied to the soil over a long period of time. This was further noted by [40] when manure applied to the soil significantly increased carbon and nitrogen levels in the soil, leading to improved soil physical properties. Also, biomass carbon was reported to have significantly increased when organic fertilizer was applied to barley, wheat, beans, maize, cotton, and rice [43]. These studies were limited to rice, wheat; maize, beans, barley, cotton, and rice cropping systems with very limited information on SOC sequestration studies under finger millet fertilizer application. Given that finger millet which is one of the major food security and nutrition crops for smallholder farmers in the semi-arid tropical regions of Sub-Saharan Africa is threatened by production constraints like low soil fertility and climate change [41], there is, therefore, need to assess the effect of manure application on SOC and soil fertility management in finger millet production in the semi-arid regions of sub-Saharan Africa.

4.2. The Role of Inorganic Fertilizer Application on Soil Carbon Sequestration

Inorganic fertilizers provide readily available nutrients to plants and therefore have an immediate influence on the growth of the plant [3]. Nitrogen and phosphorus application especially in cereals results in vegetative growth and consequently high biomass production. This in turn influences the amount of carbon (C) and Nitrogen (N) stocks in soil [44]. Also, [45] reported that, inorganic fertilizers application enhanced soil organic matter (SOM and biological activity in the soil due to increased plant biomass production and organic matter return to soil in form of decaying roots, litter, and crop residues.

On the contrary, [46] reported carbon and nitrogen accumulation in newly cultivated farmland to be influenced by a combination of organic and inorganic fertilizer applications. Cereals have been reported to highly respond to nitrogen-based fertilizer application leading to increased biomass and hence influencing the SOC levels in the soil [48]. The plant biomass, when returned to the soil, plays a big role in adding SOC to the soil through the decomposition and mineralization processes that organic residues undergo [42].

4.3. The Role of Legume-Cereal Integration on Soil Carbon Sequestration

Legumes play important role in soil fertility and land degradation mitigation through biological nitrogen fixation and soil erosion control, thus playing major components of integrated soil fertility management in sub-Saharan Africa [51]. Most areas in sub-Saharan Africa and Uganda in particular, legumes are planted as sole crops and rotated with cereals where the latter benefits from the residual nitrogen from the legumes or they are intercropped with cereal, especially maize [52]. Intercropping is mainly done to minimize the risk of total crop failure and to maximize utilization of land and labor in addition to the complementary benefits associated with growth pattern, aboveground cover, rooting depth and density, water, and nutrient demand are often derived from intercropping cereals with legumes [53]. Different legumes fix nitrogen at varying rates and also generate varying biomass. This biomass contributes to SOC stocks and enhances soil fertility and grain yield [23].

Studies conducted in West Africa, particularly in Nigeria, on the effect of rotation of Mucuna pruriens with maize for soil fertility management in maize production [54, 55] reported grain yield increase of between 25-50% and improvement of SOC and soil fertility. In Kenya, [52] reported a grain yield increase of between 21-24% when maize was intercropped with Mucuna pruriens. However, limited studies have been conducted on legume integration and fertilizer application to enhance soil fertility in finger millet production, especially in drier areas of the globe.

5. Nitrogen, Phosphorous, and Potassium Status in Ugandan Soils

Large proportions of the soils in Uganda are highly weathered and consequently, low in nutrient reserves especially N, P, K, Mg, Ca, and S. The soils therefore, have limited capacity to supply nutrients that meet the crops' growth requirements [43–50]. Some of the soils in Uganda are acidic, leading to high Aluminum toxicity and this is a common phenomenon in Ferralsols and Acrisols soils. These soils constitute more than 70% of Uganda's total land area on which most of the crop production is done [50]. The situation is not any different in the eastern part of Uganda where soils are characterized by highly weathered Plinthisols, light-textured Ferralsols and vertisols. These soils are often low nutrients, especially N and P as a result of their inherent soil characteristics and high nutrient mining due to poor agronomic practices coupled with climate change [6]. Given the above characteristics of the soil and prevailing farming practices, cereals especially finger millet production in Uganda has been reported to be declining [15]. There is a need to address this bottleneck if finger millet yields are to be enhanced.

