Building critical SOC concentration as a major pathway for improving nutrient use efficiency in sub-Saharan Africa

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Abstract
Building and maintenance critical Soil Organic Carbon (SOC) concentrations in tropical soils could be the greatest soil fertility challenge in sub-Saharan Africa (SSA). Measures that can boost SOC restoration to critical levels remain less understood. A study was conducted on a Ferralsol in sub-humid Uganda to explore the critical range of SOC concentrations for optimal response of maize to added N fertilizer. Computations were made to estimate the amount of carbon required for SOC restoration using the available organic C materials. Maize grain yield response to N rates was assessed with 0, 25, 50, and 100 kg N ha^{-1} in 30 fields of low fertility (SOC<1.2%), medium fertility (SOC=1.2-1.7%) and high fertility (SOC>1.7%). Non-linear regression models predicted 1.9-2.2% SOC as the critical concentration range for high yields. Theoretical projections suggest that high quantities of organic materials (19-65 t ha^{-1}) are needed every year to build SOC to critical levels. Some organic materials can be potentially applied continuously 10 to 12 times in a year such as compost, bean-trash and *mucuna pruriens,* and as low as 2 times for biochar. The projections demonstrated the difficulty in restoring SOC to optimal levels due to scarcity of materials especially among the resource constrained farmers in SSA.

Key words: Critical SOC, restoration, nutrient use efficiency

Introduction

Soil Organic Carbon (SOC) is an important indicator of soil and crop productivity among smallholder farming system in Sub-Saharan Africa. However, SOC content has declined especially in over-cultivated soils of smallholder farms (Musinguzi et al., 2015). Studies have demonstrated poor yield response and low efficiency to applied N fertilizers in soils with low and high SOC (Ebanyat, 2009). Restoring and maintaining soils at optimal conditions is crucial for high nutrient use efficiency to added mineral N fertilizer and better yields. The search for critical SOC levels is one vital step for attaining optimal conditions. This would improve soil aggregation, soil structure, water retention, nutrient retention, biotic activity, C sequestration, fertilizer use efficiency and crop productivity. The critical SOC would also act as a benchmark for soil fertility restoration and management for sustainable land use intensification especially in the tropics. The optimal soil condition with critical SOC is therefore a good pathway for improving nutrient use efficiency. However, it remains unknown on how the critical SOC concentrations can be restored among the smallholder farmers in SSA. This piece of work attempted to explore the critical SOC concentrations and potential organic inputs that could contribute to SOC restoration in the SSA.

Materials and methods

A total of 30 fields were used during the long (March to June) and short (September to December) seasons. The experiments were laid out in a split-plot randomized complete block design. The experiments were established on fields of low, medium and high fertility, with <1.2%, 1.2-1.7% and >1.7% SOC respectively. The fields were replicated five times for each category. The field types/fertility levels represented main plots. The four nitrogen levels (0, 25, 50 and 100 kg N ha-1) applied as Urea were broadcast in the sub-plots (6 m x 5 m). To alleviate nutrient limitations, P and K were basally band applied at the rates of 25 and 60 kg ha^{-1}, respectively. Maize (*Longe 5*) was sown at a spacing of 25 cm x 75 cm. Stover and grain yield were measured. Non-linear regression models were fitted for the establishment of critical SOC concentrations.

Theoretical projections based on published literature were made to estimate potential implications of building SOC to critical concentrations. Different organic materials that are commonly applied in tropical soils in SSA were documented from published articles (Table 1). The elemental C composition associated with each of the selected materials was used to estimate the amount of C that is required to restore SOC to critical concentrations. The exponential model decay constant (k) (day^{-1}) for different organic materials commonly used in the tropics were obtained from published literature (Table 1). The quantity of organic materials that must be applied to build and maintain critical SOC concentration was estimated (Table 1). The half-life was used as a reference for application of organic materials in order to restore organic material decomposed to half the original material mass.

