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Managing Soil Health in Africa (MASHA) by Re-carbonization of Agro-Ecosystems

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SOIL health refers to its capacity to sustain multiple ecosystem services (ESs) for human wellbeing and nature conservancy through coupled cycling of carbon with other elements. Among numerous key indicators, soil organic matter (SOM) content is widely considered the heart of soil health. However, most cropland soils of Africa in general and that of Sub-Saharan Africa (SSA) in particular have been subject to anthropogenic climate change, in which soil has been a source of greenhouse gases since the dawn of settled agriculture, and thus leading to reduction in SOM content and aggravation of other degradation processes. The optimum level of SOM content may range from 2-4% for soils of the temperate climate compared with 1.5 -2.5% in those of tropical regions. However, soils of most agro-ecosystems in Africa have been subjected to land misuse and soil mismanagement, and thus are, severely depleted of their SOM content because of extractive farming practices. These systems can lead to a negative nutrient budget and thus mining of nutrients with the attendant severe depletion of SOM content in the root zone to often as low as 0.25% or less. Thus, agronomic productivity, use-efficiency of inputs (e.g., fertilizers, irrigation, energy-based farm operations, seeds of improved varieties or choice of other species of animals or plants) and the nutritional quality of food produced is low. The way food is produced and consumed in SSA and other ecoregions can adversely affect health of soil, plants, animals, people, ecosystems, and the planetary processes. Extractive farming can disrupt soil-based "One Health" concept. The widely observed trend of a downward spiral aggravated by soil degradation also signifies the importance of inter-connectivity and other laws of ecology and principles of regenerative agriculture. It is thus pertinent that soil health of agro-ecosystems of Africa are restored by re-carbonization of soils and landscape. The term carbon sequestration implies transfer of atmospheric CO_2 into long-lived soil/tree C pools so that it is not readily re-emitted into the atmosphere. The wide range of options of sequestration of atmospheric CO_2 include oceanic, geological, chemical, and terrestrial. The goal of creating a positive soil/ecosystem C budget in terrestrial biomes can be met by adopting practices in which input of C into the soil/land exceeds the losses by decomposition, erosion, and leaching. Wide range of agronomic management practices, specifically focused on the strategy of producing more from less, include regenerative agriculture, agro-ecology, and of replenishing plant nutrients as CNPK (rather than NPK). Specific climate-resilient practices comprise of a system-based conservation agriculture (CA), cover cropping, complex farming systems, integrated soil fertility management (ISFM) and integration of crops with trees and livestock. Adoption of conservation-effective systems can be promoted through payments to farmers for strengthening of some key ESs such as sequestering C in land-based sinks, improving quality and renewability of water, strengthening below-and-above-ground biodiversity, etc. Such pro-agriculture and pro-farmer policies can be advanced through adoption of a "*Soil Health Act*" at local, state, national, sub-continental,continental and global scale.

Keywords: Food Security, Soil Degradation, Soil Fertility Depletion, Irrigation, Fertilizer Use, Sub Saharan Africa, MASHA (Managing Soil Health in Africa).

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1. Introduction

Green Revolution (GR) of the 1960s, that increased food production in Asia and South America, by-passed Africa in general and Sub-Saharan Africa (SSA) in particular. Agroecosystems of some regions in Africa are prone to low agronomic production, and as much as 25% of its population is food in-secure and vulnerable to under-nutrition and malnutrition during mid 2020s. Bonilla Cedrez et al. (2020) reported that low average cereal yield in SSA, 1266 kg/ha compared with global average of 3745 kg/ha, is the major cause of undernutrition and malnutrition. Yet, Africa is endowed with large land resources and diverse climate. Africa has cropland area of 305 M ha, of which 260 M ha is arable (Table 1). While the resource endowment is large, the population of Africa is increasing (Table 1). Consequently, the low yield of food staple crops cannot meet the needs of growing and increasingly affluent population (Table 2). The problem of low crop yields is aggravated by low area under irrigation (Table 1) along with low rate of fertilizer use (Table 3a) and low total input of fertilizer on continental scale (Table 3b). Above all, there exists wide spread problem of soil degradation and the attendant depletion of soil organic matter (SOM) content, which is among the major causes of poor soil health and poor quality and amount of food produced.

Table 1. Five Decades of Agriculture in Africa (Adapted from FAO Stat, 2024).

Metric	Unit	1970	1980	1990	2000	2010	2020	2022	2025
Cropland	Mha	178.5	188.9	203.6	231.5	264.8	300.8	304.8	-
Land area equipped for irrigation	Mha	8.4	9.3	11.1	13.2	15.1	17	17.04	-
Arable land	Mha	161.5	168.9	179.9	204	231.7	257.6	259.7	-
Population	Millions	365.5	481.5	638.2	819	1055.2	1360.7	1426.7	1530

Table 2. Average Crop Yield in Africa Over Five Decades (Adapted from FAO Stat, 2024).

Yield (Mg/ha)	1970	1980	1990	2000	2010	2020	2022	2025
Cassava, fresh	6.2	6.9	8.2	8.7	9.6	7.9	8.1	6.2
Cereals, primary	0.9	1.1	1.2	1.3	1.5	1.7	1.7	0.9
Millet	0.6	0.6	0.7	0.6	0.7	0.8	0.8	0.6
Rice	1.9	1.8	2.1	2.3	2.3	2.4	2.4	1.9
Sorghum	0.8	0.9	0.7	0.9	1.0	1.0	1.0	0.8
Sweet Potatoes	4.8	5.4	4.3	4.0	4.6	6.9	7.0	4.8
Wheat	0.9	1.1	1.6	1.8	2.3	2.5	2.7	0.9
Yams	8.4	8.8	9.7	9.8	11.6	8.2	8.4	8.4

Table 3a. Fertilizer Use in Africa (kg/ha) (Adapted from FAO Stat, 2024).

Rate (kg/ha)	1970	1980	1990	2000	2010	2020	2022
Nitrogen (N)	4.6	9.0	10.1	10.4	12.1	16.3	13.3
Phosphate (P_2O_5)	2.9	5.5	5.0	3.9	4.7	5.9	5.3
Potash (K_2O)	1.2	2.0	2.3	2.0	2.0	3.5	2.9

Table 3b. Fertilizer Use in Africa (Mt/yr) (Adapted from FAO Stat, 2024).

Nutrient (Mt/yr)	1970	1980	1990	2000	2010	2020	2022
Nitrogen (N)	0.8	1.8	2.1	2.5	3.3	5.0	4.1
Phosphate (P_2O_5)	0.6	1.1	1.0	0.9	1.3	1.8	1.7
Potash (K_2O)	0.2	0.4	0.5	0.5	0.5	1.1	0.9

Thus, achieving food self-sufficiency in Africa, and especially in SSA, is a major concern for the continent with growing and increasingly affluent human population. Schematics in Figure I show the interactive effects diverse factors including: 1) soil degradation that affects at least 65% of the land, and desertification affects 45% of Africa's land area (Hofstra & Bouwman, 2005; Koning & Smaling, 2005; Lal, 1988; Tully et al., 2015; UNEP, 2015), 2) drought stress in Africa which has displaced 2.7M people in 2024 and 5.1M children are malnourished due to drought (Gbegbelegbe et al., 2024; Ntali et al., 2023; Siderius et al., 2024), 3) negative nutrient budget (Stoorvogel et al., 1993; Stoorvogel, J.J & Smaling, E.M.A, 1990), and 4) low rate of fertilizer use..