6. Finger Millet N and P Requirements

Finger millet is a highly resilient crop and has been reported to grow under relatively harsh environmental conditions (poor soils and low rainfall) with high Nitrogen Use Efficiency (NUE) [48]. This attribute, has however not been fully explored. However, studies conducted by [56] suggest that finger millet has a unique mechanism through which small amounts of nitrogen in the soil are maximally utilized by the crop. This mechanism is associated with the genetic influence of a wide range of finger millet varieties on nitrogen utilization within the crop [48]. To maximize the above benefit of finger millet, a substantial amount of soil organic carbon is required in the soil to enhance nutrient turnover [49]. The major nutrients influencing finger millet yields in the tropic are N and P and N requirements range from 60-85 kg N ha^{-1} [57] while P requirements range from 25–69kg per hectare, depending on the agro-ecological zone and soil types. For instance, [58] recommended 60 kg N ha^{-1} on sandy clay loam soil in Kenya while [57] recommended 83 kg N ha^{-1} on degraded sandy loam soil in eastern Uganda. On the other hand, [59] recommended 69 kg P ha^{-1} for sandy loam and sandy clay soils while [57] recommended 52 Kg P ha^{-1} for degraded sandy loam soils in eastern Uganda. These recommendations were, however, based on sole cropping and no other cropping systems such as finger millet-legume integration and intercropping. The effect of legume integration on finger millet production needs to be investigated as a potential solution to addressing low soil carbon sequestration and low soil fertility in finger millet production.

7. The Role of Nitrogen and Phosphorus in Finger Millet Nutrition

Nitrogen and phosphorus are key nutrients in plant nutrition with nitrogen playing a key role in the metabolic processes such as photosynthesis and growth through cell division and elongation [62]. In addition nitrogen mediates cell repair, grain formation and protein synthesis and overall growth of the plant [63]. Soils with low levels of nitrogen have been noted to have dwarf crops, inadequate vegetative cover/growth, pale yellow to yellow leaves, susceptible to pests and diseases, adversely affected by both short and prolonged and generally poor yields [63].

Phosphorus on the other hand is responsible for energy storage and transfer, plant tissue and grain development [64]. It is also a critical component of Deoxy-ribo Nucleic Acid (DNA) and Ribo Nucleic Acid (RNA) which are major building blocks in plant growth and development [62]. In photosynthesis, phosphorus is a major source of energy that aid metabolic processes leading to energy transfer to the required parts of the plant [66].

Given the role of N and P in plant nutrient, their contribution in finger millet is not isolated. However, information on the direct effect of P fertilizer application on finger millet is limited but additive and synergistic interactions between P and N have previously been reported, with low P leading to low response and uptake of N [65]. This is seen in the study of [66] where they noted finger millet response to N application to be poor or even negative in soils deficient in P, leading to low recovery efficiency. However, identification and exploitation of positive interactions is key in increasing finger millet returns (yield, quality, and nutrient use efficiency) from applied N and P under various agroecologies.

8. Finger Millet Nutrient Use Efficiency

Finger millet has been observed to have relatively high nutrient use efficiency compared to other cereals [48]. This is because of the crop's ability to dense rooting system in dry and poor soil conditions to maximize moisture and nutrient absorption and utilization [48, 56]. The high Nutrient Use Efficiency (NUE) is also attributed to the genetic influence of a wide range of finger millet varieties on nitrogen utilization within the crop [48]. Furthermore, NUE [39] has been associated with the amount of initial SOC in the soil; for example, if the SOC is >1.2%, then the NUE of finger millet could be high compared to when the soil organic carbon (SOC) is < 1.2% (40). Studies comparing the nutrient use efficiency of finger millet and carbon levels in the soil are scanty. There is, therefore, a need to determine how soil carbon levels influence the nutrient use efficiency of finger millet varieties cultivated in the drier areas of eastern Uganda.

