Integrated Soil Fertility Management Approaches for Climate Change Adaptation, Mitigation, and Enhanced Crop Productivity

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Integrated Soil Fertility Management Approaches for Climate Change Adaptation, Mitigation, and Enhanced Crop Productivity

Jayne Mugwe and Erick Oduor Otieno

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Abstract

Sub-Saharan Africa (SSA) nations are mostly susceptible to climate change impacts because they lack adequate capacity to adapt. This situation is the main reason for the declining agricultural productivity and the inability to mitigate climate change. Integrated soil fertility management (ISFM), a strategy widely promoted to improve agricultural productivity and input use efficiency, is one of the ways that may tackle climate change impacts in low-input systems akin to those in SSA. Past and ongoing research identifies key ISFM approaches for managing climate change, but these are poorly documented. Never before has there been a deliberate discussion of ISFM as a holistic approach that addresses a complete suite of soil fertility-enhancing strategies, adaptation to climate change, and greenhouse gas mitigation in SSA. This chapter, therefore, discusses seven

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(7) ISFM approaches and puts them into the perceptive of enhancing farmers' adaptability, agricultural productivity, and mitigating greenhouse gas emissions in light of changing climate. The discussion suggests that ISFM approaches (1) have strong potential to solving multifaceted problems at plot and farm levels and (2) are adaptable to diverse agro-ecological conditions as well as agricultural production systems and (3) ISFM is at the heart of climate-smart agriculture and educational development agenda. We conclude that ISFM options simultaneously address the three pillars of climate-smart agriculture, namely, food security through improved productivity, adaptation, and mitigation of GHG emissions. To promote the use of various ISFM components by smallholder farmers, rural development agencies and relevant stakeholders should formulate actionable land and resource use policies and institutionalized information dissemination strategies.

Keywords

Agroforestry · Germplasm · Inorganic and organic fertilizers · Intercropping · Legume-cereal rotation · Soil and water conservation · Triple wins

Introduction

Nations worldwide are battling with two interlinked issues: rapid expansion of population and climate change. The devastating effects of the changing climate are even worse in sub-Saharan Africa (SSA) where population growth rate is high and agricultural activities vastly rely on rainfall. The problem is further exacerbated by the fact that farmers, the majority of which are smallholder farmers, lack the ability to adapt to the current effects of climate change, possibly because the sub-continent is regarded as the poorest. Climate change causes massive losses on ecosystem services, which accompany increased pressure on and change in land use. This is more worrying since it is projected that losses associated with climate change will continue in the future, thereby affecting more economic activities and populations. About 950 million people are living in SSA, a population likely to shoot to 2.1 billion persons by the year 2050. Nearly a decade ago, roughly 815 million people were already living under either undernourished or malnourished conditions (FAO 2014b).

Agriculture has greatly relied upon desperate measures to reverse the damning statistics on malnutrition status and meeting food demands for the growing population in SSA. However, the demand for food production may be contributing to and affected by climate change. Earlier climate change studies gave importance to agriculture because it is vital for human survival and known to be sensitive to climate variations. Recent FAO report shows that greenhouse gas emissions from agricultural sectors almost doubled in nearly five decades ago. If no efforts are put in place, it is expected that these emissions will increase by an additional 30% come 2050 (FAO 2014a). The report pegs the root of the latest increase in greenhouse gas

(GHG) emission to developing nations as a result of expanded agricultural output (Bennetzen et al. 2016). Expanding agricultural land may result in increased livestock population density, consumption of fossil fuels, rapid deforestation, and the use of inorganic fertilizers. These practices point to amplified GHG emissions which also appear to be complicated by the Jevons paradox where improved efficiency of a resource may cause undesired effect (higher consumption) of that resources rather than lower its consumption (Paul et al. 2019). For instance, expanding agricultural activities has led to increased agricultural production but also caused change in land use systems that contribute to GHG emissions (Bennetzen et al. 2016).