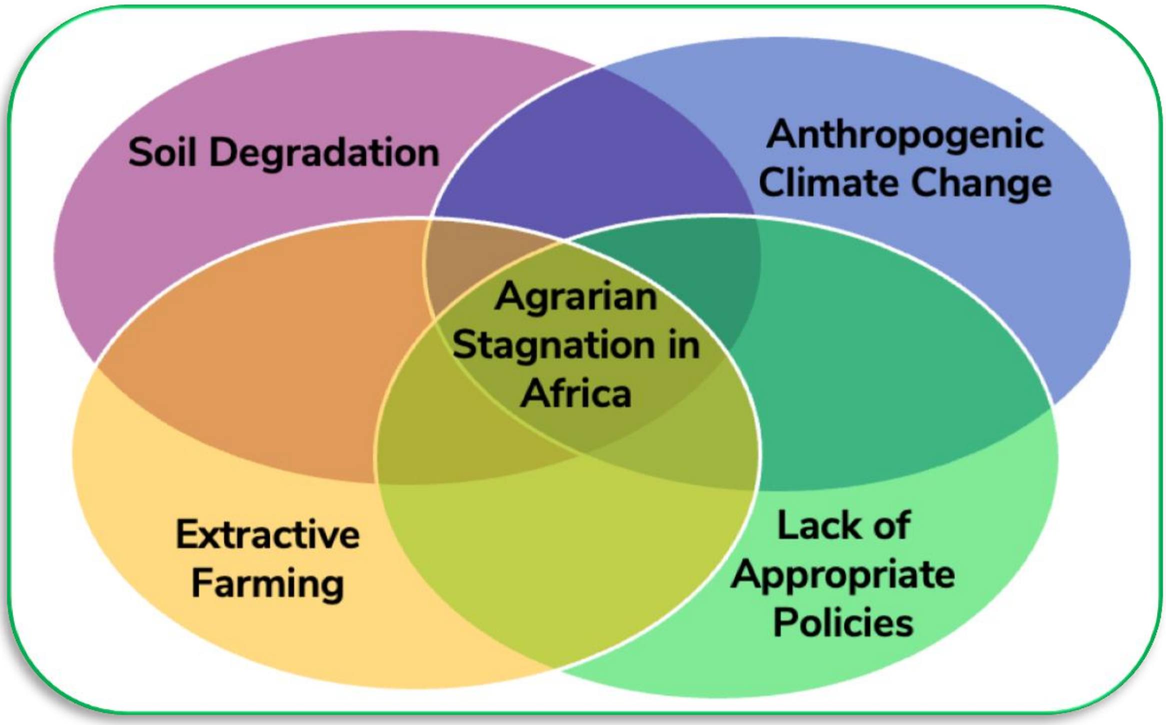

Fig. 1. Interactive effects of key factors leading to agrarian stagnation in Africa.

Thus, the objective of the present review is to outline the importance of restoring SOM content and of soil fertility and irrigation for managing soil health in Africa. The article also addresses the role of managing soil health in advancing Sustainable Development Goals (SDGs) of the Agenda 2030 of the United Nations. It focuses specifically on SDG #1 (no poverty), #2 (zero hunger), #6 (clean water and sanitation), #13 (climate action), #15 (life on land), and #16 (peace, justice, and sustainable institutions) (Regeringskansliet & Government of Sweden, 2015; UN, 2015). These and other SDGs, similar to Millenium Development Goals and Agenda 21 of The United Nations, depend heavily on sustainable management of soil and agriculture.

1.1 Causes of Agrarian Stagnation in Africa

The population in Africa is growing rapidly, although the rate of increase may vary among regions. For example, population of SSA may double between 2020 and 2050 (Statista Research Department, 2024), and the food demand triple by 2050 leading to several pedological, environmental, political, and socio-economic challenges (Devenish et al., 2023). The population of SSA of 1.1B in 2020 (Table 1) will reach 2.2B by 2050 and 3.4B by 2100. With the projected climate change, demands of the growing and increasingly affluent population will be a serious global issue of the 21st century. The adverse effects of anthropogenic climate change are being aggravated by soil degradation which is a multiplier factor. Simply put, negative effects of low and depleting soil fertility, and low and decreasing plant available water capacity, are being aggravated by the changing and uncertain climate along with the aggravating drought and heat stress (Figure 2). Agrarian stagnation, especially in SSA as characterized by low crop yield and ever widening yield gap, is driven by soil degradation and climate change, which are mutually re-enforcing processes. The problem of food and nutritional insecurity for the rapidly growing and urbanizing - population is aggravated by degrading soil with low and depleting soil fertility, and desertified ecosystems because of the low and decreasing SOM content in the rootzone of agro-ecosystems. Indeed, there is a strong interaction between low and depleting soil fertility, low and decreasing plant available water reserve, and changing and uncertain climate (Figure 2).

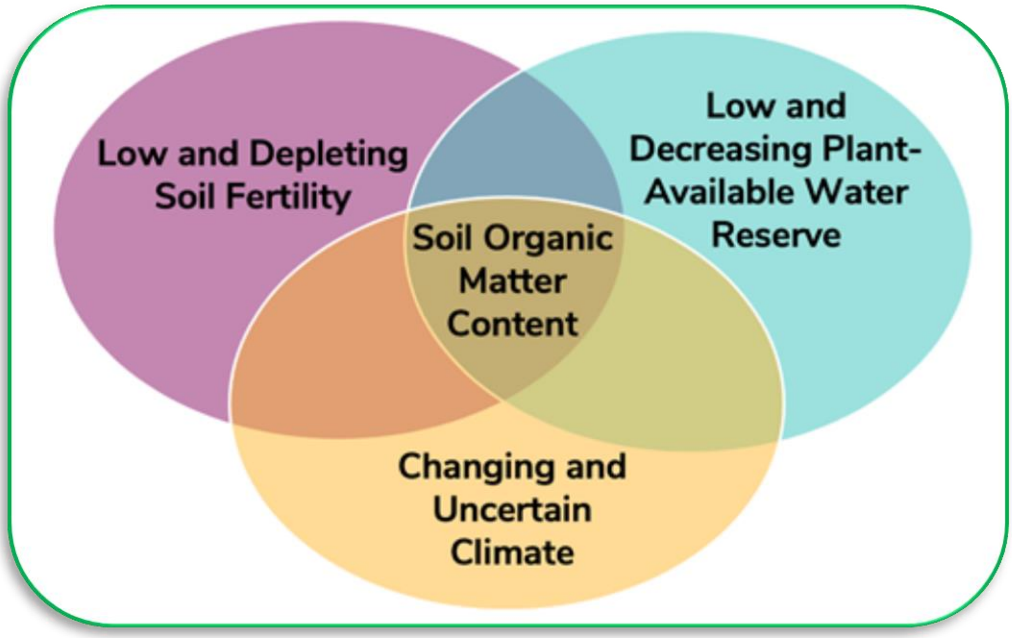

Fig. 2. Restoring and sustaining soil organic matter content for addressing the triple challenges (Trilemma) of low and depleting soil fertility, low and decreasing plant-available water reserve, and changing and uncertain climate.