9. Conclusion and Areas of Future Research

9.1. Conclusion

Soil Organic Carbon (SOC) sequestration is very important in crop production and in maintaining sound ecosystem function for sustainable crop production and environmental management.

It is undoubtedly clear that soil is a major sink for terrestrial carbon dioxide and a potential climate change mitigation strategy if sustainably utilized and managed.

Soil carbon is a food source for soil micro-organisms and an important bacteria metabolite where microbial activity plays an important role in improving soil structure.

There is limited information on the role of legumes in soil carbon sequestration in finger millet production in semi-arid agroecological zones.

Soil Organic carbon plays a big role in plant nutrition in terms of stabilizing soil conditions such as pH, water infiltration, nutrient availability, and general soil health.

9.2. Areas of Future Research

There is need to understand the effect of legumes on soil carbon sequestration and turn in semi-arid agroecologies.

There is a need to understand the factors affecting the adoption of climate-smart agricultural practices in semi-arid agro-ecologies.

Assess the Rhizosphere effect on soil carbon turn over and soil fertility management in cereal production in semi-arid environment.

Authors Contributions

J. Ekwangu contributed to research, synthesis, and writing. S. B. Tumwebaze participated in the review of the paper. T. A. A. Basamba reviewed the paper. J. S. Tenywa guided the layout and review of the paper. H. Opie participated in the paper review. B. Nabirye contributed to the review of the write-up, C. Andiku participated in the review of the manuscript and L. Owere also, participated in the revision of the manuscript. Authors reviewed the final submitted version of the article.

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References

[1] Doula MK, Sarris A. Chapter 4 - Soil Environment. In: Poulopoulos SG, Inglezakis VJ, editors. Environment and Development [Internet]. Amsterdam: Elsevier; 2016 [cited 2022 Mar 30]. p. 213–86. Available from: https://www.sciencedirect.com/science/article/pii/B9780444627339000046

[2] Ai Z, Wang G, Liang C, Liu H, Zhang J, Xue S, et al. The Effects of Nitrogen Addition on the Uptake and Allocation of Macro- and Micronutrients in Bothriochloa is chaemum on Loess Plateau in China. Frontiers in Plant Science [Internet]. 2017 [cited 2022 Mar 27]; 8. Available from: https://www.frontiersin.org/article/10.3389/fpls.2017.01476

[3] Brady NC, Weil RR. The nature and properties of soils [Internet]. 2017 [cited 2022 Mar 30]. Available from: http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1419853

[4] Havlin J. Soil: Fertility and Nutrient Management. In 2020. p. 251–65.

[5] Mudalagiriyappa, Goud BR, Ramachandrappa BK, Nanjappa HV. Influence of Customized Fertilizers on Growth and Yield of Finger Millet {*Eleusine coracana (L.) Gaertn.*} in Alfisols of Southern India. Indian Journal of Dryland Agricultural Research and Development [Internet]. 2015 [cited 2018 May 15]; 30 (1): 50. Available from: http://www.indianjournals.com/ijor.aspx?target=ijor:ijdard&volume=30&issue=1&article=007

[6] Bekunda M, Ebanyat P, Nkonya E, Mugendi D, Msaky J. Soil fertility Status, Management, and Research in East Africa. Eastern Africa Journal of Rural Development [Internet]. 2005 Jul 5 [cited 2018 May 15]; 20 (1). Available from: http://www.ajol.info/index.php/eajrd/article/view/28362

[7] Havlin J, editor. Soil fertility and fertilizers: an introduction to nutrient management. 7th ed. Upper Saddle River, N. J: Pearson Prentice Hall; 2005. 515 p.

[8] Epstein E. The anomaly of silicon in plant biology. Proc Natl Acad Sci U S A. 1994 Jan 4; 91 (1): 11–7.