Results and discussion

The critical SOC range of 1.9-2.2% resulted in the highest agronomic efficiency and yield to applied N (Figure 1). Details can be obtained from Musinguzi et al. (2016). The theoretical projections for building SOC to critical levels demonstrated high variability in the amount of organic materials that are required to restore SOC in low fertility soils. It was evident that raising SOC to the critical range of 1.9-2.2% requires large quantities of organic materials. These ought to be applied continuously depending on the rate of decomposition (rate of exponential decay) in a given soil environment. With reference to the elemental C composition of materials in Table 1, soils of low SOC would require the highest amounts of organic materials in a range of 23-123 t ha^{-1} for SOC restoration

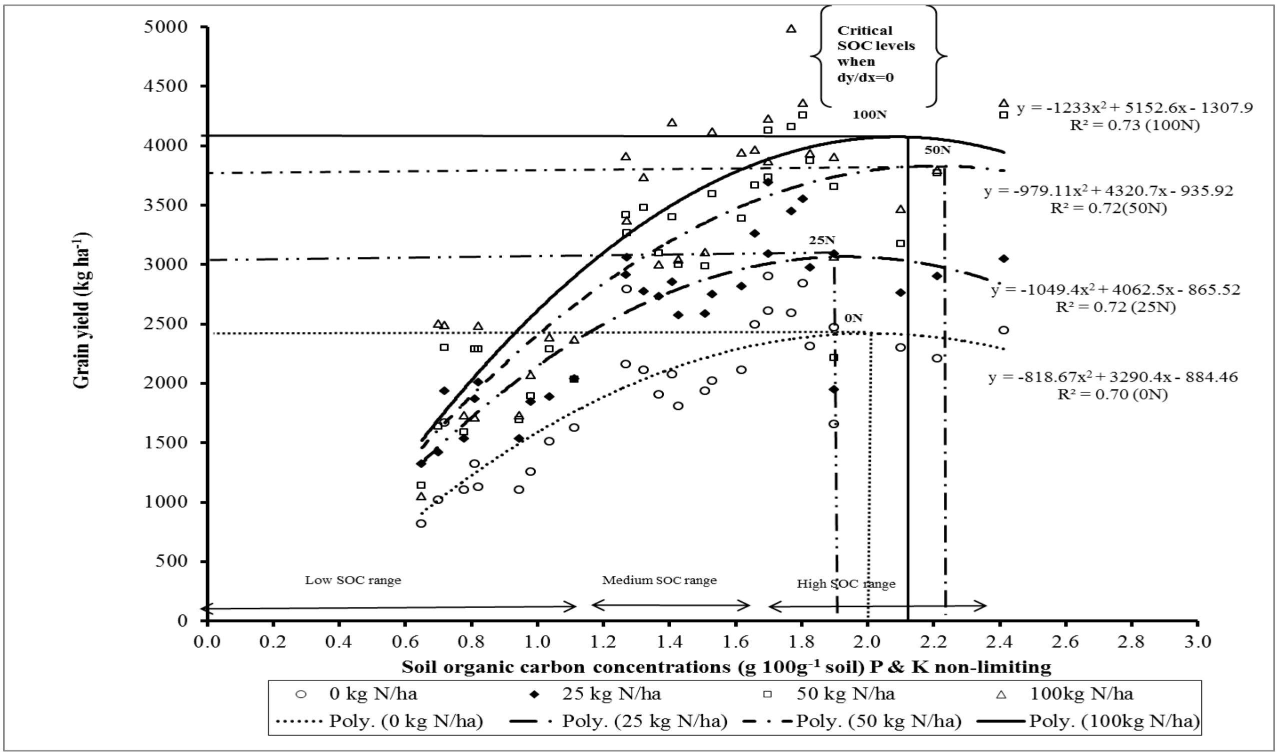

Figure 1. Non-linear model fitting of maize grain yield response to added nitrogen fertilizer under soils of different SOC ranges in a Ferralsol in Uganda

Table 1. Estimated quantities of organic materials required to restore SOC to critical levels, the material quality classes and the associated decay constants