Economic losses exerted by climate change are overwhelming. In a span of about two decades (between 1998 and 2017), losses emanating from global climate calamities surpassed US$. 2 trillion (UNISDR 2018). It is for this reason that the Paris Agreement recognizes the need to avert, minimize, and address losses and damages caused by climate events (UN 2015). Farmers in SSA are adopting integrated soil fertility management (ISFM) as a change and an adjustment to their agronomic practices. Changes and adjustments to farmers' agronomic practices will be critical in achieving the recommendations of the Paris Agreement and also address Sustainable Development Goals (SDG 1: No Poverty and SDG 2: Zero Hunger). The purpose of this chapter is thus to demonstrate how ISFM is best placed in averting economic and social or otherwise losses caused by climate change through meeting climate-smart agriculture (CSA) triple wins: pillar 1 (food security through increased productivity), pillar 2 (increased reliance to adapt to changing climate), and pillar 3 (mitigation of GHG emissions).

Conceptualized Relationship Between ISFM and Climate-Smart Agriculture

Integrated soil fertility management and CSA are a continuum. Integrated soil fertility management refers to a set of soil fertility management practices that comprise unison use of mineral and organic fertilizers and improved germplasm, combined with prerequisite knowledge of adapting the practices to local conditions, aimed at maximizing agronomic use efficiency of the applied nutrients and increasing crop productivity (Vanlauwe et al. 2010). In ISFM, there is an emphasis on the use of best practices, suitable germplasm, appropriate fertilizers and organic resources, and good agronomic practices (Vanlauwe et al. 2014). On the other hand, climate-smart agriculture is designed to operate within three pillars: (1) secured food through increased productivity (pillar 1), (2) increased reliance to adapt to changing climate (pillar 2), and (3) mitigation of greenhouse gas (GHG) emissions (pillar 3) (FAO 2010).

ISFM steps in to replace conventional organic fertilization by farmers, which cannot cope with increased demand for large quantities of nutrients by crops while also reducing the environmental impact of inorganic fertilization which is often expensive and inaccessible by smallholder farmers (Matusso et al. 2014). Therefore, ISFM addresses the three important pillars of CSA by building on possible trade-offs and synergies arising from crop production within a changing climate (FAO 2017). Components of ISFM can cushion farmers from the frequencies and intensities of extreme climatic events like high temperatures, droughts, and floods. This can be achieved through:

(i) Improved germplasm
(ii) Intercropping
(iii) Legume-cereal rotation
(iv) Combined use of organic manures with inorganic fertilizers
(v) Crop-livestock production system
(vi) Agroforestry
(vii) Improved water and soil management

ISFM Technologies and How They Address CSA Triple Wins

Improved Germplasm

The latest development in ISFM is the use of improved germplasm that is adaptable to local conditions. Climate change modifies ecological conditions; therefore, to adapt to the changes, farmers must adopt technologies that either stop the modifications or sustain life within the modified conditions. To this effect, improved crop seeds address three important aspects: disease and resistance and/or tolerance to pests, high yielding, and drought resistance. The importance of integrating genetic advancements in ISFM and addressing farmers' adaptability within the changing climate is summarized by Matusso et al. (2014) and includes but not limited to increased yields, free from pests and diseases, tolerance to droughts, efficient in nutrient uptake and utilization, early maturing, ability to resist lodging during excessive rains, diversity of crops, and durability.

Traditional germplasms of crops like cassava, sorghum, yam, open-pollinated maize, beans, sweet potatoes, peanuts, and cowpeas have provided food security in various SSA countries for decades. They have been termed as climate-smart crops in recent literature (Khatri-chhetri et al. 2016). These crops play an important role in ensuring food security in SSA amid the eminent threats resulting from the changing climate. It is imperative to acknowledge the role plant breeding plays in genetically engineering climate-resilient crops to adapt to the projected effects of climate change on yields. Consequently, traditional crops and the introduction of new varieties result in diversified food crops and increased agricultural production systems that are adaptable to climate change without pressurizing scarce traditional crops.

Improved soil fertility is crucial for the crop germplasms to sustain their regulatory and provision roles like nutrient cycling, pest and disease resistance and/or tolerance, and food security. Cassava is regarded as a drought-tolerant and climate-smart crop; however, Pypers et al. (2011) found that the use of its improved germplasm alone did not increase yield unless components of ISFM are included. Molecular breeding has led to the improvement of crop varieties that can tolerate low soil fertility and increased nodulation (i.e., for leguminous crops). Legume germplasms are important ISFM components that when intercropped or rotated with cereal crops, biologically improve soil fertility within cropping systems thus, considerably reducing the use of inorganic fertilizer, improving food security and diversity, and reducing GHG emissions (Muyayabantu et al. 2013).