[9] Pavlovic J, Kostic L, Bosnic P, Kirkby EA, Nikolic M. Interactions of Silicon With Essential and Beneficial Elements in Plants. Frontiers in Plant Science [Internet]. 2021 [cited 2022 Apr 4]; 12. Available from: https://www.frontiersin.org/article/10.3389/fpls.2021.697592

[10] Dewitte O, Jones A, Spaargaren O, Breuning-Madsen H, Brossard M, Dampha A, et al. Harmonisation of the soil map of Africa at the continental scale. Geoderma [Internet]. 2013 Dec 1 [cited 2022 Apr 4]; 211–212: 138–53. Available from: https://www.sciencedirect.com/science/article/pii/S0016706113002401

[11] Gonzalez-Roglich M, Zvoleff A, Noon M, Liniger H, Fleiner R, Harari N, et al. Synergizing global tools to monitor progress towards land degradation neutrality: Trends. Earth and the World Overview of Conservation Approaches and Technologies sustainable land management database. Environmental Science & Policy [Internet]. 2019 Mar 1 [cited 2022 Apr 4]; 93: 34–42. Available from: https://www.sciencedirect.com/science/article/pii/S1462901118306543

[12] Hellemans T, Landschoot S, Dewitte K, Van Bockstaele F, Vermeir P, Eeckhout M, et al. Impact of Crop Husbandry Practices and Environmental Conditions on Wheat Composition and Quality: A Review. J Agric Food Chem [Internet]. 2018 Mar 21 [cited 2022 Apr 4]; 66 (11): 2491–509. Available from: https://doi.org/10.1021/acs.jafc.7b05450

[13] Keesstra SD, Bouma J, Wallinga J, Tittonell P, Smith P, Cerdà A, et al. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. SOIL [Internet]. 2016 Apr 7 [cited 2022 Apr 4]; 2 (2): 111–28. Available from: https://soil.copernicus.org/articles/2/111/2016/

[14] Gebreyohannes A, Shimelis H, Laing M, Mathew I, Odeny DA, Ojulong H. Finger Millet Production in Ethiopia: Opportunities, Problem Diagnosis, Key Challenges and Recommendations for Breeding. Sustainability [Internet]. 2021 Jan [cited 2022 Dec 1]; 13 (23): 13463. Available from: https://www.mdpi.com/2071-1050/13/23/13463

[15] Owere L, Tongoona P, Derera J, Wanyera N. Farmers' Perceptions of Finger Millet Production Constraints, Varietal Preferences and Their Implications to Finger Millet Breeding in Uganda. Journal of Agricultural Science [Internet]. 2014 Nov 15 [cited 2018 May 15]; 6 (12). Available from: http://www.ccsenet.org/journal/index.php/jas/article/view/33956

[16] Devi PB, Vijayabharathi R, Sathyabama S, Malleshi NG, Priyadarisini VB. Health benefits of finger millet (Eleusine coracana L.) polyphenols and dietary fiber: a review. J Food Sci Technol [Internet]. 2014 Jun [cited 2019 Nov 15]; 51 (6): 1021–40. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4033754/

[17] Goron TL, Raizada MN. Genetic diversity and genomic resources available for the small millet crops to accelerate a New Green Revolution. Front Plant Sci [Internet]. 2015 [cited 2018 May 15]; 6. Available from: https://www.frontiersin.org/articles/10.3389/fpls.2015.00157/full

[18] Patil D. Agrobiodiversity and Advances in the Development of Millets in Changing Environment. In 2020. p. 643–73.

[19] Musinguzi P, Ebanyat P, Tenywa JS, Basamba TA, Tenywa MM, Mubiru DN. CRITICAL SOIL ORGANIC CARBON RANGE FOR OPTIMAL CROP RESPONSE TO MINERAL FERTILISER NITROGEN ON A FERRALSOL. Experimental Agriculture [Internet]. 2016 Oct [cited 2018 Oct 24]; 52 (04): 635–53. Available from: http://www.journals.cambridge.org/abstract_S0014479715000307

[20] Andriamananjara A, Rakotoson T, Razanakoto OR, Razafimanantsoa MP, Rabeharisoa L, Smolders E. Farmyard manure application in weathered upland soils of Madagascar sharply increase phosphate fertilizer use efficiency for upland rice. Field Crops Research [Internet]. 2018 Jun [cited 2018 Nov 12]; 222: 94–100. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378429017315472

