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# Soil Organic Carbon Thresholds and Nitrogen Management in Tropical Agroecosystems: Concepts and Prospects

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## Abstract

Soil organic carbon (SOC) is a potential soil fertility indicator for regulating nitrogen application in tropical farming systems. However, there are limited studies that have discussed SOC thresholds above or below which crop production could be diminished, or at which no or high response to nitrogen (N) application can be realized. This review explores the drivers of SOC concentration relevant for the establishment of thresholds. We further evaluate existing SOC thresholds for provoking no yield response or significant response to added N fertilizer. Key drivers for SOC concentration relevant in establishing thresholds are mainly climate, topography, texture, and land use management. Soil organic carbon threshold for sustaining soil quality is widely suggested to be about 2% below which deterioration may occur. For added N fertilizer management, specific SOC thresholds seem quite complex and are only valid after assuming other factors are non-limiting. In some soils, SOC levels as low as 0.5% result in fertilizer responses and soils as high as 2% SOC also respond to small N doses. Minimum SOC thresholds can be identified for a given soil type, but maximum thresholds depend on crop N requirements, crop N use efficiency and amount of N applied. However, there seem to exist critical total SOC ranges that could be targeted for optimal indigenous N supply and integrative soil functional benefits. These can be targeted as minimum levels in soil fertility restoration. In all, it is still difficult to establish a single minimum or maximum SOC threshold value that can be universally or regionally accepted.

**Keywords:** critical level, soil organic carbon fractions, tropical soils, efficiency, yield

## 1. Introduction

Soil Organic Carbon (SOC) is a key physical and chemical parameter critical for nutrient management in tropical farming systems. The soil parameter provides integrative benefits in protecting the environment and sustaining agriculture. Some scientists have described SOC as a ‘universal keystone indicator’ in soil fertility management (Ssali, 2000; Loveland & Webb, 2003), making it a good candidate and an appropriate tool for managing soil fertility heterogeneity among farmer fields in Sub-Saharan Africa (SSA), with the lowest fertilizer use levels in the world (Dobberman, 2005), and agronomic nitrogen use efficiency (Sanginga & Woomer, 2009; Vanlauwe et al., 2011). Nitrogen recovery efficiency hardly exceed 50% (Cassman, Dobermann, & Walters, 2002; Terry, 2008), and could be even far below 30%. Adaptation strategies to soil heterogeneity using affordable soil indicators like SOC would improve farmer decisions to effectively apply N. There are already signals that smallholder farmers are aware of this positive correlation between soil nutrient status and SOC levels (Murage, Karanja, Smithson, & Woomer, 2000; Hossain, 2001). Farmers commonly know SOC as property associated with a dark or black soil that is particularly for enhancing plant productivity. However, SOC has been declining due to high intensity of decomposition and high turnover rates in the tropics (Yang, 1996; van Keulen, 2001). This has led to low soil fertility and increased the demand to apply mineral N fertilizers. The establishment of SOC thresholds is one measure that can be employed to regulate N application and minimize environmental pollution. What is unclear in the tropics and even globally are the critical SOC levels or thresholds that must be present to regulate the application of external fertilizers. Such levels are key in short and long-term soil fertility restoration in areas with negative nutrient balances. There have been efforts to explore SOC threshold levels, but in the context of desirable soil properties and the inherent nutrient supply for crops (Six, Elliott & Paustian, 2000; Chenu, Bissonnais, & Arrouays, 2000; Loveland & Webb, 2003). In this piece of work, therefore, we consider the concepts and prospects of SOC thresholds and N management. We discuss (i) SOC threshold concept and driving factors controlling SOC concentration (ii) thresholds values below or above which no yield response or significant response to the added N fertilizer is possible (iii) the restoration of critical SOC levels using the Integrated Soil Fertility Management approach. This work attempts to contribute to the understanding of SOC as a potential soil fertility indicator for managing tropical soils.

## 2. Defining Soil Organic Carbon Thresholds

Tropical agro-ecosystems are characteristic of low dependence on the external application of fertilizer (Buresh, Sanchez, & Calhoon 1997). The major source of nitrogen supply in such farming systems is SOC through the process of mineralization. However, there are thresholds of SOC below which no mineralization or above which high mineralization takes place. Smith and Dumanski (1993) defined thresholds as critical levels above which a system responds significantly to stimuli. Pieri (1995) on the contrary defined thresholds considering the environmental aspect. He defined thresholds as values of certain variables above which a significant shift or rapid negative change takes place. In this section, we define thresholds in the context of SOC, nitrogen management and soil environmental quality. This follows a growing demand to improve applied fertilizer use efficiency for most farmers in tropical SSA. One of the interventions in managing field heterogeneity includes the categorization of soil fertility into grades of poor, medium and good fields using SOC as an indicator. However, critical SOC amounts or thresholds that can guide the decision making for several farmers to add N fertilizer remain oblique.

Too much or too little SOC can equally be an environment threat leading to pollution or loss of biodiversity. It is common to conclude that increasing soil organic matter by applying organic materials is good practice. However, the addition of excess inputs need to be applied with caution as this can lead soil nutrient imbalances of nitrogen or phosphorus, and can lead to pollution of surface and ground waters. Low SOC amount is also an environmental threat since low fertility results in low biomass yield. Such level can also result in significant fertilizer loss because of low buffer or retention capacity. Oades, Gillman and Uehara (1989) noted that applying extra levels of organic residues can lead to acidification due to nitrification. Application of extra amounts of carbon can also result in the crusting of soil surface, decreased hydraulic conductivity, and increased run-off (Haynes & Naidu, 1998). The minimum and maximum SOC thresholds at which soils can support crop production while sustaining a friendly environment remain a less explored option in tropical soils.

