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Soil health and climate change: Implications for food security in Sub-Saharan Africa

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Abstract

Climate change and increasing climate variability present new challenges affecting human society in the 21st century. In an unfortunate twist of fate, the poorest countries whose economies and livelihoods largely rely on natural resources in sub-Saharan Africa (SSA) are amongst the most vulnerable. The impact of climate change and climate variability on crop growth and yields is largely determined by their impact on soil health and the capacity of crop varieties to adapt to the changing climate and weather patterns. Success stories of improved land productivity and climate resilience as a function of integrated soil fertility management (ISFM) interventions are widespread in sub-Saharan Africa. In a trial carried out across four districts in western Kenya, improved cereal-legume intercrop technologies increased maize yield by between 2.8 and 3.3 t/ha (≈ 300%). Further, across varying agroecosystems in 5 sub-Saharan African countries (Kenya, Uganda, Rwanda, Tanzania, Ghana), P fertilization + innoculation increased soybean crop yields by more than 200% in each country. Similarly, maize yield increases of up to 300% were observed in the drought stricken Sadore and Dasso regions in Niger upon use of appropriate fertilizers. The carbon input to the soil from these systems exceeded 2 t/ha implying that these systems are capable of mitigating climate change through carbon sequestration. The observed improved yields were linked to the capacity of ISFM to improve soil fertility, enhance soil organic matter, boost the soil water holding capacity and water use efficiency. The soil organic matter is crucial in soil nutrient processing and soil water retention. A number of challenges, related to inputs, information and markets constrain wide scale use of ISFM in SSA. Bringing these ISFM benefits to scale require agricultural policy reforms on access to appropriate fertilizer and seed inputs, agricultural advisory services and access to output markets.

Keywords: Crop Yield Improvement; ISFM; Climate Change; Sub-Saharan

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1. Introduction

Climate change is one of the most significant challenges facing human society in the 21st century (IPCC, 2007). Industrialization has led to the release of greenhouse gases (GHGs) into the atmosphere, with subsequent changes in the earth's temperature and weather systems. The historical climate record for Africa shows warming of approximately 0.7 degree Celsius (ºC) over most of the continent during the 20th century, a decrease in precipitation over large portions of the Sahel and an increase in precipitation in east and central Africa (Desanker, 2002). These warming trends and changes in precipitation patterns are expected to increase more rapidly concurrent with increase in the frequency of occurrence of such extreme weather events as droughts, floods and storms (Desanker, 2002). Predictions of the magnitude and rate of changes in temperature and precipitation into the future are subjects of considerable uncertainties, but scenarios for Africa indicate future warming across the continent ranging from 0.2°C per decade to more than 0.5°C per decade (Hulme, 2001; Desanker and Magadza, 2001). This warming will be greatest over the interior semi-arid margins of the Sahara and central southern Africa, with the median projected additional increase in average annual temperature in comparison to present day conditions likely to reach between 3ºC to 4 ºC by 2100 (Desanker and Magadza, 2001). The smallholder farmers who constitute over 60% of households in SSA are amongst the most vulnerable. Their future livelihoods in terms of food security, health, education and wealth under the increasing temperature and varying precipitation is worrying. Their susceptibility to climate change is driven by all the three elements of vulnerability: exposure, sensitivity and adaptive capacity (IPCC, 2007). Exposure refers to the nature and degree to which a system is exposed to significant climatic variations. Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli, while adaptive capacity is the ability of a system to adjust to climate change including climate variability and extremes, moderate potential damages, or cope with the consequences.

While traditionally the climate extremes like droughts and flooding were predictable, the variations and unpredictability of amount and distribution of rainfall, temperature, flooding and droughts have increased in the last 3 decades. In Kenya, for instance, prior to 1990, droughts and famines occurred in a cyclic pattern once every 10 years on every fourth year of a decade (1964, 1974, and 1984). In the last two decades the droughts and floods have become irregular and more frequent, disrupting the traditional disaster prediction and preparedness systems (Table 1). These disruptions have confused the players in the agricultural value chain, particularly the farmers, policy makers, extension workers and donors, confounding their capacity to prepare for eventualities.