[21] Dynarski KA, Bossio DA, Scow KM. Dynamic Stability of Soil Carbon: Reassessing the "Permanence" of Soil Carbon Sequestration. Frontiers in Environmental Science [Internet]. 2020 [cited 2022 Apr 4]; 8. Available from: https://www.frontiersin.org/article/10.3389/fenvs.2020.514701

[22] Xu S, Sheng C, Tian C. Changing soil carbon: influencing factors, sequestration strategy and research direction. Carbon Balance and Management [Internet]. 2020 Feb 17 [cited 2022 Apr 4]; 15 (1): 2. Available from: https://doi.org/10.1186/s13021-020-0137-5

[23] Myaka FM, Sakala WD, Adu-Gyamfi JJ, Kamalongo D, Ngwira A, Odgaard R, et al. Yields and accumulations of N and P in farmer-managed intercrops of maize-pigeonpea in semi-arid Africa. Plant and soil [Internet]. 2006 [cited 2018 Dec 6]; Available from: http://agris.fao.org/agris-search/search.do?recordID=US201301103166

[24] Tittonell P, Giller KE. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Research [Internet]. 2013 Mar 1 [cited 2018 Oct 24]; 143: 76–90. Available from: http://www.sciencedirect.com/science/article/pii/S0378429012003346

[25] Hermans TDG, Whitfield S, Dougill AJ, Thierfelder C. Bridging the disciplinary gap in conservation agriculture research, in Malawi. A review. Agron Sustain Dev [Internet]. 2020 Feb 1 [cited 2022 Dec 16]; 40 (1): 1–15. Available from: https://link.springer.com/article/10.1007/s13593-020-0608-9

[26] Thierfelder C, Baudron F, Setimela P, Nyagumbo I, Mupangwa W, Mhlanga B, et al. Complementary practices supporting conservation agriculture in southern Africa. A review. Agron Sustain Dev [Internet]. 2018 Mar 6 [cited 2022 Dec 16]; 38 (2): 16. Available from: https://doi.org/10.1007/s13593-018-0492-8

[27] Lal R. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science [Internet]. 2004 Jun 11 [cited 2022 May 15]; 304 (5677): 1623–7. Available from: https://www.science.org/doi/10.1126/science.1097396

[28] Lal R, Lorenz K, Hüttl RF, Schneider BU, von Braun J. Terrestrial Biosphere as a Source and Sink of Atmospheric Carbon Dioxide. In: Lal R, Lorenz K, Hüttl RF, Schneider BU, von Braun J, editors. Recarbonization of the Biosphere: Ecosystems and the Global Carbon Cycle [Internet]. Dordrecht: Springer Netherlands; 2012 [cited 2022 May 15]. p. 1–15. Available from: https://doi.org/10.1007/978-94-007-4159-1_1

[29] Lal R, Smith P, Jungkunst HF, Mitsch WJ, Lehmann J, Nair PKR, et al. The carbon sequestration potential of terrestrial ecosystems. Journal of Soil and Water Conservation [Internet]. 2018 Nov 1 [cited 2022 Oct 31]; 73 (6): 145A-152A. Available from: https://www.jswconline.org/content/73/6/145A

[30] Anokye J, Logah V, Opoku A. Soil carbon stock and emission: estimates from three land-use systems in Ghana. Ecological Processes [Internet]. 2021 Jan 29 [cited 2022 May 15]; 10 (1): 11. Available from: https://doi.org/10.1186/s13717-020-00279-w

[31] Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, et al. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment. 2013; 164: 80–99.