Low agronomic yield and poor nutritional quality of food produced in Africa, leading to wide spread and perpetual problem of under-nutrition and malnutrition, is attributed to the interaction effects of 4 primary factors: soil degradation, anthropogenic climate change, use of extractive farming practices, and lack of appropriate policies which can incentivize and motivate land managers (farmers, ranchers, and foresters) to break the yield barriers, enhance productivity, and put on track two SDGs (Figures 1 and 2). These causes must be addressed through appropriate strategies which will increase agronomic productivity in Africa.

1.2 Strategies to Advance Food Security in Africa

There exists a large yield gap in Africa, especially so in SSA. Translating science into action (e.g., growing improved varieties, using conservation agriculture(CA) based on retention of crop residue mulch and growing cover crops in conjunction with agroforestry and integration of crops with trees and livestock, increasing use of fertilizers and expanding land area under irrigation) can lead to increase in agronomic productivity while advancing SDG #1 and #2. The strategy is to identify the soil/ecoregion specific causes and address these through adoption and upscaling of the best management practices (BMPs). Importance of managing soil fertility, and soil water reserve in the context of climate change, and other causes of agrarian stagnation are discussed below.

1. Soil Fertility and Plant Nutrient Management

Low crop yield is attributed to a low rate of fertilizer use on continental scale compared with the global and regional average use. For example, fertilizer use in SSA is about 13-20 kg/ha. yr compared with world average of 146 kg/ha in 2022 (Dimkpa et al., 2023). Low soil fertility (especially of secondary and micronutrients), widespread soil degradation, and changing climate are major challenges to achieving SDG #1 and #2. It is widely argued that agricultural productivity must be enhanced to alleviate undernutrition and malnutrition in SSA (Jayne & Sanchez, 2021).The low inputs of fertilizer in SSA is an issue,and it is estimated at 14 kg/ha compared with 141 kg/ha in South Asia, 151 kg/ha in the European Union, 175 kg/ha in South America and 302 kg/ha in East Asia (Bonilla Cedrez et al., 2020). Drought stress is another strong determinant of low crop yield. Deficiency of secondary and micronutrients (Otieno et al., 2024) along with drought stress and heat wave (supra-optimal soil temperatures) are among major determinants of low agronomic productivity. The low rate of fertilizer use (Table 3a) and low input of total fertilizer (Table 3b) are aggravating nutrient depletion ,and are multiplier of the risks of soil degradation and the attendant low quality and quantity of food produced. Decline in SOM content is strongly linked with the decline in soil fertility, which is a serious problem in SSA and the continent on the whole (Asule et al., 2023). Decline in SOM content leads to major challenges in achieving food and nutritional security and advancing Sustainable Devlopment Goals (SDGs) of the United Nations (Figure 3) In this context, four basic laws to be observed in relation to managing soil fertility and plant nutrients are as follows:

a. The Law of Return – Sir Albert Howard (1945) advocated The Law of Return which is based on the premise of leaving soil for the next generation in a state that is as healthy or healthier as it was handed over by the previous generation. It involves returning nutrients to the soil in the same or greater quantities than that were removed or used to grow crops or raise animals. In other words, soil is like a bank-account and no one can draw more than what was deposited in it without jeopardizing its functions or productive capacity.

b. Law of Minimum – Proposed first by Carl Sprengel in 1826 and later popularized by Justus Van Liebig in the 19th century, the Law of Minimum states that plant growth is limited by the scarcest nutrient or resource rather than the total resources available. It is the most basic principle in management of soil fertility.

c. Law of Optimum – This is used in management of plant nutrients and is aimed at achieving the targeted crop yield through soil testing and nutrient management. Law of Optimum, as the unifying principle that bridges the gap between the Law of Minimum and the Law of Maximum, is used to achieve the targeted crop yield by test-based management of soil fertility and other agronomic constraints.

d. Law of Maximum – The Arthur Wallace Law of Maximum (2003) states that crop growth is proportional to about 70 growth factors and resources comprising of nutrients and water which must be used judiciously to maximize use efficiency and minimize wastage or leakage into the environment. Indeed, crop growth cannot exceed the aggravated value of the plant growth factors.

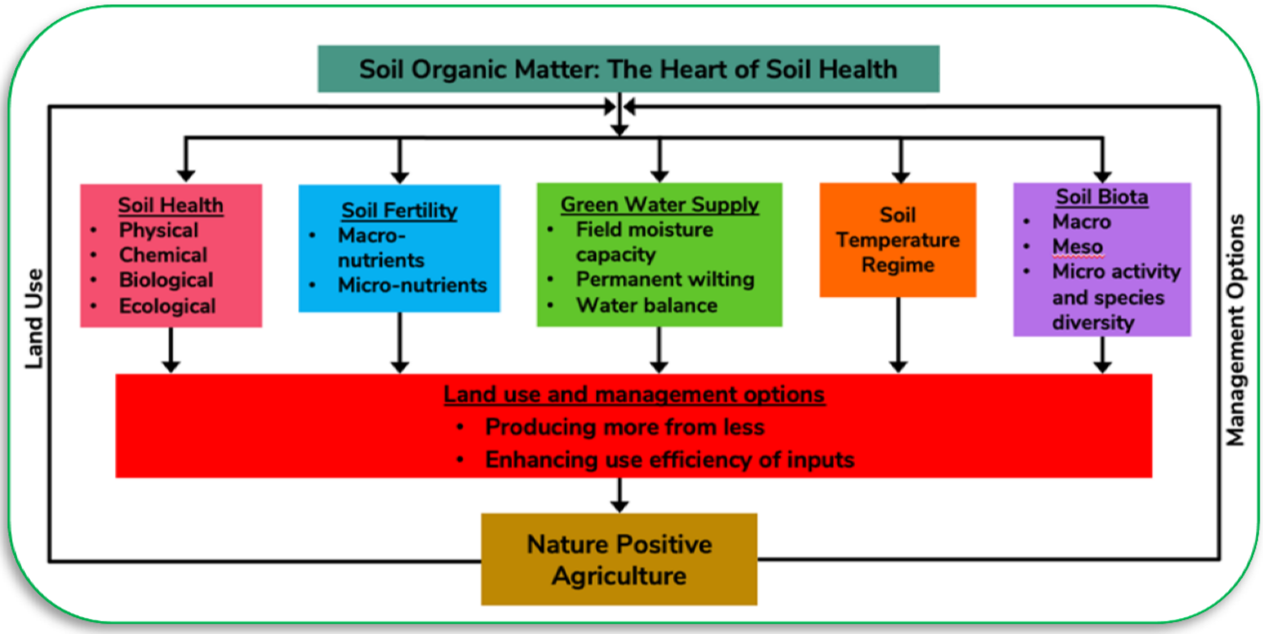

Fig. 3. Effects of soil organic matter content on soil health and its management for producing more from less.