We present a hypothetical conceptualization of the SOC thresholds (in the context of concentrations) that must be maintained to sustain crop production, with or without organic or mineral fertilizers. SOC levels which are environmentally sound are assessed. Though several studies in the tropics have not debated much on threshold levels, but elsewhere in temperate climate, there is wide acceptance that it remains difficult to have universal thresholds. As one of the potential soil fertility indicators for tropical soils, the contribution of SOC in the tropics need to be understood to enable proper soil functioning and sustain yields. Figure 1 illustrates the role of SOC in influencing crop response to added fertilizer but also suggests levels for sustaining soil quality, crop yields and environmental quality. It illustrates that there is a minimum SOC threshold value that is necessary to realize some responses to applied N (point X), and a maximum level above which no response to N fertilizer is evident for a given crop (point Y). Conceptual terms of sensitivity and resilience are applied as suggested by Coughlan (1995). Notably, low or high SOC levels tend to result in low response to the added fertilizers or low sensitivity. This consequently leads to low nitrogen use efficiencies and reduced environmental quality due to leaching. At very low SOC levels, there are clear evidences of low resilience, but after attaining a certain threshold value, resilience is improved. Point A is the minimum SOC amount to sustain soil quality/crop production with some resilience, and point B is the maximum SOC amount above which an environmental threat is possible. The whole framework that is conceptualized in this work provides a scheme for further research on tropical soils, and as such, opens up discussion on maintaining critical thresholds for sufficient nitrogen application, crop productivity and environmental safety.

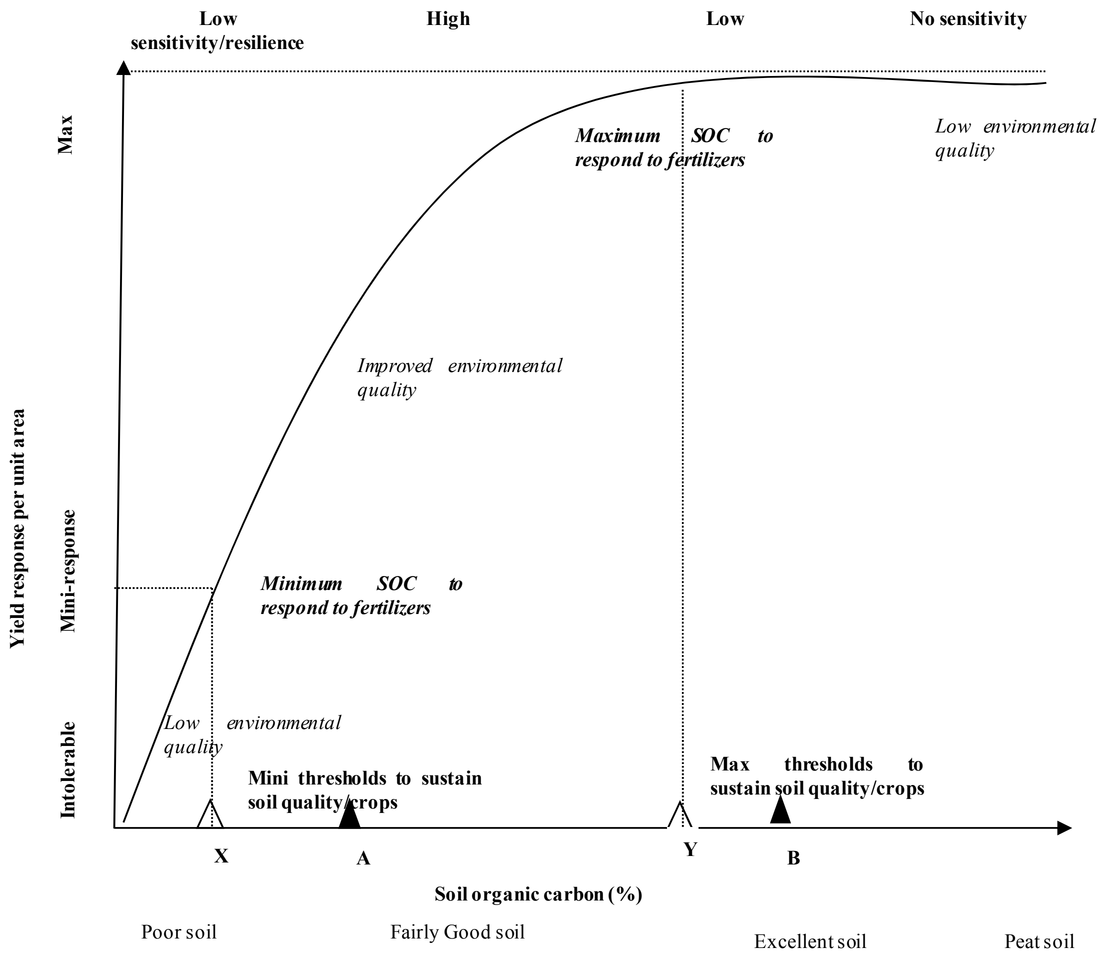

Figure 1. Conceptual diagram of SOC thresholds for response to added N, sustainable crop production and environmental quality