[32] Batjes N h. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science [Internet]. 1996 [cited 2022 May 15]; 47 (2): 151–63. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2389.1996.tb01386.x

[33] Batjes NH. Options for increasing carbon sequestration in West African soils: an exploratory study with special focus on Senegal. Land Degradation & Development [Internet]. 2001 [cited 2022 May 15]; 12 (2): 131–42. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/ldr.444

[34] Powlson DS, Whitmore AP, Goulding KWT. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. European Journal of Soil Science [Internet]. 2011 [cited 2022 May 15]; 62 (1): 42–55. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2389.2010.01342.x

[35] Patrick M, Tenywa JS, Ebanyat P, Tenywa MM, Mubiru DN, Basamba TA. Soil Organic Carbon Thresholds and Nitrogen Management in Tropical Agroecosystems: Concepts and Prospects. Journal of Sustainable Development [Internet]. 2013 Nov 6 [cited 2018 Oct 24]; 6 (12). Available from: http://www.ccsenet.org/journal/index.php/jsd/article/view/29014

[36] Carter MR, Sanderson JB, MacLeod JA. Influence of compost on the physical properties and organic matter fractions of a fine sandy loam throughout the cycle of a potato rotation. Canadian Journal of Soil Science [Internet]. 2004 May [cited 2018 Dec 5]; 84 (2): 211–8. Available from: http://www.nrcresearchpress.com/doi/10.4141/S03-058

[37] Bruun TB, Elberling B, Christensen BT. Lability of soil organic carbon in tropical soils with different clay minerals. Soil Biology and Biochemistry [Internet]. 2010 Jun 1 [cited 2018 Dec 6]; 42 (6): 888–95. Available from: http://www.sciencedirect.com/science/article/pii/S003807171000026X

[38] Steiner C, Teixeira WG, Lehmann J, Nehls T, de Macêdo JLV, Blum WEH, et al. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant and Soil [Internet]. 2007 Feb [cited 2018 Dec 6]; 291 (1–2): 275–90. Available from: http://link.springer.com/10.1007/s11104-007-9193-9

[39] Musinguzi P, Ebanyat P, Tenywa JS, Mwanjalolo M, Basamba TA, Tenywa MM, et al. Using DSSAT-CENTURY Model to Simulate Soil Organic Carbon Dynamics Under a Low-Input Maize Cropping System. Journal of Agricultural Science [Internet]. 2014 Apr 14 [cited 2018 May 15]; 6 (5). Available from: http://ccsenet.org/journal/index.php/jas/article/view/32835

[40] Yang R, Su Y zhong, Wang T, Yang Q. Effect of chemical and organic fertilization on soil carbon and nitrogen accumulation in a newly cultivated farmland. Journal of Integrative Agriculture [Internet]. 2016 Mar 1 [cited 2019 Mar 7]; 15 (3): 658–66. Available from: http://www.sciencedirect.com/science/article/pii/S2095311916616477

[41] Gupta Choudhury S, Yaduvanshi NPS, Chaudhari SK, Sharma DR, Sharma DK, Nayak DC, et al. Effect of nutrient management on soil organic carbon sequestration, fertility, and productivity under rice-wheat cropping system in semi-reclaimed sodic soils of North India. Environ Monit Assess. 2018 Feb 5; 190 (3): 117.

[42] Hs D, Bs B. Effect of long-term differential application of inorganic fertilizers and manure on soil CO_2 emissions. Plant, Soil and Environment [Internet]. 2016 May 26 [cited 2019 Mar 7]; 62 (No. 5): 195–201. Available from: http://www.agriculturejournals.cz/web/pse.htm?volume=62&firstPage=195&type=publishedArticle

[43] Wang G, Luo Z, Han P, Chen H, Xu J. Critical carbon input to maintain current soil organic carbon stocks in global wheat systems. Scientific Reports [Internet]. 2016 Jan 13 [cited 2019 Feb 25]; 6: 19327. Available from: https://www.nature.com/articles/srep19327

[44] Hao Y, Wang Y, Chang Q, Wei X. Effects of Long-Term Fertilization on Soil Organic Carbon and Nitrogen in a Highland Agroecosystem. Pedosphere [Internet]. 2017 Aug 1 [cited 2019 Mar 7]; 27 (4): 725–36. Available from: http://www.sciencedirect.com/science/article/pii/S1002016017603862

[45] Singh Brar B, Singh J, Singh G, Kaur G. Effects of Long Term Application of Inorganic and Organic Fertilizers on Soil Organic Carbon and Physical Properties in Maize–Wheat Rotation. Agronomy [Internet]. 2015 Jun [cited 2022 Oct 31]; 5 (2): 220–38. Available from: https://www.mdpi.com/2073-4395/5/2/220