Researchers have continued to support the use of improved biological materials in promoting food security as they amplify farmers' ability to improve food security and resilience to climate change. The Agricultural Research Institute of Guinea developed maize variety (Perta) that not only yields up to 7 to 8.5 t ha^{-1} and is resistant to leaf blight, spot, and streak but is also less vulnerable to lodging (Diallo et al. 2016). Also, some drought-tolerant crops comprise improved varieties that exhibit early flowering and fruiting. This ensures that the crops can escape the effects of late-season droughts without a reduction in yields and improve shelf-life of farm produce to ensure that farmers can strengthen season-to-season food security. For instance, storage durability of improved germplasm of black ripe olives improved since the storage for 8 months did not have a significant effect on volatiles (López-lópez et al. 2019). Tomato (*Solanum lycopersicum* L.) germplasms have been genetically improved to increase their antioxidant compositions (Pinela et al. 2019). These crop varieties may mitigate possible effect of climate change on human health.

An interactive effect of improved fodder germplasm and soil fertility can build a resilient livestock production system. Intercropping fodder crops in main cropping farms is a widely adopted practice that farmers use to control soil erosion and improve soil fertility through nutrient cycling. Integrating fodder grasses and organic amendments is an option that can greatly improve both crop yield quantity and quality and soil fertility. The International Centre of Insect Physiology and Ecology (ICIPE) in Kenya developed a multifunctional push-pull technology that uses legume fodder (*Desmodium*) to improve soil fertility and control pests. This technology has been effective in increasing maize yield and quality in Western Kenya where *Striga* weed, stemborers, and soil fertility are the main production constraints (Kassie et al. 2018). The perennial fodder grasses like *Brachiaria* species, *Pennisetum purpureum*, and *Napier* grass in the push-pull system result in extra benefits such as nitrogen (N) fixation, addition of soil organic matter, and controlling soil erosion and weeds while also sustaining the production of high-quality fodder necessary for livestock health and milk quality that in turn contribute to increased income and improved food security among smallholder farmers (Kassie et al. 2018). The use of chemical fertilizers considerably reduced in a leguminous fodder production system, thereby scaling down GHG emissions via reduction in the use of nitrogenous fertilizers.

It is important to note that even with the improved crop varieties, the timing of planting activities is crucial given that most SSA countries heavily depend on rain-fed agriculture, which is prone to effects of extreme weather events such as drought spells occurring early or late during the cropping season. Evidence shows that farmers have been resilient and adaptable to exposure to dry spells by embracing ISFM (Katengeza et al. 2019). Zimbabwean farmers have benefited in moderate delays in planting to escape early-season dry spells (Mutsamba et al. 2019). The timing is also likely to protect crops from heavy rainfall events. A simulation study projected that crop yields along Lake Tana in Ethiopia will likely be affected by more rainfall events (Yang et al. 2020).

Intercropping

Intercropping is the practice of simultaneously cultivating two or more crops on the same piece of farm. A staggered intercropping strategy is also being practiced by farmers in different parts of the SSA continent. This strategy entails planting two or more crops on the same piece of land, but the second crop is planted after the first one has reached physiological maturity. It is also called relay intercropping, which is more practicable in regions experiencing longer cropping seasons. The underlying principle is to benefit all the crops in the system by enhancing resource use efficiency within the farm. Farmers in SSA have intercropped various crops to improve soil fertility; increase yields per unit area; control weeds, pests, and diseases; and prevent soil erosion. Farmers in Southern Africa, to a lesser degree, intercrop maize with Bambara nuts, cowpeas, and groundnuts, while their counterparts in Eastern Africa predominantly intercrop maize with beans. Therefore, one of the intrinsic advantages of intercropping is its adaptability to a wide range of production systems such as tree crops (fruits), vegetables, grains, and fodder production.