## 3. Determinants for SOC Amount and Distribution

In tropical agro-ecosystems, the application of SOC as a potential indicator for nitrogen management partly depends on its total amount, the quality of fractions, and their level of influence on soil properties. The amount of added organic carbon input (vegetation, roots, crop residues, wastes) and the rate of loss (carbon dioxide from tillage, microbial decomposition) determine the amount of SOC present at a given time (Krull et al., 2004). There are vast effects of high SOC contents on soil properties such as the formation of stable aggregates, soil surface protection against runoff and erosion, and improved functioning of biological components. Other effects on soil functions include improved ion exchange capacity, reduced bulky density, increased water holding capacity and macro and micronutrient availability (Carter & Stewart, 1996; Carter, Angers, Gregorich & Bolinder, 2003). However, there is high variation of SOC in tropical farming systems, which tend to limit efforts geared towards establishing thresholds for N application. Thus any attempts to understand thresholds require exploring the drivers of SOC variability. Dick and Gregorich (2004) suggested a function for the key drivers that influence SOC capacity (Equation 1):

$$\text{SOC (capacity)} = f\text{ (climate, topography, texture, disturbance, inputs)} \qquad (1)$$

Depending on a range of factors, SOC content varies. We discuss the effect of a range of these factors on affecting SOC. From Equation 1, we notice that the first three factors cannot be managed. The farmer is a driver for the last factors that influence the balance between all the carbon inputs and losses. Farmer induced heterogeneity has already been reported as the key cause of soil fertility variations (Zingore, 2006; Tittonell, 2008). In the past, Jenny (1941) had attributed SOC variations to factors such as topography, climate and management while edaphic factors were considered as secondary.

We discuss some of the drivers of SOC amounts in various soil types as per equation 1, and we propose an equation that can apply to the tropical soils. Land use management is identified as lead drivers of SOC amounts. From Dick and Gregorich (2004), we therefore propose 4 factors that are critical in driving SOC amounts at a time (Equation 2).

$$\text{SOC capacity} = f\,(\text{texture, climate, topography, land use management}) \tag{2}$$

Texture is one of the major determinants of SOC content at a given time and is key for the establishment of SOC thresholds for N management. Individual particle sizes have different influence on SOC amounts as affirmed in several works on SOC and texture (Korschens, Weiger, & Shulz, 1998; Dick & Gregorich, 2004). In tropical soils, there are direct relationships in the level of concentrations of SOC, clay or clay + silt, especially on work conducted on kaolinitic types of soils (Feller & Beare, 1997; Zinn, Lal, Bighama, & Resck, 2007). Differences in clay content for different soils can result in SOC equilibrium (Christensen, 1992), thus, proper definition of texture for tropical soils is important. For cases of high clay content, SOC equilibrium is easily reached. This is usually attributed to the capacity of the clay soil to stabilize products decomposed from organic residuals, which sandy soils can easily lose (Christensen, 1992). Other than the clay, the mineralogy also contributes to stabilization (Bruun, Elberling, & Christensen, 2010). In one long term trial conducted for 90 years (Korchens et al., 2008), soils typical of sand with 3% clay content resulted in an equilibrium at 0.7% SOC but for soils with 21% clay, this was realized at 2.0%. The lower and upper limits were proposed from these datasets with about 4% clay at 1% and 1.5% SOC while for soils with 38% clay, 3.5% and 4.4% SOC were suggested as the set limits. The concept of equilibrium is therefore critical in understanding role of texture on influencing SOC and N supply.

Climate and topography are key parameters in the tropics that influence the dynamics of SOC, and can regulate the determination of thresholds. Major climatic parameters include temperature, rainfall, solar radiation, wind speed, and relative humidity. Temperature can affect stability of SOC thresholds, especially in a soil type where the temperature quotient (Q10) is about 2 (Yang, 1996; De Ridder & van Keulen, 1990). This can lead to high intensity of decomposition thus rapid SOC decline. Precipitation also influences SOC mineralization and organic litter breakdown (Feller & Beare, 1990). High dependence on rain-fed farming needs to be monitored to regulate possible negative effects. Topography also influences soil properties including soil organic matter (Raghubanshi, 1992; Ebanyat, 2009). Topography influences SOC by controlling soil water balance, and erosion processes (Tan, Lal, Smeck & Calhoun, 2004). Site specific characterization of slope position, slope percent and other topographic features are important in identifying and managing critical SOC levels.

Land use management directly determines the amount of SOC present at a time. A description of various land uses in the past and in the present status in terms of vegetation cover is vital. The quality and quantity of organic material littered derived from a given land use directly influence SOC levels (Palm, Gachengo, Delve, Cadisch, & Giller, 2001). Common organic materials applied include animal related manure, plant residues, and compost. Soils with organic materials or residuals that have a low C:N favour decomposition. Management approaches that involve use of materials for mulching or soil erosion control disrupt SOC pools (Kanyanjua, Mureithi, Gachene, & Saha, 2000). The choice of land use management practice is, thus, a prime source of SOC loss especially for a tropical soil. Practices such as conventional tillage, biomass harvesting, burning, use of excess fertilizers, herbicides and pesticides threaten efforts to sustain critical SOC levels. Conventional tillage threatens SOC capacity as it exposes organic matter that has been protected (Doran & Smith, 1987). In other tropical farming systems outside Africa, reduced tillage has been adopted. This practice increases Particulate Organic Matter (POM), as a result of slow decomposition of crop residues (Tan, Lal, Owens, & Izaurralde, 2007). Several workers like Christensen (2001) have observed that POM is higher in undisturbed soil than in the long-cultivated cropland soils. Thus, land use management is key driver to observed variations in SOC, and affects amount of potentially mineralisable N.