Soil degradation and ecosystem desertification are serious problems in Africa. Principal causes ,effects and management options for protection ,restoration and sustainable management of soil resources are outlined in Figure 4.Therefore, depleted and degraded soils of Africa must be managed by strictly following the four laws outlined above, and especially for bridging the yield gap (Miti et al., 2024). Soil fertility management practices must be identified for site-specific conditions with due consideration of locally available resources, and a judicious use of synthetic fertilizers in conjunction with indigenous and scientific knowledge (Dugué et al., 2024). Combining biofertilizers with chemical fertilizers for soil-specific situation is essential to improve both productivity and the nutritional quality of food crops (Dimkpa et al., 2023; Ishfaq et al., 2023) to eliminate malnutrition in Africa. While there is no conclusive evidence about the nutritional security of organic vs. inorganically fertilized food crops (Aina et al., 2023), yet integrated soil water fertility management (ISWFM and ISFM) is an important option to restore soil fertility, improve water conservation, and sustain/increase agronomic productivity (Gowing et al., 2020; Horner et al., 2021; Laub et al., 2023; Mponela et al., 2023; Ndegwa et al., 2023). However, wherever feasible, use of bioresources and organic farming should be encouraged (Akanmu et al., 2023; Daniel et al., 2022; El Bilali, 2020; Oyeogbe et al., 2022). In addition, micronutrients (e.g., Zn) are also critically important and should be applied as fertilizers (Manzeke-Kangara et al., 2021; Mossa et al., 2021). Soil fertility management can be improved by all approaches available (Stewart et al., 2020). The rate of fertilizer use in Africa must be increased to about 50 kg/ha by 2035 and 100 kg/ha by 2050, and 150 kg/ha by 2075 and beyond.

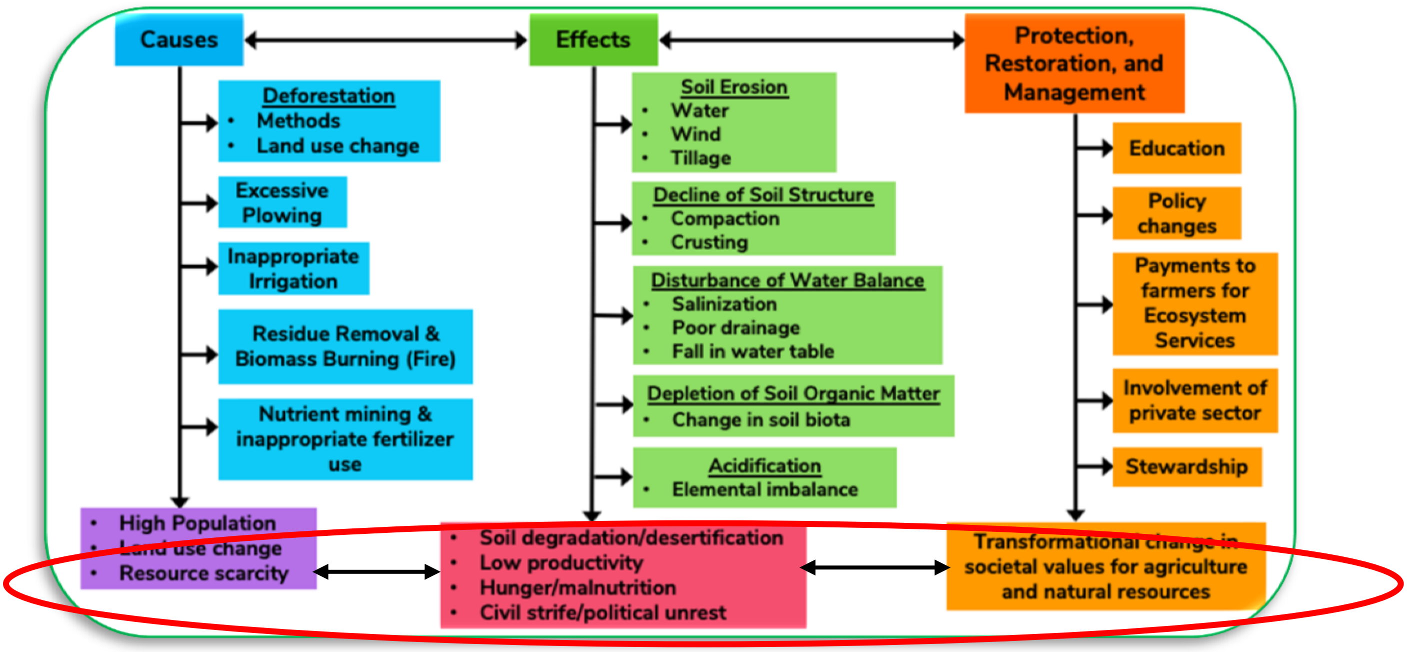

Fig. 4. Soil degradation in Africa: Causes, effects, and management options.

2. Drought Management and Soil Water Conservation

Whereas supplemental irrigation is widely used in northern Africa, rainfed agriculture is practiced on 80% of agricultural land in SSA, which is strongly vulnerable to extreme climate events (Ayanlade et al., 2022). On the continent as a whole, only 13.5 M ha of the cultivated area is irrigated (You et al., 2011). Only 3.5% to 5% of crop land area in SSA is equipped for irrigation as compared with 37% in Asia (FAO, 2016). Yet, several regions in SSA have a potential to expand the crop land area under irrigation. Public-private partnerships may be important to expanding land area under irrigation in SSA (Houdret et al., 2017). You et al. (2011) estimated that an additional 24 M ha of crop land area can be equipped for irrigation over the next 50 years or until 2060. If this were to happen, it would be an equivalent to 178% increase over existing area of 13.5 M ha, and both small scale and large scale irrigation could be economically viable options (You et al., 2011).

As much as 30-60% of SSA is vulnerable to severe and extreme drought. A small proportion of cropland area is equipped for irrigation in SSA , and yield of rainfed crops are low (Table 2). In some harsh environments of SSA (i.e., shallow rooting depth, low plant-available water capacity, high frequency of extreme events, and scarce surface/ground water resources), water scarcity and drought stress may even be a more severe constraints than low soil fertility and lack of plant nutrients (Ikazaki et al., 2024). Lack of water is especially critical in soils receiving chemical fertilizers. Under these conditions, soil and water conservation and management is important to enhancing and sustaining productivity on rainfed lands and making the entire region as a whole capable of achieving food self-sufficiency (Siderius et al., 2024). Furthermore, increase in productivity of rainfed agriculture may also be an important factor to limit the projected need for additional expansion of agricultural land use by >25% with adverse impacts on C emissions because of deforestation and the attendant loss in biodiversity (Siderius et al., 2024). Vulnerability to drought stress may be aggravated by the current and projected increase in extreme-events or the so called drought-flood syndrome (Du & Xiong, 2024). Therefore, measuring and improving crop water productivity (CWP) is the key factor in improving and sustaining productivity of dryland farming, and in mitigating the adverse impact of extreme events (Mpakairi et al., 2024). In this context, conserving soil, storing water in the root zone (green water) and enhancing its availability is the key determinant of agronomic yields in rainfed croplands (Burrows et al., 2023). Yet, soil moisture content is not adequately considered in modeling studies of climate change, food security, and human health (Burrows et al., 2023). Therefore, water-efficient irrigation systems must be used during drought periods (Brempong et al., 2023). Indeed, irrigation expansion in SSA can increase agriculture productivity and adapt crops to climate change (Beltran-Peña & D'Odorico, 2022). In addition, water infiltration rate of soil must be improved to reduce losses of water runoff and increase soil and groundwater recharge. Mens et al. (2023) suggested that high water infiltration rate can be maintained by avoiding bare soil, establishing woody plants, and favoring species with thin leaves and avoiding those with a low wood density in regions such as the East African drylands (Mens et al., 2023).