Viewed in the context of ISFM, intercropping is a multifunctional solution to multifaceted problems. Cereal-legume intercrop has been successful in addressing multiple objectives at farm and household levels. Intercropping is an important pathway that improves farmers' resilience through increased food production, enhanced household incomes, food crop diversification, improved soil fertility, and risk management. For instance, farmers in Southern Africa, especially Malawi, benefited from 170 kg N ha^{-1} and 300 kg N ha^{-1} biologically fixed N by grain and green manure legume species, respectively (Mhango et al. 2012). Intercropping is attractive to farmers because of its potential to improve household income and land use efficiency as depicted by a land equivalency ratio (LER) greater than one (Matusso et al. 2014). Application of mineral fertilizer in cassava-bean intercrop not only increased yields of both crops but also resulted in an additional US$. 1000 ha^{-1} in the highlands of Sud-Kivu, DR Congo (Pypers et al. 2011). Maize-soybean intercrop was found in other parts of DR Congo to be beneficial because the area-time equivalency ratio was more than one, while a combination of organic (*Tithonia diversifolia*) and mineral fertilizer in the production system resulted in the highest monetary advantage index (Muyayabantu et al. 2013). Furthermore, intercropping crops of different levels of susceptibility to climate change is a mutualistic strategy that manages climate-associated risks such as crop failures, pests and diseases, and exposure to extreme weather conditions.

As a climate change mitigation pathway, intercropping also reduces GHG emissions as documented from an example in Ethiopia where it reduced nitrous gas emission and increased methane (CH_4) uptake (Raji and Dörsch 2020). A meta-analysis study revealed increased soil organic carbon (SOC) from diverse intercropping systems cultivated under conservation tillage with the application of organic fertilizers (Morugán-coronado et al. 2020). Furthermore, Nabel et al. (2016) showed that intercropping *Sida hermaphrodita* with *Medicago sativa* fertilized with digestate fertilizer energized marginal soils, improved yields, increased fixation of atmospheric N, and reduced its leaching. Intercrops may also enhance SOC in the form of soil organic matter (SOM), thus translating to reduced CO_2 emission.

Legume-Cereal Rotation

Crop rotation entails cultivating a series of different crop species in the same piece of land in sequenced cropping seasons. Thus, legume-cereal or cereal rotation is the practice of sequentially rotating a legume crop with a cereal crop in subsequent seasons. This practice serves to prevent the exhaustion of the same set of nutrients, control soil erosion, break the life cycle of pests and diseases, improve soil fertility, and increase crop yields. The integration of legumes in a cropping system serves to provide food security, generate income, and maintain environmental health among SSA smallholder farmers. The most popular legume crops among SSA farmers include cowpea, groundnut, soybean, and common beans. Legume-cereal rotation is widely practiced in SSA under various production systems including crop-livestock production (Monti et al. 2019) and usually involves maize (*Zea mays*)-legume rotation.

Legume-cereal rotation offers strategic entry points to ensuring food security among smallholder farmers in SSA (Fig. 1). A recent review of 44 publications summarized the advantages of legume-cereal rotation in SSA as a sustainable intensification approach (Franke et al. 2017). The authors found an additional annual

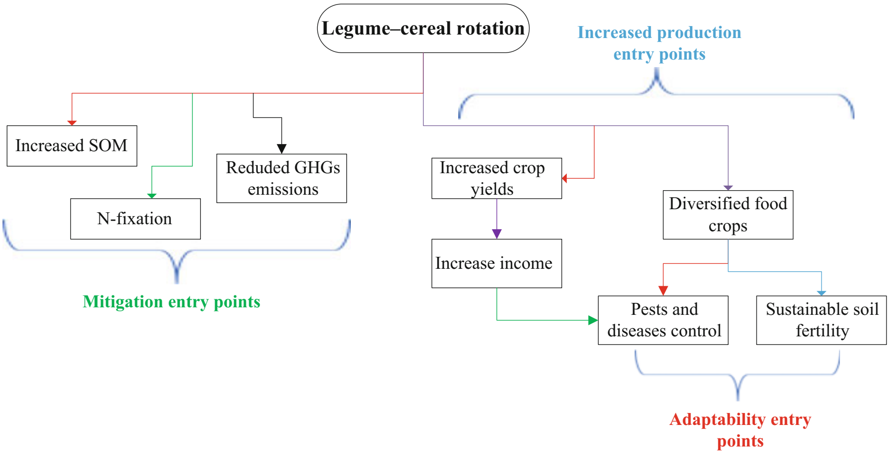

Fig. 1 Legume-cereal rotation entry points to increased productivity, mitigation, and adaptation to climate change

average increase of 0.41 t ha^{-1} cereal yield following legume cropping compared to mono-cropping, increased N and P availability, improved SOM, and reduced incidences of pests, diseases, and *Striga* plant attacks. Crop rotation when practiced under conservation tillage and residue management controls nutrient cycling by influencing soil microorganism diversity and soil enzymatic activities. The enhanced microbial communities constitute beneficial microorganisms that compete with soil-borne pathogens, hence suppressing diseases. The practice also controls climate-induced weeds and improves the response of applied phosphorus (P) (Víllora et al. 2019).