In addition, climate change exacerbates the impact of many other biophysical and socio-economic challenges faced by smallholder farmers in SSA like health, degrading land resource bases, poor policy environments and deterioration of societal "safety nets" (Mapfumo et al., 2013). In particular, projections show that by 2055 the yield of cereals could decrease by between 10 and 20% relative to the yield levels for 1990 to 2000 period, if appropriate adaptation mechanisms are not developed and adopted (Jones and Thornton, 2003; Ringler et al., 2010). As the population is continuously increasing against fixed land size, the agricultural systems must adapt to the changing climate and climate variability to maintain and increase crop yields to feed the growing population.

Table 1. Synopsis of droughts and flooding incidences in Kenya 1992-2009

Year	Event	Region	Estimated number of people affected
1992/1993	Drought	Northern, Central and Eastern Provinces	1.5 million
1996/1997	Drought	Countrywide	1.4 million
1997/1998	Floods	Countrywide	1.5
1999/2000	Drought	Country wide	4.4 million
2002	Floods	Western and Nyanza provinces	150,000
2004/2005	Drought	Countrywide	2.3 million
2005/2006	Drought	Countrywide	2.5 million
2008/2009	Drought	Countrywide	10 million

Source: Rarieya and Fortun (2010)

The impact of climate change and its variability on crop growth and yields is largely determined by its impact on soil health and the capacity of crop varieties to adjust to changing climate and weather patterns (Brevik, 2013). With the expected shortening of cropping seasons in eastern and west Africa, the yields of longer duration crop varieties, which are higher yielding, will decrease significantly as a result of terminal phase droughts. This implies that the niches for longer duration crop varieties may change. Often, such shifts can significantly decrease the national food security as development and testing of new crop varieties with a capacity to produce under the changed climate is a long term process.

This study aimed to evaluate hypotheses that: i) integrated soil fertility management (ISFM) technologies can either maintain or boost crop yields even under the changing climate in sub-Saharan Africa and, ii) when implemented appropriately, ISFM technologies are financially attractive to smallholder farmers in sub-Saharan Africa.

2. Methodologies

2.1. Data collection

The data and information used for development of this paper were derived from both secondary (legacy data) and primary sources (raw data). Legacy datasets were derived from published reports of trials conducted in Kenya, Uganda, Tanzania, Rwanda, Mozambique, Niger, Mali, Zambia, Ghana and Nigeria. Raw data was derived from soil fertility/crop yield enhancement trials conducted in Kenya, Uganda, Tanzania, Rwanda and Malawi for the period between 2009 and 2014. Market data on input costs and output prices was collected through market survey in the regions where the field trials were conducted.

2.2. Data analysis

Crop yield data was analyzed by use of Genstat 18th edition software. The yield differences between ISFM plots and farmer practice plots were computed to represent ISFM effects. The cumulative treatment costs were calculated from the costs of seed, fertilizer, inoculum, labor, weeding, harvesting, threshing and transport of produce from the farm to the point of sale (Shiluli et al., 2003). The financial returns of various interventions were calculated by multiplying yield (tonnes/ha) with average farm gate price of each tonne. Benefit-cost ratio was calculated by dividing total financial returns with total costs. Net benefits were calculated as the difference between gross benefit and total costs.

3. Results, synthesis and discussions

3.1. Effect of climate change on soil health and crop yield

The climate driven increasing atmospheric temperature and changing patterns of precipitation will modify the soil system through their influence on decomposition rates, which could increase the turnover of soil organic carbon. The organic carbon is a key driver for soil structural stability, soil microbial diversity and population and the related processes of nutrient cycling and dynamics within the soil system. A wide range of studies have also shown that the elevated atmospheric carbon dioxide (CO_2) and temperature associated with the changing climate could affect plant growth through alteration of photosynthesis, respiration, C and N metabolism, transpiration and stomatal sensitivity (Brevik, 2013, Chakraborty et al., 2014). In the conditions of low soil nutrient status that are common in most parts of SSA the higher nutrient turnover will rapidly increase nutrient deficiency aggravating the problem of poor crop growth and poor yields. The biological, chemical and physical functions of 'soil health' deteriorate with changing climate due to a number of reasons, key among them being:

i. Increasing turnover of soil organic matter: Approximately 50% of soil organic matter is soil organic carbon. With climate change, it is predicted that the global temperatures will rise. Past laboratory and field experiments have shown that the higher temperatures could speed the rate of soil organic matter turnover (Kirschbaum, 2000). As organic matter is the key driver for microbial diversity that is crucial for nutrient processing, this has a capacity to decrease the soil's ability to retain and supply most of the crucial nutrients that are required for crop growth.
ii. Decreasing soil moisture content and soil water holding capacity: Plants require adequate water for nutrient uptake, transport and photosynthesis. The high temperatures increase losses of water from the soil through evaporation and evapotranspiration. The increase in temperature coupled with declining rainfall resulting from climate change, is projected to cause negative moisture balance in over 10% of arable areas in sub-Sahara Africa with no previous history of moisture deficit (IPCC, 2007). Further, if not well managed the temperature driven decline in soil organic matter will lead to a decline in soil water holding capacity especially in regions where sandy soils are pre-dominant.
iii. Nutrient depletion: The unexpectedly higher rainfall and flooding is often associated with heavy nutrient losses via soil erosion, leaching and denitrification.

As indicated in Table 2 the gap between the potential yield and actual crop yield for most farmer fields in SSA especially for cereals often exceed 4 t/ha. For legumes, the yield gap exceeds 1.5 t/ha. These low yields are often associated with poor soil health (AGRA, 2013). The climate change could push the gap further. The interventions that boost soil fertility and hence soil health, often referred to as integrated soil fertility management (ISFM), have shown great promise for increasing crop yields and adapting agricultural systems to climate change and variability (AGRA, 2014).

Table 2. Maize yield gap for selected countries in sub-Saharan Africa

Country	Current farmers' mean yield (t/ha)	Research station mean yield (t/ha)	Yield gap (t/ha)
Ethiopia	1.3	5.5	4.2
Ghana	1.5	5.5	4.0
Kenya	1.8	6.7	4.9
Malawi	1.6	6.5	4.9
Mali	1.0	5.5	4.5
Mozambique	1.3	6.0	4.7
Nigeria	1.5	5.5	4.0
Tanzania	1.5	6.5	5.0
Rwanda	0.8	5.5	4.5
Uganda	1.7	6.0	4.3
Zambia	1.5	5.5	4.0

Sources: FAOSTAT (2010); Haggblade & Plerhoples (2010); Haggblade & Hazell (2010)

ISFM refers to a set of soil fertility management practices that include the combined use of fertilizer, organic inputs and improved planting materials coupled with the knowledge on how to adapt them to local conditions for improved nutrient use efficiency and crop productivity (Vanlauwe et al., 2010). They include, rotation of cereals with legumes, intercropping of cereals with legumes, manure applications, fertilizer application and various other forms of soil nutrient management practices coupled with use of appropriate planting materials and good agronomic management. For example, intercropped or rotated cereals benefit from nitrogen that is fixed by the preceding or rotated legumes in addition to sustaining better ground cover which reduces soil water and nutrient losses through evaporation and soil erosion. Ground cover also decreases the compacting and crusting effects of raindrop, thereby helping in maintenance of soil porosity, water infiltration, soil water retention and rain water use efficiency (Shaxson et al*.,* 2014). Integrated soil fertility management technologies can therefore improve the soil physical, chemical and biological characteristics (soil health), and support adaptation of agro-ecosystems to the changing climate and climate variability. They are especially best options for the majority of smallholder farmers in SSA who, due to in-ability to afford recommended amount of fertilizer, need to combine various inputs or implement different crop combinations to meet the crop nutrient requirements. In the following paragraphs, we illustrate how ISFM has boosted soil health, improving the capacity of agricultural systems to boost food security and adapt to climate change.