Globally, irrigated area accounts for 24% of croplands but it produces 40% of food (Mehta et al., 2024). Supplemental irrigation in Africa is used on about 4-6% of the cropland area (Xie et al., 2021) (Table 1). In comparison, the proportion of area equipped for irrigation in Asia increased from 20% in 1961 to 39% in 2006 (Kajisa, 2021). Irrigated cropland area in SSA can be expanded from 13.5 M ha at present to 24 M ha in some countries where the water resources are available (You et al., 2011). Conservation and judicious management of water, especially the soil water in the root zone, is important to achieving and sustaining food self-sufficiency in SSA. Flood plain wetlands of SSA are an under-utilized resource probably because of health-related issues (i.e., malaria, river blindness, bilharzia). Therefore, adopting practices of eco- intensification and diversification in flood plain wetlands of SSA (river Niger in West Africa, Nile in North Africa, Congo in Central Africa) can improve agronomic production because these ecosystems have large available green water reserves (Ayyad et al., 2022). These flood plain wetlands are especially suitable to increase rice production because under harsh conditions, rice yields are significantly less stable and only about 33% of that obtained under favorable conditions (Duvallet et al., 2021).

Water and food are intricately inter-connected. It is estimated that there are over 300 million drinking water and irrigation ponds globally, and that is where 90% of the world's standing irrigation water is stored (Farrar et al., 2022). The average per capita water consumption for food was 1300 m^3/capita.yr in year 2000, and it is projected to increase to 1400 m^3/capita.yr in 2050 and 1500 m^3/capita.yr in 2100 corresponding with volume of water consumed by humanity at 8,200 km^3/yr, 13,000 km^3/yr and 16,500 km^3/yr in 2000, 2050, and 2100, respectively (de Marsily, 2021). Is this much water available on Earth, and water scarcity can lead to food deficit and civil strife or political unrest? Therefore, judicious use of water and conservation of the finite fresh water resources is of critical significance considering that more than two-thirds of the world population is experiencing water scarcity (Farrar et al., 2022).

Because of the close link between food, energy and water (FEW); there is a growing interest in understanding of the "FEW Nexus". Sector-based resource management approaches contribute to insecurities of food, energy, and water. Yet, multi-centric, multi-dimensional, and spatiotemporally dynamic of the Nexus is complex and uncertain, and needs dedicated tools to understand it (Taguta et al., 2022). For example, Simpson et al., (2023) assessed the The FEW Nexus index (also called WEF index) of 54 African nations, and observed that African countries are performing sub-optimally in the FEW Nexus index because of the widespread problem of the insecurity of water, energy, and food. They recommended implementation of interventions for achieving FEW security needs based on planning from an integrated perspective to optimize synergies and minimize trade-offs. There also exists a close link between FEW and SDGs of the Agenda 2030 of the United Nations. Based on analysis of 35 households in Harare, Zimbabwe, Gandidzanwa and Togo (2022) observed that the use of underground water is common for low and high-income areas, firewood and charcoal are preferred for cooking in the low-income suburbs but gas is used in high-income areas (Gandidzanwa & Togo, 2022). Uncontrolled urban agriculture is aggravating water pollution. Taguta et al. (2022) reported that the FEW Nexus tools are rapidly being developed with a current number of ~46 tools and models (Taguta et al., 2022). However, as many as 61% of these are unreachable to intended users, ~70% lack key capabilities such as geospatial features and transferability in spatial scale and geographic scope, and 30% of tools are applicable at local scales. Thus, there is a vast scope for improvements in the FEW Nexus tools.

3. Restoration of Soil Organic Matter Content

Soil of agro-ecosystems of Africa in general and those of SSA in particular are strongly depleted of their SOM content. Yet, SOM is the heart of soil health (refer Figure 3) and it must be maintained at 1.5 to 2.5% in the rootzone by creating a positive soil/ecosystem C budget. Indeed, as much as 65% of agricultural land is degraded (Zingore et al., 2015), and have low SOM content in the root zone. Among predominant degradation processes, depletion of SOM content is a widespread problem in agroecosystems of Africa. SOM content in top 30 cm depth of most cropland soils is often lower than the optimal range in specific soil and the eco-region. Thus, depleted and degraded soils of SSA and elsewhere may not be responsive to inputs such as use of improved varieties and application of fertillizers and amendments.

Extractive farming ,along with serious erosion by water and wind, are among reasons for depletion of the SOM in Africa The SOM concentration of 0.2 to 0.5% is often observed in Africa (especially SSA) because the predominantly resource-poor and small landholder farmers cannot afford the return of biomass carbon (crop and animal residues and waste) and use of external inputs. Thus, low crop/animal productivity and low nutritional quality of the food products are commonly observed. Under these situations, re-carbonization of soils by a deliberate creation of a positive soil/ecosystem C budget is the best option. Thus, maintaining an optimum level of SOM content in the rootzone is critical to improving use efficiency of input, producing nutrition-rich food, reversing soil fertility decline, improving soil quality or functions, putting SDGs of Agenda 2030 on track, and making agriculture a part of the solution to restoring the environment and for adaption to and mitigation of the climate change such as extreme events and the drought-flood syndrome.

Low SOM content and the attendant problem of soil degradation in Africa leading to low agronomic yield and poor quality (low nutrient density) of food are the serious and alarming consequences. Indeed, the primary control or drivers of low SOM stock in the rootzone are poorly understood. Based on an on-farm study of 1108 cultivated plots in Malawi, Tu et al. (2022) reported that strong predictors of SOM stock include clay content and vegetative cover (Tu et al., 2022). Appropriate management practices included crop diversity, residue incorporation, and weed presence. Other studies have observed the importance of agroforestry (Alamu et al., 2023; Zayani et al., 2022) and its use in conjunction with biochar (García-López et al., 2024; Zubairu et al., 2023), along with effective measures of soil and water conservation (Brempong et al., 2023; Diop et al., 2022), CA (Amadu et al., 2021; Devkota et al., 2022; Entz et al., 2022; Simwaka et al., 2020), and biofertilizers (Daniel et al., 2022) can create a positive soil C budget and to re-carbonization of the depleted soils of Africa. Shrub-intercropping of food crops is a special case of agroforestry (Bright et al., 2021).

Restoration of SOM content is also essential to adaptation and mitigation of anthropogenic climate change. Re-carbonization of the terrestrial biosphere (soils and vegetation) is a truly win-win-option because of its positive impact on addressing under-nutrition and malnutrition, adaptation and mitigation of climate change, improve farm income and alleviate rural poverty in SSA. Accomplishment of this goal would require implementation of policies which are pro-nature, pro-agriculture and pro-farmers. These policies must also make provisions for payments to farmers for strengthening ecosystem services. While private sector can play an important role, it is critically important that agriculture profession is given the due respect and dignity that it deserves. This transformation will also require change of curricula from kindergarten to primary, middle, high school and college level so that sustainable agriculture and soil management, and environment are integral to the education at all levels including in curricula of college of public health and medicine.