[46] Su YZ, Wang F, Suo DR, Zhang ZH, Du MW. Long-term effect of fertilizer and manure application on soil-carbon sequestration and soil fertility under the wheat–wheat–maize cropping system in northwest China. Nutr Cycl Agroecosyst [Internet]. 2006 Jul 1 [cited 2019 Mar 7]; 75 (1): 285–95. Available from: https://doi.org/10.1007/s10705-006-9034-x

[47] Fayisa BA, Welbira GD, Bekele DA. Determination of Optimum Rates of Nitrogen and Phosphorus Fertilization for Finger Millet (*Eleusine coracana L. Gaertn*) Production at Assosa Zone, in Benishangul – Gumuz Region of Ethiopia. Advances in Sciences and Humanities [Internet]. 2016 Jun 17 [cited 2018 Nov 29]; 2 (1): 1. Available from: http://www.sciencepublishinggroup.com/journal/paperinfo.aspx?journalid=323&doi=10.11648/j.ash.20160201.11

[48] Gupta S, Gupta SM, Gupta AK, Gaur VS, Kumar A. Fluctuation of Dof1/Dof2 expression ratio under the influence of varying nitrogen and light conditions: involvement in differential regulation of nitrogen metabolism in two genotypes of finger millet (Eleusine coracana L.). Gene [Internet]. 2014 Aug 10; 546 (2): 327–35. Available from: http://www.sciencedirect.com/science/article/pii/S0378111914006350

[49] Nkonya E. Strategies for Sustainable Land Management and Poverty Reduction in Uganda. Intl Food Policy Res Inst; 2004. 152 p.

[50] Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, et al. Integrated Soil Fertility Management: Operational Definition and Consequences for Implementation and Dissemination. Outlook on Agriculture [Internet]. 2010 Mar 1 [cited 2018 Jun 18]; Available from: http://journals.sagepub.com/doi/pdf/10.5367/000000010791169998

[51] Ngosong C, M. Mfombep P, C. Njume A, S. Tening A. Integrated Soil Fertility Management: Impact of < i> Mucuna< /i> and < i> Tithonia< /i> Biomass on Tomato (< i> Lycopersicon esculentum< /i> L.) Performance in Smallholder Farming Systems. Agricultural Sciences [Internet]. 2015 [cited 2018 Jun 18]; 06 (10): 1176–86. Available from: http://www.scirp.org/journal/doi.aspx?DOI=10.4236/as.2015.610112

[52] Willey RW. Intercropping Its Importance And Research Needs Part 1. Competition And Yield Advantages Vol-32 [Internet]. MPKV; Maharastra; 1979 [cited 2018 Dec 6]. Available from: http://krishikosh.egranth.ac.in/handle/1/2056350

[53] ICRISAT. Annual report 2013 [Internet]. Issuu. 2013 [cited 2018 May 15]. Available from: https://issuu.com/icrisat/docs/annual_report_2013

[54] Kamara AY, Ewansiha SU, Menkir A. Assessment of nitrogen uptake and utilization in drought tolerant and Striga resistant tropical maize varieties. Archives of Agronomy and Soil Science [Internet]. 2014 Feb 1 [cited 2018 Nov 29]; 60 (2): 195–207. Available from: https://doi.org/10.1080/03650340.2013.783204

[55] Kumar A, Metwal M, Kaur S, Gupta AK, Puranik S, Singh S, et al. Nutraceutical Value of Finger Millet [Eleusine coracana (L.) Gaertn.], and Their Improvement Using Omics Approaches. Front Plant Sci [Internet]. 2016 [cited 2018 May 15]; 7. Available from: https://www.frontiersin.org/articles/10.3389/fpls.2016.00934/full

[56] Ebanyat P, de Ridder N, Bekunda M, Delve RJ, Giller KE. Efficacy of Nutrient Management Options for Finger Millet Production on Degraded Smallholder Farms in Eastern Uganda. Frontiers in Sustainable Food Systems [Internet]. 2021 [cited 2022 Dec 14]; 5. Available from: https://www.frontiersin.org/articles/10.3389/fsufs.2021.674926