	Selected organic material (% C content; References)	Equivalent organic material to restore C (t ha^{-1}) in fields of lowest SOC to the critical 2.2% level			Resource quality classes by Palm et al., 2001	Exponential model decay constant (*k*) day^{-1}	Estimated half life	Frequency and quantities required for restoration
		<0.6% to 2.2%SOC	1.2% to 2.2% SOC	1.7% to 2.2% SOC				
1	Mature compost (24 % C, Kimani & Lekasi et al., 2004)	123.8 - 81.6	81.6 - 39.3	39.3	Class I (High N, low lignin and PP*)	0.019	36	65 t ha^{-1} (applied 10 times)
2	*Mukuna Pruriens* (42.94% C Dauda et al., 2006)	69.2-45.6	45.6-21.9	22	Class I (High N, low lignin and PP*)	0.023	30	36.5 t ha^{-1} (12 times applied)
3	Cow dung (35 % C, Lekasi et al., 2001)	84.90 - 56	55.93-27	27	Class II (High N, high lignin, low PP)	0.011	63	
4	*Sesbania sesban* litter (37.2% C Palm et al., 2001)	79.9-52.6	52.6-25.4	25.4	Quality class I (High N, low lignin and PP*)	0.042	17	_
5	*Calliandra calothyrsus* litter mass (46.28% Palm et al., 2001)	64.2-42.3	42.3-20.3	20.3	Class II (High N, high PP*, low lignin)	0.012	58	_
6	Maize stover (41.2% C Palm et al., 2001)	72.1-47.5	47.5-22.9	22.9	Class III (Low N, low lignin)	0.0093	75	39t ha^{-1} (5 times a year)
7	Bean trash (54.1% C, TSBF database, 1997)	79.9-52.6	52.6-25.4	25.4	Not classified	0.021	33	29 t ha^{-1} (11 times)
8	*Eucalyptus salign* (litter) (46.13% C, Palm et al., 2001	59.5-39.2	39.2-18.9	18.9	Class IV (Low N, high lignin)	0.0072	96	35 t ha^{-1} (4 times ayear)
9	Biochar-Wood derived (85.1% C)	34.9-23	23-11	11	Not classified	0.004	173	19 t ha^{-1} (applied 2 times/year)

PP* = Polyphenols, SOC= Soil organic carbon, N =total nitrogen in plants

Depending on the rates of decomposition/exponential decay constant (day^{-1}), the amount of organic materials that may be required to build SOC to the critical range would entirely depend on the quality of the material (Table 1). The majority of high quality organic materials decompose faster when incorporated in the tropical soils and can reach a half-life within 17 to 96 days (Table 1). Using the half-life as the strategic time for applying organic materials, SOC levels increase steadily. Any measures that could inhibit or slow down complete material decomposition are important in building SOC. It is also notable that different organic materials have different half-lives and exponential decay rates, and the frequency of material addition for C restoration varies over time. For some materials that are highly decomposable (short half-life), it is estimated that these may be applied 12 times in a year (eg. *Mukuna pruriens*), and as low as 2 times per year for biochar for building SOC (Figure 1). The timely and consistent application of materials is therefore important to build SOC notwithstanding the scarcity of these materials in low fertility fields and accurate estimation of half-life to add organic materials. Soil organic carbon maintenance and restoration is therefore a major soil fertility management challenge in SSA. With efforts geared towards finding solutions for increasing nutrient use efficiency, restoring SOC to critical levels in soils in SSA, will have beneficial results and help increase the agricultural productivity of the soils in that region.

Conclusion

Building and maintaining SOC in tropical soils is a critical issue which must be addressed to boost production of food, fuel, fodder and fibre; and contribute to mitigating climate change through C sequestration. Improving soils with low SOC concentrations from 0.6% to critical levels of about 1.9-2.2% is challenging. Increasing the quantity of organic materials together with their continuous application seems promising. However, it is important to engage different stakeholders such as researchers, policy makers and farmers to devise mechanisms on how to counter the challenge related to out-sourcing for the different materials that are not easily available. Long-term research studies are also needed to validate the theoretical underpinnings demonstrated in this work. Economic implications need to be considered so as to make sound judgment for future use. This would contribute to overcoming what we are conceiving as the 'soil fertility challenge of the century' whose implications in sub-Saharan Africa can be enormous on land use, food security, climate change, and livelihoods.

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