The challenging task of restoring SOM stock of severely depleted soils of Africa, especially those of SSA, also indicate the importance of integrating crops and trees with the livestock to formulate soil/site-specific complex and integrated farming systems. Livestock-based systems have been observed to regenerate soils and landscape while transforming agri-food systems in Africa (Paul et al., 2023) and producing healthy and environmentally sustainable food (Beal et al., 2023). Multifunctionality and diversity of livestock grazing systems have a broader geographic application with positive impacts on soil C and N regulation (Ickowicz et al., 2023). Despite numerous benefits, livestock farming in Africa (e.g. Senegal) operate far below the optimum production potential due to several socio-economic, cultural, and biophysical factors which must be systematically addressed (Eeswaran et al., 2022). Re-carbonization of soils of Africa can also be accomplished by adoption of site-specific techniques of eco-intensification (Fan, 2020), especially when it is adopted in context of double cropping, integration of crops with trees and livestock, and growing carbon on land (carbon-farming) so that it can create another income stream for farmers. To enhance country commitments to restoring SOM stocks in agroecosystems, there is a need to develop cost-effective and simple methods of measurement and monitoring in relation to assessing the impact of land use and farming systems (Wiese et al., 2021). Modeling of SOM dynamics is also a useful tool to assess management effects on soil and environments (Abegaz et al., 2022).

Risks of accelerated soil degradation in Africa can be minimized by enhancing and sustaining the SOM stock in soils of agroecosystems. The SOM stock, the heart of soil health, must be restored and sustained for high crop yield and better nutritional quality. Adoption of CA can enhance SOM stock Africa (Mgolozeli et al., 2020). In Malawi, Simwaka et al. (2020) documented that adoption of CA improved SOM stock and stable fraction of particulate organic carbon (Simwaka et al., 2020). Furthermore, maize-legume intercropping with CA had 33% to 73% more total SOM depending on soil and ecoregion. Simwaka and colleagues recommended that farmers should be encouraged to minimize tillage, retain residue mulch on the soil surface, and practice crop rotation. For example, a study on water yam (Dioscorea alata) in Ivory Coast documented that rainfall and SOM stocks were the important determinants of tuber yield in West Africa. Another study on maize production in Zimbabwe by Thierfelder et al. (2022) showed that total soil N and C content were strong predictors of maize yield and above ground biomass in clayey but not in sandy soils (Thierfelder et al., 2022). Thierfelder and colleagues reported that despite a strong effect of CA management on soil C and N in sandy soils, crop productivity was not affected in sandy soils. They emphasized a wholistic management approach in sandy soils and input of C into soil in various forms such as biomass from cover crops and tree components, and crop residues in conjunction with a judicious use of fertilizers. Similarly, manure from livestock would also improve productivity of sandy soils as was observed by Eeswaran et al. (2022) in Senegal . An on-farm study of 1108 cultivated plots across central and southern Malawi by Tu et al. (2022) showed that clay content is the strong predictor of SOM content (Tu et al., 2022). Among the management practices assessed, agronomic yield was affected by crop diversity, residue incorporation, and weed presence because of their positive effects on SOM stock. Surprisingly, use of fertilizer N was not a strong determinant of crop yield. SOM stock in Africa can be improved by recycling of agricultural by-products as compost or mulch. In Senegal, Faye et al. (2021) observed that millet yield was strongly affected by SOM content, pH, and the number of trees in the field (Faye et al., 2021). Study by Faye and colleagues emphasized the importance of local techniques and knowledge to maintaining agronomic productivity under harsh environments . Indeed, low use efficiency of N and of irrigation is attributed to low level of SOM content. Simply put, managing soil health in Arica (MASHA), through restoration of SOM content, is critical to achieving not only high crop yield but also improving nutritional quality of food.

4. Indigenous Knowledge, Traditional Crops, and Gender-Responsive Approaches

Subsistence farmers of Africa mostly use indigenous knowledge in producing crops, raising livestock, managing global warming, preserving food, and surviving the period of food shortage. These encompass a range of management including crop rotations, mixed/intercropping, manage pests and pathogens. In South Africa, Kom et al. (2024) suggested that indigenous knowledge must focus on enhancing socio-economic factors and assist farmers in improving harvest storage facilities, because of high post-harvest losses (Kom et al., 2024). Daba et al. (2023) observed that post-harvest losses in groundnut may be as much as 8.9% in Ghana and 31% in Uganda (Daba et al., 2023). The traditional or forgotten crops are important to achieving food and nutritional security. Among these are legumes and common beans or pulses (Lisciani et al., 2024) which are essential to addressing malnutrition. Cassava is an important root crop and it is an all-year-round economic and reliable staple food which is grown on 16.8 M ha and its average tuber yield varies between 5.7 and 9.6 Mg/ha (Adebayo, 2023). There is a large scope to improve the mean average yield of cassava at continental level (Srivastava et al., 2023).

There are also traditional food trees such as Soursop or Annona Senegalensis Pers. It is a multi-purpose tree species (Donhouedé et al., 2023) and is called wild custard apple or African custard apple. There are also dual-purpose crops which can be used both for grains and fodder to enhance nutritional security in SSA. Examples of these crops characterized by high yields and nutrient density include cowpea, pearl millet, and sorghum (Akplo et al., 2023). Common bean seeds are excellent source of protein along with minerals, vitamins, and other compounds which have disease-suppressive effects when included in diet (Cominelli et al., 2022). In Angola, Baumgärtel et al. (2022) observed that local food plants have high nutritional properties and thus potential to combat malnutrition: cowpea grains contain high quality protein for human consumption and enrich soil by N fixation (Baumgärtel et al., 2022; Omomowo & Babalola, 2021). Pigeonpea has similar attributes. Along with pulses (cowpeas, pigeon peas), bambara groundnut is also a nutritious food crop. However, it is an underutilized crop and has a high potential to improve food and nutritional security (Tan et al., 2020) while also enhancing soil fertility by N fixation. African yam bean (Sphenostylis) is an annual legume which produces bean seeds in pod and tubers in the soil (Adegboyega et al., 2020). It can enhance food and nutritional security in SSA while also enhancing soil fertility. Sustainable intensification of grain legumes can enhance food and nutritional security and restore degraded soils (Nassary et al., 2020).

Yam (Dioscorea) is an important food for millions of people in West Africa (Pouya et al., 2022). A study by Danquah et al. (2022) reported that IFSM along with improved staking options can enhance and sustain yam production. However, yams require more fertile soils (than cassava). In Burkina Faso, Heller et al. (2022) observed that yams are produced in continuous rotation on degraded soils with rainfall of 610-960mm . However, intensified yam production may be limited by farmer’s low purchasing power of yam seed tubers, fertilizers, and labor. An on-farm study conducted in different eco-regions of Ivory Coast by Pouya et al. (2022) indicated that most important factors affecting tuber yields of yam were the total amount of rainfall received during the yam growing period and tuber initiation and maximum canopy development and the SOM stock in the 0-30cm layer). Pearl millet is the sixth most important cereal crop and is suitable for production in SSA (Satyavathi et al., 2021). In Senegal, Faye et al. (2021) observed that indigenous practices increased millet yields (Faye et al., 2021). Similar to pearl millet, sorghum is also widely adapted in SSA (Andiku et al., 2021). Sorghum and pearl millet are important cereals for SSA. In arid and semi-arid regions of SSA, cactus is another plant with a highly nutritional value. It is a hardy plant adaptable to harsh environments such as deserts. However, cactus is underutilized in SSA and needs to be studied for human use (Du Toit et al., 2021). There are also numerous African vegetables with high nutritional value (Shayanowako et al., 2021) such as amaranth. Small landholders in Africa also cultivate orange-fleshed sweet potato. However, extractive farming without inputs of fertilizers/manure can deplete soil fertility (Conz et al., 2021). Taro (Colocasia) is another tuber crop which is widely used as food staple in SSA (Juang et al., 2021). Tuberous crops like cassava and others require careful management of plant nutrient such as input of K (Adiele et al., 2020). In Ethiopia, Atnaf et al. (2020) observed that white lupin has a large potential for use for food, feed, cash, health, and restoring soil fertility (Atnaf et al., 2020).