3.2. Closing the yield gap through the combination of organic and inorganic fertilizers

There is consensus among agricultural experts that jump-starting agricultural performance for smallholder farmers in SSA requires the combination of organic and inorganic fertilizers, not either, alone or none. In this strategy, the grain and biomass yield is improved at a lower cost relative to production with fertilizer alone. Furthermore, the returned organic resources improve soil organic matter improving the soil water retention - a characteristic that is crucial for adapting agro-ecosystems to the declining moisture regime under climate change. Studies have also linked long term use of organic resources on agricultural farms to improvement in soil carbon sequestration (Lal, 2004) and reduction in N_2O emission (Mutegi et al., 2010), thus boosting climate change mitigation.

Over the last 2 decades over 50 combinations of ISFM practices have been developed, tested and validated for various agro-ecosystems in Africa. Continued experimentation by Alliance for a Green Revolution in Africa (AGRA)supported partners spread in over 10 African countries have shown that in more than 70% of agro-ecosystems in SSA, cereal crop yields can be doubled or tripled through use of appropriate ISFM technologies while the yields of grain legumes can be boosted by at least 50% (AGRA, 2014). Similar approaches and success stories have been reported in eastern, western and southern Africa by teams of scientists drawn from the International Plant Nutrition Institute (IPNI), Wageningen University, International Centre for Tropical Agriculture (CIAT), and the *International Institute of Tropical Agriculture (*IITA) and other partners while working under the auspices of the Bill and Melinda Gates Foundation (BMGF) funded N2Africa Program, fertilizer industry funded 4R-nutrient stewardship and the AGRA funded country level soil health consortia program (Jama et al*.,* 2013, Woomer et al*.,* 2012). Below we present case studies of how ISFM technologies and innovations have worked in eastern and southern Africa.

Case 1: Impact of cereal-legume intercropping on crop yield in western Kenya

A common farmer practice in western Kenya is growing monocultures of either cereals or legumes without external fertilization. The cereal and legume grain yield in these types of systems are estimated at below 1.5 t/ha for cereals and 1 t/ha for legume crops (Jama et al., 1997). Through a grant and technical support from AGRA, the Kenya Agricultural and Livestock Research Organization (KARLO) established 136 maize-legume intercrop demonstrations in western Kenya lasting 3 years, starting in 2010. The demonstrations highlighted intercropping of maize with common beans, soybeans and groundnuts in 4 districts. Phosphorus fertilizer was applied at a rate of 20 kg P/ha at planting while nitrogen fertilizer was applied as a top-dressing at a rate of 60 kg N/ha. Across the four districts, improved cereal-legume intercrop technologies increased maize yield by between 2.8 and 3.3 t/ha (300%). In addition, farmers harvested between 1.3 and 1.5 t/ha of legume grains in comparison to a baseline of less than 1 t/ha.

Case 2: Effect of fertilization and inoculation on soybean grain yields

Soybean-cereal rotation trials were conducted in Kenya, Uganda, Tanzania, Rwanda and Malawi for 3 consecutive years from 2009. The trials were used for evaluation of the effect of basal P application and inoculation on soybean grain yields. The results suggested that planting soybeans with P fertilizer without inoculation (P only) could increase grain yields by 50 to 100% relative to the farmer practice across all the 5 countries under evaluation (AGRA, 2013, Jama et al., 2013).

By moving a step further to inoculate the seeds that were planted with basal P application, soybean yields increased further by up to 70% above the yields for P only (without inoculation) plots. The average yields for P + inoculum plots were 1 t/ha higher than those from the controls. The cereal crops following P + innoculum plots in the rotation were about 100% higher than yields from the control (2 to 3.5 tons/ha higher) across the 5 countries (AGRA, 2013, Jama et al*.,* 2013). Other studies have shown that legume yields can even be boosted further by supplying limited doses of starter N at the establishment phase (Abate et al*.,* 2012, Osborne and Riedell, 2006). This is crucial for meeting N demand prior to complete nodule development. Following full nodulation, the external N application may limit soybean nitrogen fixation capacity (Abaidoo et al*.,* 2007, Hodgins et al*.,* 2015). A meta-analysis of six hundred and thirty-seven data sets (site–year–treatment combinations) (Salvagiotti et al., 2008) concluded that N fertilization would only be profitable where N fixation is not able to meet the total N demand of high yielding soybean and where the soybean to N price ratio is 2 or more. Although soybean prices have risen dramatically in recent years, N prices have risen too, resulting in soybean to N price ratios that still would not favor N applications for N fixing soybeans in many environments (Salvagiotti et al*.,* 2008).