Crop rotation promotes a resilient food production system and mitigates against GHG emissions in a number of entry points (Fig. 1), attributed to atmospheric N fixation by rotational legume crops, increased household income, and judicious use of mineral fertilizers. This has been exemplified in different ways. For instance, farmers can use it to improve farming profitability, dodge effects of droughts, improve soil aggregation and SOC content, and improve yields of both food and pasture crops. Legume rotations are more efficient in reducing N_2O emission in subtropical maize production systems compared to nitrification inhibitors (Antoni et al. 2015); however, relatively labile C from legume residue limits the denitrification process. As demonstrated by Antoni et al. (Antoni et al. 2015), there was a 50% lower N_2O emission in sorghum after legume rotation. Increased N_2 fixation and reduced CO_2 emission have been observed in the dryland ecosystem when biochar is applied to the legume-cereal rotation system (Azeem et al. 2019). A simulation study projects reduced N_2O emissions under legume crop rotation production systems indifferent future climatic scenarios in rain-fed agriculture (Ma et al. 2018).

There are specific examples where crop rotation is combined with other soil fertility-enhancing inputs in the ISFM context. For instance, crop rotation complemented with a combination of mineral fertilizer and farmyard manure may be an effective way of reclaiming chemical fertility of degraded soils (Ahmad et al. 2014). Biochar application is a promising ISFM component capable of increasing crop yields and sequestering C. A long-term study conducted in Kenya on the application of combined biochar and inorganic fertilizer in a maize-soybean rotation stabilized crop yields (Kätterer et al. 2019). The authors reported 60% C sequestration over 10 years when biochar and mineral fertilizer are combined, with this strategy having an additive effect on maize and soybean yields. They also reported that this strategy increased the yield of subsequent soybean without fertilization by 0.6 Mg ha^{-1}. Approximately 80% of smallholder farmers in Burundi experienced an average increase in maize yield of 22% after rotating with climbing beans, while the cost-benefit ratio more than doubled when diammonium phosphate fertilizer was applied under the system (Niyuhire et al. 2017).

Combined Use of Organic Manures with Mineral Fertilizers

Integrated soil fertility management evolved from sole use of mineral fertilizers around the 1960s during the Green Revolution era. However, as a result of environmental concerns associated with excessive use of mineral fertilizers, organic inputs were integrated around the late 1970s to increase agronomic use efficiency of the inputs, with the need to adopt soil fertility management technologies to local conditions emerging in the early 2000s (Mugwe et al. 2019). Mineral fertilizer is viewed as an important input needed to meet food and feed demands arising from the growing population and diminishing land size and soil fertility. This is mirrored in the fact that the amount of inorganic fertilizer use is expected to increase in SSA, giving rise to environmental concerns because it is projected that currently, nearly half of the applied fertilizers are lost into the environment (Wang et al. 2019). If not well managed, this will translate to increased GHG (nitrous oxide and carbon dioxide) emissions. On the other hand, smallholder farmers in SSA are endowed with various organic inputs. In Kenya, inputs like compost, farmyard, *Tithonia diversifolia*, *Calliandra calothyrsus*, *Leucaena trichandra*, and livestock manure have been promoted (Mucheru-Muna et al. 2007). There are recent suggestions that organic manures should substitute for inorganic fertilizers in totality (Wang et al. 2017). However, there is a caveat to this suggestion as it is unlikely that organic inputs can meet the heavy nutrient demands of intensified agricultural production systems common among smallholder farmers in SSA.