5. Regenerative Agriculture and Agroecology

Regenerative agriculture (RA) and agroecology (AE) are being widely used to achieve eco-intensification of agriculture in Africa (Madsen et al., 2021). However, it is also argued that agroecology per se eco- cannot put SDG #2 on track in Africa because of the severe problem of replenishing soil fertility. Thus, there is an urgency to combine improved varieties with judicious use of external inputs (e.g., fertilizers, irrigation, pest control, reduce post-harvest losses) to achieve higher productivity while making agriculture in Africa as a part of the solution to preserve and restore natural resources and achieve food and nutritional security (Mudombi-Rusinamhodzi & Rusinamhodzi, 2022). Scientifically proven practices, however, must be evaluated under on-farm conditions with farmer participation at all levels such as was done with regards to adoption of CA in East Africa by Entz et al. (2022) (Entz et al., 2022). Entz and colleagues observed that bonding social capital through networks of farmer-farmer and farmer groups support soil and water conservation among resource-poor farmers. Among high-resource farmers, however, increased women bargaining power in farm input purchases supported fertilizers and manure use. Traditional knowledge is also pertinent to managing soil fertility in Africa (Occelli et al., 2021). For example, termite mound soils are used as a source of NPK by small landholder farmers in Southern Africa (Chisanga et al., 2020). In Tanzania, Mponela et al. (2023) also assessed gender influence on soil fertility management.

5.1 Policies for Small Landholder Farmers of Africa

Africa is not on track to achieve SDG #2 (zero hunger) because of rapid population growth, resource-poor farmers, and lack of appropriate policies. Future farming, in addition to producing an adequate amount and nutritious food, must also restore the environment, adapt/mitigate climate change, alleviate poverty, and meet other SDGs. On average, farms in Africa are often <1 ha. In addition, countries in SSA, The Middle East, and North African (MENA) region are also prone to natural and anthropogenic stressors leading to food and nutritional insecurity (Namany et al., 2023). Thus, there is a strong need for policies which can incentivize and motivate farmers and ranchers in Africa towards a broader focus of rural development to alleviate poverty (SDG #1) and achieve zero hunger (SDG #2). Giller et al. (2021) raised pertinent questions: 1) "Who are the farmers of the future?", and 2) "What is a farm?", and envisioned that future farming will be: i) more environmentally-friendly, ii) less external input dependent, and iii) focused on regionalized production systems leading to recoupling of arable and livestock farming because of the inherent resilience of the integrated farming systems against anthropogenic climate change and other emerging threats of biotic and abiotic stresses, and persistent predominance of small farms (<1 ha) in Asia, Africa, and Central America (Giller, Delaune, Silva, Descheemaeker, et al., 2021). Thus, policies are needed which are pro-nature, pro-farmer, and pro-agriculture to eliminate poverty especially rural poverty (SDG #1) and end hunger (SDG #2). Yet, smallholder farmers are not always able to deliver the expected rate of economic growth such as that needed in Africa (Giller, Delaune, Silva, van Wijk, et al., 2021), and thus the future of farming and who will feed the Africa and the world remain to be the key questions. The basic problem is of the societal perception of the farming profession, which leaves a lot to be desired. Farming professions, at all levels, from farmers to academicians, must get the respect that it rightfully deserves.

5.2 Transforming Agriculture in Africa

Africa is endowed with natural resources (soil, climate, water, eco-regions, biodiversity) and human capital to become the breadbasket of the world. The low crop yield of food staples can be easily doubled, tripled, and even quadrupled by adoption of known and scientifically proven technologies. In this context, some Dos and Don'ts of agriculture are outlined in Table 4, and transformative changes needed in African agriculture are outlined in Table 5.Important action plan to be prepared and implemented at village, district/county, state, national, and continental level include the following:

1. Increase the rate of input of fertilizer per hectare of cropland from 20 kg/ha in 2024 to 50 kg/ha by 2035, 100 kg/ha by 2050, and 150 kg/ha by 2075 and beyond. Chemical fertilizers should be used in combination with biofertilizers.
2. Increase the land area equipped for irrigation from 6% in 2022 (17 M ha out of 260 M ha, Table 1) to 40 M ha by 2050, 60 M ha by 2075 and 100 M ha by 2100 by expanding small scale and large scale irrigation scheme. Area under drip sub-fertigation must be increased.
3. Restore SOM content of cropland soils from 1.5% to 2.5% in the rootzone (30 cm) as an important strategy for an effective use of CA in combination with retention of crop residue mulch, cover cropping and agroforestry. Integration of crops with trees and livestock is an important strategy. Land managers should be rewarded through payments for SOM improvement at the rate of US $50/credit of CO_2 equivalent. Restoration of SOM would involve widespread adoption of carbon farming or growing carbon on land as a farm commodity.

4. Private sector must play a critical role in translating known science into action, providing inputs of fertilizers, irrigation, improved seeds, no-till seeder, and machinery for harvesting and secure storage of farm produce. Value addition of food products, processing and packaging, is also needed to enhance income and reduce food waste.

5. Strong cooperation is needed between the public and private sectors, and policies are needed to strengthen the cooperation. Political will power is critical to bring about the much needed and long overdue transformation of agriculture in Africa. Policies must be pro-agriculture and pro-farmer and especially those which empower the women.

6. Urban agriculture is needed to feed the rapidly growing cities in Africa (Table 5). City planners must consider growing 15 to 20% of food supply (fresh vegetables, etc.) within the city limits. Modern sky farming, environmentally-controlled agriculture, and home gardening must be enhanced and incentivized to feed the rapidly urbanizing cities in Africa. Urban agriculture may involve recycling of water and nutrients in urban waste with careful consideration of sanitation and other health-related issues.

7. Education is needed to change the mindset of decision makers in Africa and elsewhere who are interested in transforming agriculture so that Africa becomes the next bread basket of the world. Education is needed with regards to the followings:

- Farmers and the locals,
- Farmers' support service: advisory network for farmers or related issues,
- Farmers' association, self-defense association, etc.,
- Politicians, stakeholders or in general, decision-makers in the planning operations,
- Planners of agricultural production based on scientific data and maps,
- Establishers of database on spatial distribution of farmers, land, nutrient content of the soil degradation processes,
- Civil servants of the Ministry who call for applications to support soil degradation, nutrient supply, irrigation, etc. to target the possibly best areas for development with the best solutions, materials, knowledge, equipment, etc.