3.3. Economic impact of ISFM practices

Economic analysis carried out on data from 10 ISFM projects across eastern, southern and western Africa yielded benefit-cost ratio values greater than 2 (Table 3). Benefit-cost ratio is a good indicator of financial attractiveness of an intervention (Kaizzi et al., 2011). Opportunity cost for resource poor people with little access to money is often 100% of the actual value due to other high priority uses of available funds (CIMMYT, 1988). Therefore, benefit-cost ratio of more than 2 is required for an investment to be attractive especially in SSA (Kaizzi et al., 2011). A benefit-cost ratio of 1 implies that the returns are equal to the inputs and, therefore, there is no livelihood improvement from investment. A benefit-cost ratio value of less than 1 implies losses of human, financial and capital resources. This implies that the ISFM interventions discussed in the aforementioned studies were financially attractive.

3.4. ISFM technologies and soil health in the context of climate adaptation

As the grain yield increases, so does the inconsumable above- and below-ground biomass. In the maize-legume intercropping study presented as case 1 the seasonal non-grain above-ground dry biomass yield of maize was estimated at between 4.5 and 6 t/ha which was more than 1.5 tonnes higher than the maize dry biomass yield in the farmer practice. Additionally, the intercropped legume produced > 1.5 t/ha of dry matter above-ground biomass per season. The total seasonal carbon input into the soil from the above-ground biomass was therefore, in excess of 3.5 t/ha. Similarly in the soybean example presented as case 2, the average above ground biomass yield was in excess of 3 t/ha, which translates to about 1.4 t/ha of organic carbon. The estimated annual amount of carbon inputs can more than double if the leaf fall, the below-ground root biomass and carbon rhizo-deposition through lysates and various forms of plant exudates are taken into account (Kuzyakov and Domanski, 2000). Models estimate that with annual return of 3 to 5 t C/ha the soil organic matter and associated soil health (physical, chemical and biological processes) can be maintained at an appreciable yet stable level (Rasmussen et al., 1980). Earlier studies in the central region of Kenya have demonstrated a significant response of soil microbial diversity and other soil health parameters when soil organic matter improved (Kapkiyai et al., 1998). Further as the intercropped and rotated crops mature at different times, soil ground cover is assured for a longer period in a year reducing direct exposure of soil to the sunlight. This slows down the turnover of soil organic matter and soil moisture losses through evaporation. While working in western Kenya Verchot et al. (2007) demonstrated that in addition to doubling maize crop yields, relative to bare land, improved fallows could improve the soil water retention by about 30%.

Table 3. Effect of ISFM on performance of different crops and financial attractiveness

Country	ISFM Intervention	Crop	Yield Change (t/ha)	*Benefit-Cost ratio
Kenya (Western)	Maize-Legume Intercrop	Maize	+4 (300%)	1.8-2.2
Uganda (Isingiro)	Improved seeds + fertilizer + crop rotation	Soybean	+1 (100%)	2.0-2.3
Tanzania (SHT)	Improved seeds + fertilizer + Maize-legume rotation	Maize	+4.5 (300%)	2.1-2.5
Ghana	Maize -legume rotations + improved seeds + fertilizer	Soybean	+1.5 (150%)	2.3-2.7

**Benefit cost ratio of more than 2 shows financially attractive technologies; SHT-Southern Highlands of Tanzania; (Source: Authors' calculations from AGRA grantees data)*

In a study carried out in the drier agro-ecosystems in Niger, ICRISAT (ICRISAT, 1984) demonstrated more than a 2-fold increase in crop yields and water use efficiency due to fertilizer application on two contrasting sites (Table 4). This type of moisture management is crucial for dealing with climate variability because in a business as usual scenario, only 10-30% of the rain water is used by crops, while the rest could be lost through surface runoff and evaporation (Falkenmark and Rockström, 2004).