## 4. Soil Organic Carbon Thresholds and Soil Properties

In sub-Saharan Africa (SSA), there has been less work on the fractionation of SOC, yet there are some fractions that are critical in determination of thresholds, for example particulate organic matter that Swift & Woomer (1993) regarded as an organic fertilizer. If such SOC fractions are below or above critical levels, the desirable soil functions may be reduced or improved respectively. Krull, Skjemstad and Baldock (2004) discussed some of the minimum and maximum thresholds of SOC, above or below which the effects of SOC on soil functions are noticeable. However, Sparling and Schipper (2002) argued that other than defining such maximum values, it is reasonable if minimum SOC levels are established to inform the farming community on levels below which there would be loss of important soil characteristics. In the temperate climate, several authorities suggest a threshold value of SOC of about 2% (about 3.4 % soil organic matter) (Howard, P. J. A., & Howard, D. M., 1990; Huber et al., 2008). In the tropics, SOC levels that are required to maintain a desirable soil function have had less attention. For aggregate stability, various authors suggest 2% SOC as a minimum value for maintaining a stable structure, and levels below 2% usually result in rapid instability. On the application of the Emerson crumb test, Greenland, Rimmer and Payne (1975) found that for SOC levels less than 2%, soil aggregates were unstable while those with 2-2.5% SOC were averagely stable. SOC levels above 2% were very stable. For water holding capacity, variations in SOC also influence soil water retention (Haynes & Naidu, 1998). Depending on amount of C present in these fractions, high levels can lead to high water retention. Thus, this can affect nitrogen and water use efficiencies. However, what remains unclear is whether the labile SOC fraction is more influential than the recalcitrant fraction (Olk & Gregorich, 2006). For Cation Exchange Capacity (CEC), Eshetu, Giesler, & Högberg (2004) suggested 2% as a minimum SOC threshold value required to sustain this parameter. In all, critical SOC levels for proper functioning of soil properties are key for sustaining healthy soils and crops. The 2% SOC levels that have been suggested in temperate regions is yet to be proved for tropical soils where soil fertility decline is at its peak. Restoration measures that lead to an acceptable minimum SOC level are important.

## 5. Soil Organic Carbon Thresholds for Crop Response to Applied Nitrogen Sources

Crop responses to added N fertilizer is a function of total N present (potentially mineralisable N), crop N demand, and capacity of soil to hold N from losses due to leaching, erosion, volatilization. If soil properties and crop management aspects are ideal, crop response to added N fertilizer can be a function of SOC amount, but there must be a critical SOC range for minimum and highest yield response, and below which added fertilizer results in no response (also discussed in Figure 1). Use of organic N fertilizer can be challenging in assessing crop response to its application. Organic fertilizer has diverse nutrient components and is not a focus for this discussion. The focus is on mineral fertilizer with particular focus on adding N fertilizers.

Efforts to determine these SOC thresholds/critical ranges for some farming systems for nutrient management exists in some countries but remain dismal. Mapfumo (2006) conducted a study in Zimbabwe on a sandy soil (Arenosol) with 120 fields categorized into three different rainfall zones using maize as the test crop. Very low and sometimes no response to added fertilizer was evident in fields having less than 4.6 g C kg$^{-1}$ SOC. However, SOC values in a range 4.6 and 6.5 g C kg$^{-1}$ (Mapfumo, 2006) resulted in high variations to fertilizer response. Yield increase in fields with SOC higher than 6.5 g C kg$^{-1}$ were also noted. Excessive use of organic related inputs, to as high as 20 t ha$^{-1}$, did not enhance total SOC to more than 8.5 g C kg$^{-1}$. This suggested that the application of organic matter in some farming systems does not always result in improved SOC content, and the sand particle sizes seem to have reached saturation points. Thus depending on the texture of the soil, SOC thresholds can vary depending on soil type.

In a similar study by Berger et al. (1987) in West Africa, a very low SOC level 3.5 mg kg$^{-1}$ in the northern Guinean zone, with dominantly Leptosols was reported as the lowest minimum level required for added nutrients to respond. Bationo, Lompo, & Koala (1998) further established that even SOC levels as low as 1.7 mg kg$^{-1}$ would result in a nutrient response of added fertilizer. Though these studies were conducted in a range of soils in different regions of Africa, they seem to agree with some authors who agree that it is difficult to have one standard universal SOC value of minimum or maximum levels for responses to added fertilizer to be evident. In all, SOC levels of less than 10 g kg$^{-1}$ without adding organic matter can be too low and can result to disequilibrium in nitrogen supply to plants. For example, SOC below 0.5% can supply less than 50 kg N ha$^{-1}$, and it was estimated by Carsky and Iwuafor (1995) that such SOC levels can only result to about 1000 kg ha$^{-1}$ of maize under normal rates of NUE. Application of fertilizers or other organic inputs on soils with SOC as low as 1.7 mg kg$^{-1}$, can still sustain production as noted in West Africa.

In East Africa region, Foster (1976) recommended 20.5 g kg$^{-1}$ (2%) SOC level as appropriate for supporting crop production. Soil organic carbon levels that would result in no crop response to added fertilizer remain unknown for various soils and climatic zones. Therefore, targeting critical SOC amounts for highest fertilizer use efficiency and optimal crop yield can be challenging. Soil organic carbon thresholds can be different for various nutrient amounts in a given soil and crop. However, it can be hypothesized that there is a critical SOC range at which a particular N fertilizer could result in high use efficiency, assuming that other factors are not limiting. Such a critical range of total SOC amount must be related to qualities or quantities of labile/non-labile fractions that can lead to optimal indigenous N supply and integrative soil functional benefits. This implies the contribution of SOC fractions in this assessment cannot be underrated.

### *5.1 Conceptualization of Critical SOC Ranges/Thresholds for Optimal NUE and Yields*

The efficiency of any management conducted on a field many times depends also on soil quality. Figure 2 illustrates various hypothetical scenarios generated from a poor, medium, and good fields. Too good and too poor soils can result in low N recovery efficiency efficiencies (Figure 2). In cases that SOC is low, soil physical and chemical parameters are equally poor. Addition of N fertilizer may easily be lost easily due to poor the nutrient retention capacity. At higher SOC levels, with good soil quality, the N recovery efficiency can be low due to high N mineralization favored by good soil condition. This conceptual diagram (Figure 3) suggests that there exist critical SOC ranges that can result in highest nutrient recovery efficiencies. Maintenance of such ranges is key for long-term soil fertility management of tropical soils.