Impacts of changing climate on agricultural productivity and household income of smallholder farmers can be significantly managed by effectively pulling together both mineral and organic inputs (Fig. 2). The ideal strategy is thus to integrate organic and inorganic fertilizers. There exists mutualistic interaction between these two inputs that enhance their agronomic use efficiency. Inorganic fertilizer improves the mineralization of organic inputs, while organic inputs increase uptake of inorganic nutrients, thus synchronizing plant nutrient demand and supply. With this strategy, empirical studies have shown that farmers are able to increase yields, improve soil fertility, and increase household income while lessening greenhouse

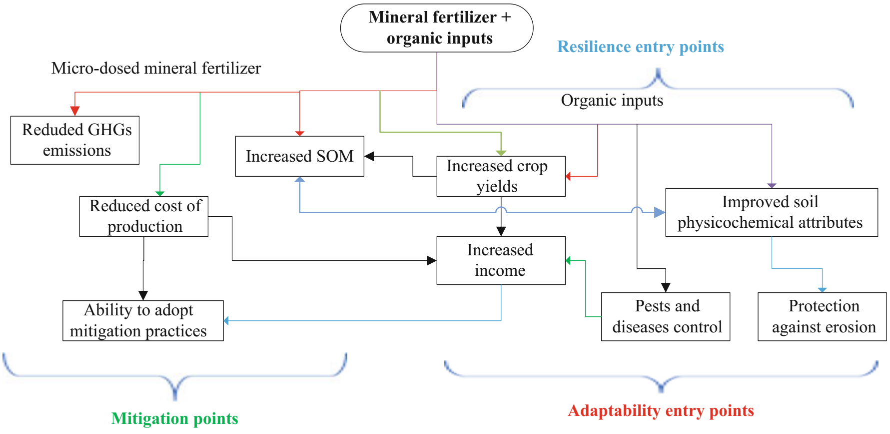

Fig. 2 Conceptualized relationship between mineral fertilizer and organic input integration and productivity, adaptation, and mitigation

gas emission. It is feasible to increase C sink in cultivated soils via organic fertilization, while it is also possible to sustain agricultural production by reducing inorganic fertilizer by supplementing with organic inputs without compromising agricultural productivity.

The concept of micro-dosing is rapidly gaining momentum among researchers. The concept is strongly backed by historical and present trends of mineral fertilizer use by SSA smallholder farmers. The majority of the farmers have adopted the use of inorganic fertilizer to a lesser extent, partly because of the high costs and possible negative effects of the fertilizers to soil productivity. However, the management of agricultural productivity requires subtle use of organic inputs to ensure general soil health and mineral fertilizer to sustain food production in tropical and subtropical soils of SSA amidst the raging effects of climate change. Most of the soils are highly weathered and experience leaching of nutrients in addition to being exposed to erosion by wind and water. Effective management of mineral fertilizers is thus crucial (Vanlauwe et al. 2014). Micro-dosing is one of the ways that can ensure effective management of mineral fertilizers that increase nutrient use efficiency of the fertilizers with little to no negative effects on the environment. It entails reducing the application rate of mineral fertilizer. A household survey of 1536 SSA farmers found that the use of mineral fertilizers and manure was a strategy used by the farmers as climate change adaptation mechanism (García et al. 2018).

There are numerous practical examples of the benefits of supplementing micro-dosage of mineral fertilizers with inorganic inputs in view of climate change. Agro-ecological advantage of micro-dosing is closely associated with climate change adaptability and mitigation (Fig. 2). For instance, farmers in Mali recorded modest economic returns for low investment in inorganic fertilizers as micro-dosing enhanced efficient water use, suppressed *Striga hermonthica*, and promoted early harvests (Kahsay and Hansen 2016). In Kenya, combining inorganic inputs with mineral fertilizers increased both maize yield and profitability in an on-station experiment (Mucheru-Muna et al. 2014). Application of *Tithonia diversifolia*, compost, and neem cakes (*Azadirachta indica*) was found to keep parasitic nematodes at bay for long periods in Kenya (Atandi et al. 2017). Long-term application of organic inputs lowers soil respiration, thereby reducing CO_2 emissions (Sun et al. 2018). These inputs increase soil resilience to climate change. Further, granulation of mineral fertilizers with nitrification inhibitors will ensure reduced N_2O emissions. This may offset the negative impacts of climate variations on agricultural productivity at relatively cheaper costs.