Table 4. Grain yield and water use efficiency (WUE) for millet in Sadore and Dasso (Niger)

Treatment	Sadore		Dasso	
	Yield (t/ha)	WUE	Yield (t/ha)	WUE
With Fertilizer	1.6	4.1	1.7	4.3
Without Fertilizer	0.5	1.2	0.8	2.0

Source: Bationo et al. (2006)

A combination of soil water management and nutrient enhancement works better to improve crop yields and optimize water use efficiency than either of them applied separately as a result of positive system interactions (Bationo et al., 2006). Many past water conservation development projects have invested billions of dollars in soil and water conservation especially in moisture-stressed environments. They mostly did not include soil fertility improvement and management components. Water harvested in this manner mostly failed to enhance optimal expression of crop genetic potential in respect to crop yield because soil fertility is key to improved water use efficiency (Table 4). Conversely, water availability is crucial for improvement of fertilizer use efficiency (Reij et al., 1996). Extended soil water retention and the interaction between soil fertility management and water have the potential to buffer crop varieties from falling out of their original niches.

3.5. Policy implications for climate adaptation and soil nutrient management with ISFM

To a large extent, adoption of ISFM practices by farmers is driven by availability and access to appropriate inputs within accessible distances (Vanlauwe and Zingore, 2011). In SSA, sustained input availability has worked well in parts of Kenya, Uganda, Tanzania and Malawi especially when there are workable policies to support private-public partnership relationships through public support for establishment and management of private agro-dealer networks. Access to inputs cannot work in these and most other SSA countries where over 50% of farmers are classified as either poor or extremely poor unless innovative input financing mechanisms are established to stabilize the input supply and demand chains. Over the last two decades the input prices have more than doubled while the employment rates and incomes have declined. The majority of smallholder farmers cannot, therefore, afford sufficient inputs without external support. There is a need for state intervention through such mechanisms as smart subsidies and tax relief on agricultural inputs to lower input costs and hence boost affordability. Experts and donors recommend smart subsidy systems with a clear exit strategy enabling the target farmers to eventually graduate from subsistence to commercial (Morris et al., 2007, World Bank, 2007). Caution should also be taken to create a balance between the subsidy program and existence of a profitable private sector, because the private sector is a crucial source of employment and economic growth. Further, policies that can boost availability of affordable financing will improve farmer access to inputs and use of ISFM practices.

In addition to issues related to inputs, most farmers lack technical capacity to implement ISFM technologies independently. Therefore, they, require effective extension services to understand which technologies work for various soil types, social and economic conditions. At present, in most African countries the ratio of extension staff to farmers is about 1:1000 against the recommended ratio of 1:400. But even the ability of available extension staff to offer quality agricultural advisory services is often constrained by various capacity challenges. Policies that could boost the capacity and quality of extension services through improved recruitment rates, in-service training and provision of tools for agricultural advisory work are crucial. Within this extension package it is also possible to make use of innovative extension approaches like mobile phones, videos, television and radio programs.

Finally, farmers will not sustainably invest in yield-boosting technologies when remunerative markets for surplus are not available. Good markets serve to provide resources that can be used for purchasing inputs and pay back for the initial input credits. Often good markets for surplus produce in SSA are not accessible by farmers. As a result, it is estimated that approximately 30% of food produced in SSA is wasted before reaching the market (Lynd and Wood, 2011). To boost crop yield with ISFM, there is a need for public investment in the areas of access to markets through provision of information on availability of remunerative markets, market research, promotion of value addition and reduction of market barriers.

4. Conclusions

We conclude that climate change affects soil health and, therefore, crop yields. Appropriate use of ISFM technologies has the potential for arresting deterioration of soil health and adapting agricultural systems to the changing climate. ISFM interventions are boosting grain and biomass yields of both cereals and legumes, thus boosting food security and carbon inputs into the soil. Further the water use efficiency is better under ISFM than under farmer practices. This enhanced water use efficiency is a crucial buffer for crops against moisture stress resulting from highly variable seasonal rainfall distribution. The science is clear that ISFM is a crucial intervention for adapting agriculture to climate change, but for ISFM interventions to work properly, there is need for policies that support enhanced access to quality inputs, access to quality extension services and access to remunerative markets for agricultural outputs.

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