Table 4. Some Dos and Don’ts for Agriculture in Africa

Dos	Don’ts
1. Conservation agriculture	1. Burning of crop residues
2. Agroforestry	2. Plowing and bare soil surface
3. Recycle crop and animal waste	3. Flood-based irrigation
4. Provide clean cooking fuel	4. Extractive farming
5. Protect prime agricultural land against urbanization	5. Broadcasting of fertilizers
6. Include soil, environment, and agriculture in curricula of school and colleges	6. Puddling (wet plowing) of rice paddies
7. Enact soil health act	7. Uncontrolled grazing of livestock
8. Enact “Rights-of-Soil” and “Rights-of-Nature” Acts	8. Traditional fuel for cooking
9. Pay farmers for ecosystem services	9. Remove crop residues
10. Enhance public/private sector partnership	10. Practice extractive farming
11. Enhance awareness about land ethics and stewardship	11. Removal of topsoil for brick making
12. Achieve zero net soil degradation	12. Use bottles for water that contain agro-chemicals
13. Promote soil-less agriculture	13. Store grains and tubers in the open
14. Enhance prestige of the agriculture profession	14. Use monoculture
15. Integrate crops with trees and livestock	15. Create negative nutrient or soil carbon budget

There is a strong need for bringing about transformational changes in agriculture in Africa so that it not only can feed itself but also become a bread basket of world. These transformational changes are outlined in Table 6 and envisage use of innovative and proven scientific methods of soil, water, climate and farming system management. The basic philosophy of the transformative agriculture is to produce more from less, conserve soil and water, restore SOM content and adopt carbon farming that creates another income stream for farmers, promote nutrition -sensitive agriculture that supports the One Health concept, and make agriculture a part of the solution to address environmental issues and advance SDGs of the U.N. Agenda 2030. Africa has the resources and human power to bring about the transformation by encacting policies which are pro-nature, pro-agriculture and pro-farmers. The nexus approach is critically important. However, in the context of Africa (SSA, MENA, Horn of Africa and Southern Africa), the FEW concept must be changed to FEWS (food, energy, water, soil) nexus (Figure 5) because the protection and restoration of soil health is critical to accomplishing food, energy, and water security in changing and uncertain climate.

Table 5. Population Growth in Africa and a Few Major Cities (millions).

Region, Subregion, country, or area	1950	1970	1990	2010	2020	2040	2050	2080	2100
Africa	228.7	366.5	634.6	1049.4	1352.6	2100.3	2527.6	3424.7	3813.9
Sub-Saharan Africa	179.6	283.3	493.3	845.1	1106.6	1776.8	2167.7	2979.8	3351.5
Cairo	2.5	5.6	9.9	16.9	20.9	--	--	--	--
Lagos	0.3	1.4	4.8	10.4	14.4	--	--	--	--
Nairobi	0.1	0.5	1.4	3.2	4.7	--	--	--	--
Khartoum	0.2	0.7	2.4	4.5	5.8	--	--	--	--
Addis	0.4	0.7	1.8	3.1	4.8	--	--	--	--
Accra	0.2	0.6	1.2	2.1	2.5	--	--	--	--
Niamey	0.02	0.1	0.4	1.0	1.3	--	--	--	--

Adapted from: United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision, Online Edition. United Nations, Department of Economic and Social Affairs, Population Division (2024). World Population Prospects 2024, Online Edition.

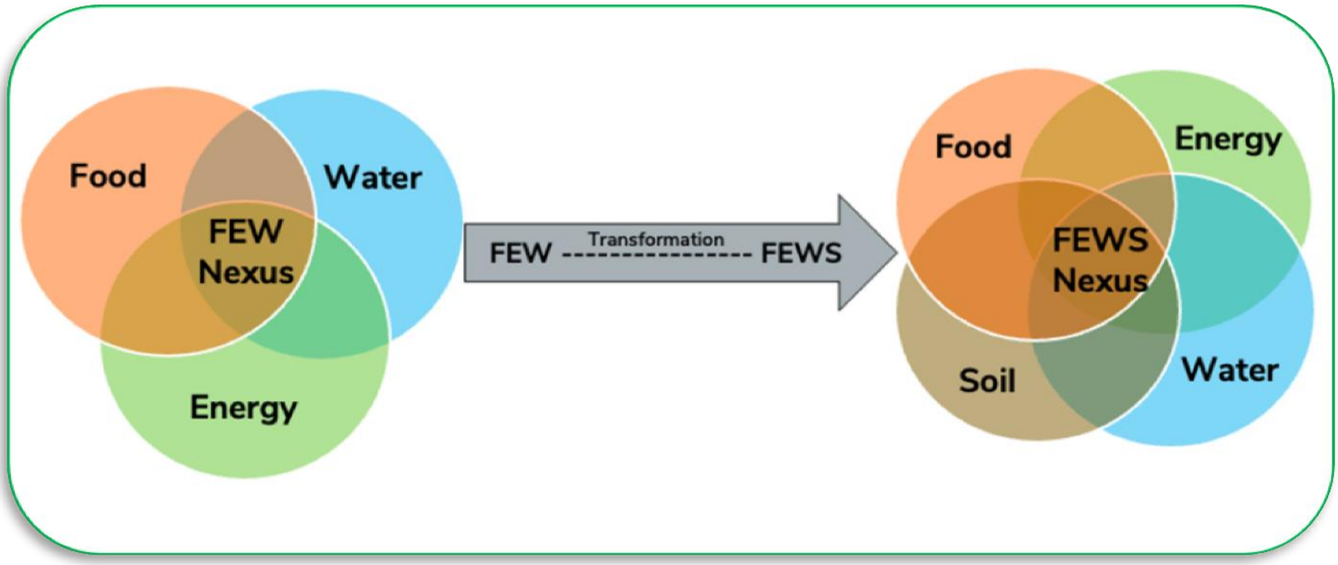

Fig. 5. Transforming the Food-Energy-Water (FEW) to Food-Energy-Water-Soil (FEWS) Nexus in Africa.

Table 6. Strategies for restoration of soil organic matter content and transformative of agroecosystems in Africa.

Problem ⟹	Transformative Change
Soil Erosion	Conservation agriculture
Water Table Depletion	Drip irrigation
Soil Organic Matter Depletion	Mulch farming, agroforestry
Poor Air Quality	Do not burn crop residues, use clean cooking fuel
Greenhouse Gas Emission	Conservation agriculture, agroforestry, fertigation (drip), integration of crops with trees and livestock
Bush Following and Shifting Cultivation	Regenerative agriculture and agroecologies
Agricultural Subsidies	Payments to farmers for ecosystem services
Hunger and Malnutrition	Nutrition sensitive agriculture
Subsistence Agriculture	Modern science-based agriculture

6. Conclusion

Africa, especially the SSA, has a vast potential to become the next bread-basket of the world. Food self-sufficiency is achievable by upscaling the known and proven scientific technology. The biophysical and socio-economic constraints must be addressed through implementation of action plan based on strong cooperation among researchers, private sectors, and policy makers. Rewarding farmers, through better marketing of agronomic produce, and payments for ecosystem services is critical to adoption of best management practices. In addition to adopting improved varieties, access to essential inputs (i.e., seeds, fertilizers, irrigation, machinery) is essential to enhancing agronomic productivity and bridging the yield gap. Implementation of pro-farmer policies is needed across Africa. Political will power is needed to implement policies which are pro-farmer and pro-agriculture. Cooperation between private sector and public sector is essential to translate science into action by promoting use of fertilizer and irrigation (drip sub fertigation) in combination with conservation agriculture and agroforestry. Africa can and will feed itself when its people and government realize that they must solve this problem and no one else can do it for them. Yes, Africa should and must feed itself by transforming its agriculture and food systems.

Declarations

Ethics approval and consent to participate

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