Soils with different SOC levels can result in responsive and less-responsive characteristics to the added nitrogen inputs. As a consequence, different agronomic efficiencies are predicted. Nutrient efficiency in such soils differ given the fact that the each soils' capacity to supply N and plants capacity to utilize nutrients is different (Fageria, Baligar, & Li, 2008). We apply the agronomic efficiency index probably as the most appropriate in evaluating applied N options that can lead to optimum yields. In a hypothetical assessment, Figures 3a and 3b illustrate critical values with an optimum agronomic efficiency of added N and yield, for soils of different responsiveness (with SOC as a lead indicator). In the two figures, a less responsive soil is poor with minimum amounts of key soil quality indicators such as SOC. A responsive soil is a good field with basic qualities that lead to high responses to added N, with critical SOC levels.

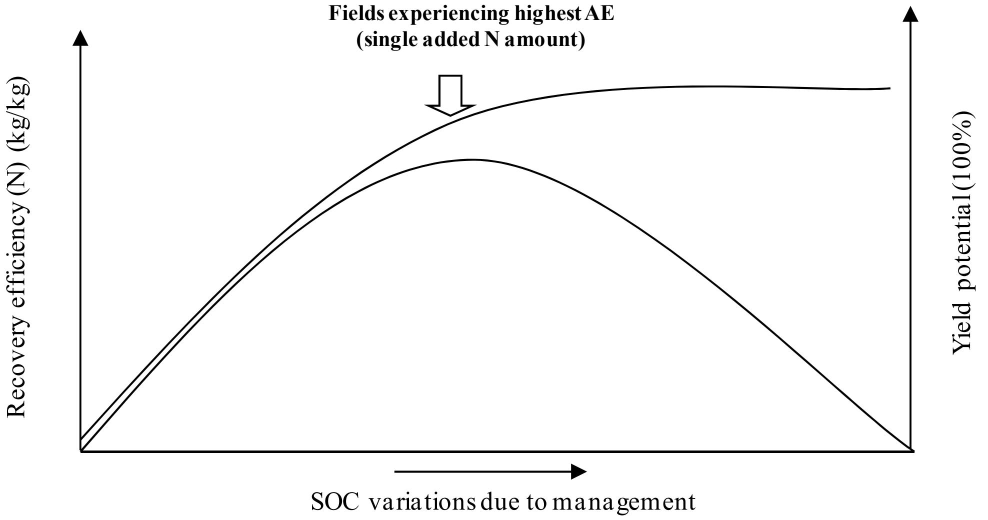

Figure 2. A conceptual relationship between SOC levels, yields and agronomic N use efficiency of crops in rain-fed tropical systems

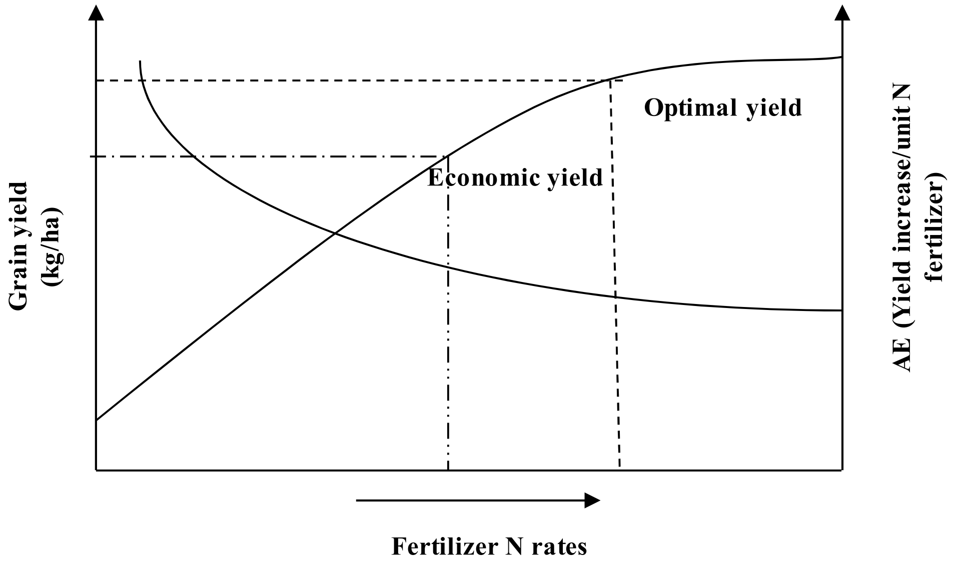

Figure 3a. A conceptual relationship between increasing fertilizer N rates as advocated by green revolution, grain yield and agronomic efficiency in a less responsive soil