Crop-Livestock Production System

Most farmers in SSA keep livestock in addition to cultivating crops, primarily for domestic consumption, hence playing a crucial role in food security. However, change toward producing for market consumption is a great driver of a paradigm shift in this type of production system if the effect of climate change on crop, livestock, and profitability of the system is managed (Ghahramani and Moore

2016).Crop-livestock production systems offers the farmers diverse sources of livelihood, which strengthens their ability not only to be food secure but also to be resilient against climate change. For instance, there would be increased production per unit area of milk, meat, and crops and the farmers obtain extra income from selling their farm produce. These diverse sources of nutrition and income are crucial when one enterprise is affected by climate change. The sale of animal manure to crop producers and sale of crop residues to livestock keepers is an adaptation strategy that farmers are increasingly taking up to beat climate change impacts. Additional income gained from such transactions may be used by the farmers to adopt soil and water conservation technologies and buy food during unfavorable seasons.

There is a direct mutualistic relationship between crops and livestock enterprises that can be explored to adapt to, mitigate against, and increase production amidst the changing climate. Manure from the livestock is used in improving soil fertility for increased crop production. Farmers in SSA keep crop stover that is used to feed livestock during the drought periods offering substitute livestock feeding strategy. Stover is an important diet for livestock in this system, accounting for about 45–60% of the feeds during dry seasons (Thornton and Herrero 2014). Though the occurrence of dry spells affects grain yields, the effect of climate change such as droughts on stover yields is not as much. Income generated from the sale of livestock products is used to buy improved crop seeds, pesticides, and fertilizers, which in turn enhance agricultural production. Farmers can also be able to buy commercial livestock feeds to supplement fodder and buy water storage tanks to water their livestock and irrigate crops during drought seasons. Furthermore, it can trigger speculative saving to deal with uncertainties related to changing climate. However, technological and technical efficiencies of this system can differ from one location to another.

Integrated soil fertility management has been crucial in sustaining crop-livestock production systems. But it still requires operational policy, informational, technical, and infrastructural environment (Thornton and Herrero 2014). One of the crucial roles of ISFM is to improve soil fertility while reducing GHG emissions in this production system, regarded as one of the production systems most vulnerable to climate change (Ghahramani and Bowran 2018). The farmers stand to benefit from increased yields and income to counterbalance the financial effects of climate change through increased efficiency in production that offers farmers important co-mitigation benefits. Simulation model predicted that Burkina Faso smallholder farmers benefit from synergistic interaction between crops and livestock when they implement intervention measures such as crop fertilization and mulching using crop residues (Rigolot et al. 2015). In Zimbabwe, fertilizing maize-*Mucuna* intercrop with manure increased fodder and maize yields to 4481 kg ha^{-1} and 2394 kg ha^{-1}, respectively, among smallholder crop-livestock farmers (Mutsamba et al. 2019). The authors also found that rotating maize and soybean increased fodder yield. The farmers also benefited from an additional US$1395 when they intercropped maize and *Mucuna*.

A crucial potential contribution of substituting or supplementing organic for inorganic fertilizer in the crop-livestock production system to climate change mitigation lies in the efficient nutrient management leading to reduced soil N_2O emission and high carbon (C) sequestration. It is possible to reduce N_2O emissions from the soil by roughly 20% and sequester nearly 40–72% from the current yearly GHG emissions from agricultural activities (Scialabba and Mu 2010). Integrating improved germplasm of fodder crops with organic and inorganic inputs can build a resilient fodder production through improved soil fertility and fodder yield and reduced susceptibility of the superior germplasms to droughts, pests, and diseases. Sales from surplus fodder can be sold and income used to adapt to shortages of production during dry seasons by buying commercial feeds for the livestock. Feeding livestock on high-quality fodder supplemented with quality commercial rations may boost livestock health to cope with the changing climate. As shown by Nampoothiri et al. (2018), quality fodder increased calves' growth rate while reducing daily CH_4 emission. The simulation approach showed that Southern Africa farmers will more likely experience low climate risks if they adopt ISFM in their crop-livestock production systems.

Crop-livestock production will continue playing an important role in addressing climate change impacts into the future. Promoting and strengthening this system requires sound institutional, policy, and informational frameworks that are simplistic but holistically delivered in a manner the smallholder farmers can easily understand. The use of integrated organic inputs and mineral fertilizers need a balanced policy in the use of the two inputs. Unbalanced policy in the use of organic and/or mineral fertilizer might have wholesome negative effect on the production system and make it not only more vulnerable but also a major contributor to climate change.