[57] Ndungu-Magiroi KW, Kasozi A, Kaizzi KC, Mwangi T, Koech M, Kibunja CN. Finger millet response to nitrogen, phosphorus and potassium in Kenya and Uganda. Nutrient Cycling in Agroecosystems [Internet]. 2017 Jul [cited 2018 May 15]; 108 (3): 297–308. Available from: http://link.springer.com/10.1007/s10705-017-9857-7

[58] Anbessa Fayisa B. Determination of Optimum Rates of Nitrogen and Phosphorus Fertilization for Finger Millet (< i> Eleusine coracana L. Gaertn< /i>) Production at Assosa Zone, in Benishangul – Gumuz Region of Ethiopia. Advances in Sciences and Humanities [Internet]. 2016 [cited 2018 May 15]; 2 (1): 1. Available from: http://www.sciencepublishinggroup.com/journal/paperinfo?journalid=323&doi=10.11648/j.ash.20160201.11

[59] Razaq M, Zhang P, Shen H long, Salahuddin. Influence of nitrogen and phosphorous on the growth and root morphology of Acer mono. PLOS ONE [Internet]. 2017 Feb 24 [cited 2018 Nov 28]; 12 (2): e0171321. Available from: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0171321

[60] Ali EA. Grain yield and nitrogen use efficiency of pearl millet as affected by plant density, nitrogen rate and splitting in sandy soil. American-Eurasian Journal of Agricultural and Environmental Science [Internet]. 2010 [cited 2018 May 30]; 7: 327–35. Available from: http://www.idosi.org/aejaes/jaes7(3)/13.pdf

[61] Ayub M (University of A, Nadeem MA (University of A, Tahir M (University of A, Ibrahim M (University of A, Aslam MN. Effect of nitrogen application and harvesting intervals on forage yield and quality of pearl millet (Pennisetum americanum L.). Pakistan Journal of Life and Social Sciences (Pakistan) [Internet]. 2009 [cited 2018 May 30]; Available from: http://agris.fao.org/agris-search/search.do?recordID=PK2010000272

[62] Opole RA, Prasad PVV, Staggenborg SA. Effect of seeding and nitrogen fertiliser application rates on field performance of finger millet. 11th African Crop Science Proceedings, Sowing innovations for sustainable food and nutrition security in Africa Entebbe, Uganda, 14-17 October, 2013 [Internet]. 2013 [cited 2018 May 15]; 127–35. Available from: https://www.cabdirect.org/cabdirect/abstract/20163288716

[63] Wafula WN, Nicholas KK, Henry OF, Siambi M. Finger millet (Eleusine coracana L.) grain yield and yield components as influenced by phosphorus application and variety in Western Kenya. Tropical Plant Research [Internet]. 2016 Dec 31 [cited 2018 Jun 16]; 3 (3): 673–80. Available from: http://www.tropicalplantresearch.com/archives/2016/vol3issue3/088.pdf

[64] Opiyo AM. Effect of Nitrogen Application on Leaf Yield and Nutritive Quality of Black Nightshade (Solanum Nigrum L.) [Internet]. 2004 [cited 2018 May 30]. Available from: http://journals.sagepub.com/doi/10.5367/0000000042530178

[65] PRASAD SK, SINGH MK, SINGH R. EFFECT OF NITROGEN AND ZINC FERTILIZER ON PEARL MILLET (PENNISETUM GLAUCUM) UNDER AGRI-HORTI SYSTEM OF EASTERN UTTAR PRADESH. 2014; 5.

[66] Milkha SA, Sukhdev SM. Interactions of Nitrogen with Other Nutrients and Water: Effect on Crop Yield and Quality, Nutrient Use Efficiency, Carbon Sequestration, and Environmental Pollution. Advances in Agronomy [Internet]. 2005 Jan 1 [cited 2018 Nov 28]; 86: 341–409. Available from: https://www.sciencedirect.com/science/article/pii/S0065211305860079