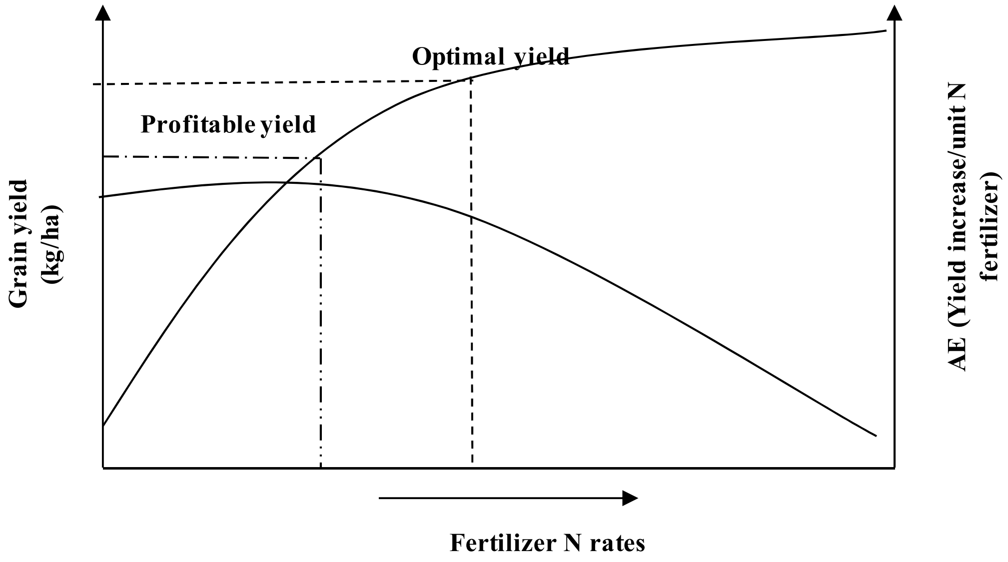

Figure 3b. A conceptual relationship between increasing fertilizer N rates, grain yield and agronomic efficiency in a responsive soil

In a less responsive good soil (Figure 3a), high agronomic efficiency prevails at low N rates while optimum yield at high N application rates. This suggests that optimum AE is always below optimum yield, at the lowest N application rate. Nitrogen rates beyond optimum yield result in low agronomic efficiency and crop response. Economic profitability is achieved at intermediate N fertilizer rates. In a responsive soil, there is a strong correlation between yield and N application rates. Agronomic efficiency is high at the start and declines only at highest N application rates (Figure 3b). Both figures suggest a critical N rate that translates in an economic yield and such a rate can be recommended for application for a given soil. However, there is a remarkable shift of the AE curves on responsive soils (backwards), and the optimal yield is obtained at low nutrient rates. As compared to AE-yield curves (Figure 3a), attaining optimum yield requires high N rates. The conceptual diagrams suggest a need to aim at building SOC in responsive soils (Figure 2b) that require less N levels and can minimize the amount of reactive N in the environment. This implies that 'optimal yield' is not a necessity, but rather attaining a 'high yield' that results in high NUE and is environmentally sensitive, is most appropriate.

However, responsiveness in some farmers' field cannot ignore the contribution of individual SOC fractions. In Figure 4, we hypothetically conceptualize the contribution of SOC fractions to regulating added N fertilizers. To attain the highest recovery efficiency (RE) of N, there is a possibility that the formation of synergies between the labile and recalcitrant carbon pools, with the lowest mineralization potential; result in the highest efficiencies (curve C). The curves A and B are a good indication of the role of each fraction to availing N supply through mineralization. The labile fraction is a common source of N, due to its high turnover, and any addition of N fertilizer may have low RE. Excessive application of N fertilizer can be lost due to low nutrient use efficiency (NUE), and can cause acidification of soils. Part B is a curvilinear with high levels of recalcitrant fractions and high labile fractions, suggesting high N supply through mineralization. A low response to added N fertilizer is possible in such a scenario (curve A). The illustration suggests that recalcitrant fractions are equally important as the labile fraction(s) in influencing added N fertilizer especially in severely depleted soils in the tropics. The contribution of soil attributes such as texture, pH, the slope gradient, CEC, mineralogy, the level of aggregation and management related factors cannot be underrated. They influence mineralization and nitrification processes. Such attributes must be well characterized as they affect the role of influential SOC fractions identified, and regulate SOC thresholds needed to ensure sustainable soil fertility and crop productivity.

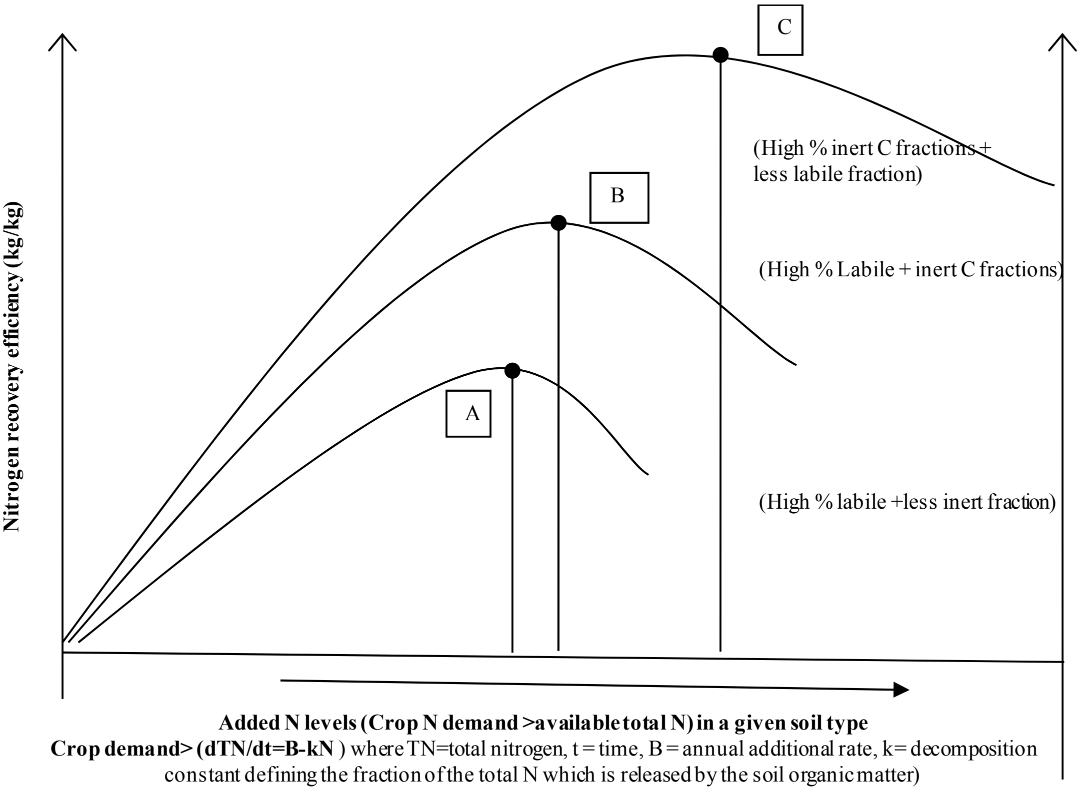

Figure 4. A conceptual illustration for yield (annual crop) responses to added N under different SOC fractions amounts and combinations

### *5.2 Towards Long-Term Soil Organic Carbon Restoration*

Soil organic carbon is a promising indicator for integrative N management under challenges of soil heterogeneity among smallholder farming systems. Measures that build and sustain SOC stocks to critical levels require special consideration. Integrated Soil Fertility Management (ISFM) is currently one measure promoted for community development and research in the regions of SSA to preserve soil quality while promoting its productivity (Sanginga et al., 2009). Vanlauwe et al. (2010) suggested an operational definition of ISFM as '*the set of soil fertility management practices that necessarily include the use of fertilizers, organic inputs, and improved germ plasm, combined with knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiencies of the applied inputs, and improving crop productivity*'. The proposed definition, however, does not fully explain or demonstrate the significancy of some factors and their role in enhancing nutrient use efficiencies, and environment efficiency. For example, ISFM aims at maximizing AE and yield, and does not consider optimizing NUE and yields. Figure 5 illustrates the current concept of ISFM and its contribution to improving agronomic efficiency of N fertilizer. In Figure 5, responsive soils to NPK, and those that are poor and less responsive are illustrated. Under the 'current practice' it is assumed that average fertilizer applied is about 8 kg ha$^{-1}$. On applying constant fertilizer rates, yield is related to AE linearly as adapted from Vanlauwe et al. (2010). It is also evident that soil fertility gradients have an impact on fertilizer responses, thus a need to adjust amount of inputs as a key approach for adapting to local soil situations.

However, obtaining high NUE efficiency that also translates into optimal yield, we propose a newly adjusted conceptual visualization of agronomic efficiency in Figure 6, from Vanlauwe et al. (2010) concept.

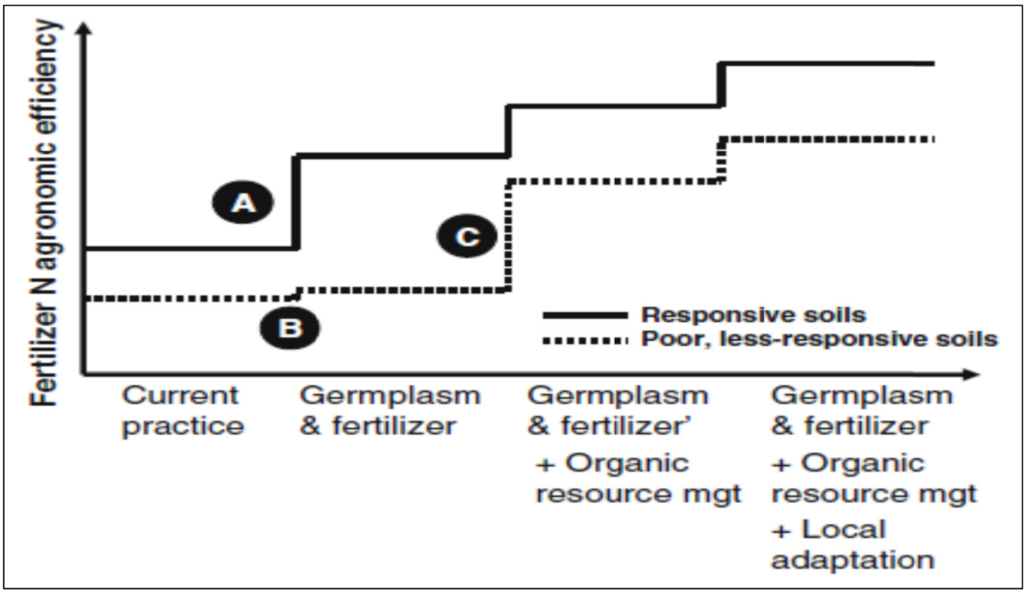

Figure 5. Conceptual relationship between the agronomic efficiency (AE) of fertilizers and organic resource and the implementation of various components of ISFM, culminating in complete ISFM towards the right side of the graph (Vanlauwe et al., 2010)

Scenario 1 (Poor and less responsive fields). The current farmer practice is representative of several produces who currently do not use external fertilizers as evidenced by the low yields. On improving the management, use of improved germ plasm, fertilizer N and organic resources (A), and adapting to local conditions, the poor fields (low SOC level) improve steadily and yield increase significantly. The contribution of the ISFM components to soil fertility improvement and agronomic use efficiency become evident. Highest increase in agronomic N efficiency is notable on adding organic resource management, but the yield potential is still slightly below other fields. In this scenario, there is low fertilizer use efficiency even with improved germplasm, suggesting high N losses through leaching. (X1).

Scenario 2 (Medium and responsive fields). The second field type also represents some fields with medium soil fertility range (medium SOC level), and any addition of fertilizer N results into high yields as compared to the poor fields. Medium fields seem to have inherent soil properties that respond to added fertilizer without necessarily adding organic resources. These fields seem to be most responsive (B), without adding organic resources probably because of inherent SOC amounts. However, the yields increase on adding organic resources, and on adapting to local situations, emphasizing the importance of ISFM. This field type shows few evidences of N loss, but can possibly arise from organic resource mineralization. The scenario also suggests that increasing SOC levels to minimum levels is key for short and long-term soil fertility restoration and nutrient management.

Scenario 3 (Good field and less responsive). Good fields (high SOC levels) are also common with heterogeneity, and under such prototypes, the agronomic efficiency is slightly high (C), but the amount of N required to reach optimal yields is less as compared to scenario B. There are high possibilities of N loss and leaching (X2) on adding extra N fertilizer. It is crucial, therefore, that right amounts are applied in the field type to satisfy crop N requirement.

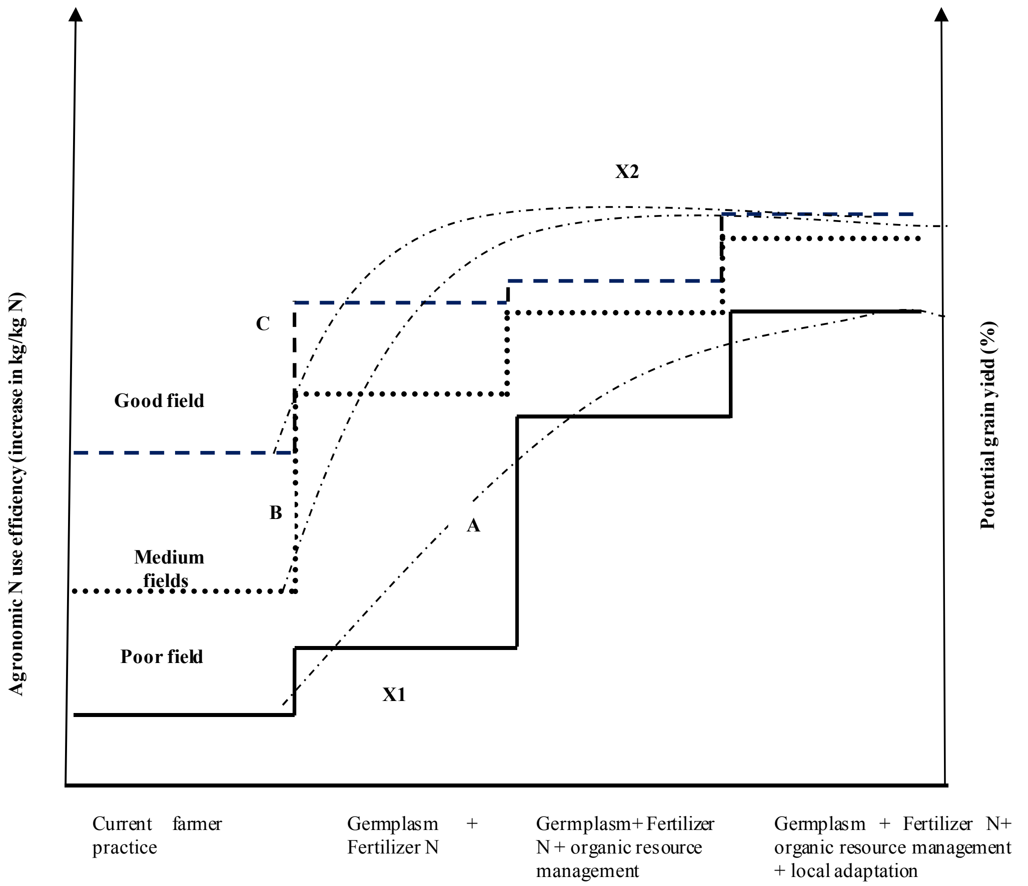

Figure 6. A revised conceptual relationship between the Agronomic Efficiency (AE) of added N fertilizers and organic resources, potential grain yield and the implementation of various components of ISFM under tropical farming heterogeneity (revised from Vanlauwe et al., 2010)

To understand ISFM in a content of optimizing agronomic added fertilizer use efficiency, and yield for sustainable land use intensification, we propose to re-define ISFM as 'a practice of ‘improving and restoring soil fertility while optimizing yields’ using a set of soil fertility management practices that necessarily includes organic and mineral fertilizers, improved germ plasm; and using a set of knowledge to adapt them to a given environment, while targeting maximizing production and recovery efficiencies of applied nutrients for sustainable land use intensification’. Efforts in building SOC to a critical threshold/level would be useful for most tropical farmers and would enhance sustainable land use intensification as reflected in scenarios 2 and 3 (Figure 6). Scenarios 2 and 3 form are presumed critical SOC levels that farmers must aim for improved N fertilizer use efficiency while overcoming food insecurity and poverty in the tropical agro ecosystems.

## 5. Conclusion

Soil organic carbon is a promising indicator for guiding N fertilizer use given its integrative benefits that lead to high N supply and soil quality. However, it is a dynamic parameter that requires characterizing the key drivers causing its variability such as texture, climate, topography, and land use management. Soil organic carbon thresholds for minimum or highest crop response to N applications are location specific, and they vary within a given soil type. Use of generalized SOC thresholds values for regulating added N application for all tropical soils remains a difficult option. In the context of crop production, critical levels need to be sustained for high nutrient use efficiency. Other drivers that affect NUE such as crop cultivar, the source and amount of fertilizer, climate, management, that influence uptake efficiency need to be controlled. In all, critical SOC amounts that contribute to a responsive soil must be maintained for tropical farmers to realize high nitrogen use efficiencies and optimal yields. Restoration measures that can lead to an acceptable minimum SOC level are important. This would also fast track efforts for Integrated Soil Fertility Management currently promoted in tropical agro-ecosystems while ensuring environmental sustainability.

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