Agroforestry

Agroforestry is a collective land management strategy where woody perennial trees are deliberately integrated into cropping land and/or in livestock production systems either in a temporal sequence or in some sort of spatial arrangement. There are economic and ecological interactions among the components of the system leading to resilience and adaptation of farm resources that are susceptible to climate change. There are three main types of agroforestry that, through interaction among respective components, enhance biodiversity and sustain food production for social, environmental, and economic rewards. These types of agroforestry include:

- **Agrisilvicultural**: a system where trees are grown together with or around crops in the same piece of land.
- **Silvopastoral**: a system where trees are grown and livestock kept in the same piece of land. The system consists of rangeland and pastures for livestock grazing.
- **Agrosilvopastoral**: a system where all the three components, trees, livestock, and crops, are integrated into a unit land.

Agroforestry forms a crucial part of agroecology and climate-smart agriculture because of its ability to co-deliver a range of provisional, regulatory, and maintenance services in the agricultural ecosystems (Fig. 3). It can thus increase the ability

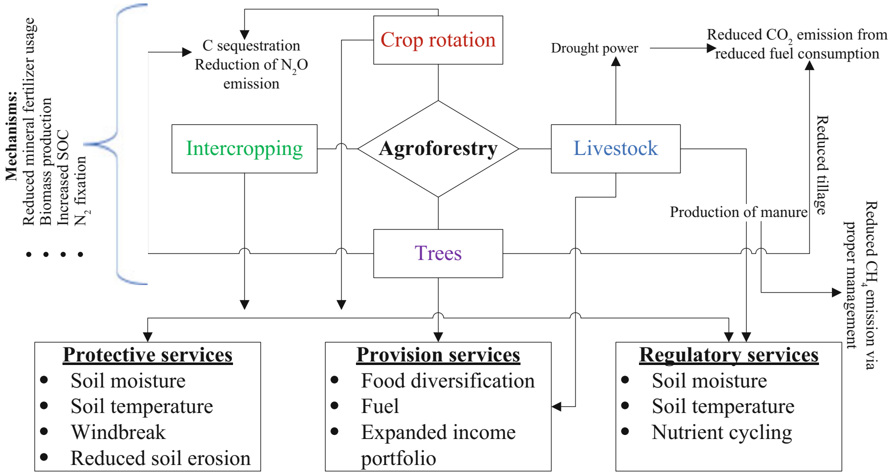

Fig. 3 Conceptualized pathways through which agroforestry addresses the triple wins of CSA

of smallholder farmers and rural communities to mitigate and adapt to the changing climate. There are positive synergies involving adaptation to the changing climate, agroforestry, and rural development (Tschora and Cherubini 2020). ISFM is a socioeconomic path to enhance the capacity of agroforestry to offer farmers benefits that translate to dealing with the challenges of climate change. The trees in the system and the manure obtained from the livestock or crop residues improve nutrient cycling and soil fertility, thus reducing energy-intensive inputs like mineral fertilizers, which are often expensive to rural farmers, increase C sequestration, and catalyze rural development. For example, agroforestry farms recorded a more than 5% increase of C sequestration between 1992 and 2015 and stored 83.7 ± 7.0 t C ha^{-1} in West Africa (Tschora and Cherubini 2020). In fact, the authors suggested that the massive adoption of agroforestry in seven West African nations could sequester nearly 135 Mt. CO_2 $year^{-1}$ in about two decades. Agroforestry farmers in Kassena-Nankana West District of Ghana attested that the practice reduced soil loss through water and wind erosion, improved soil nutrients, retained soil moisture, and enhanced household food security (Apuri et al. 2018).

Crop rotation and/or cereal-legume intercrop within the agroforestry system enhances the adaptive, mitigation, and resilience of the system to increase food security amidst the changing climate. Such activities ensure that the ground is covered throughout the year, hence regulating soil temperatures and conserving soil moisture needed for crop production. They improve soil nutrients with no or little use of mineral fertilizers, thereby reducing GHG emissions. Farmers in the SSA have traditionally practiced intercropping because of its flexibility and ability to conserve and improve soil fertility; maximize profits while minimizing risks; control pests, diseases, and weeds; and obtain balanced nutrition (Matusso et al. 2014). Land digging is considerably reduced, and weeds are smoothened by the trees under agroforestry. This reduces degradation of SOC, thus improving soil quality, and stores more carbon while improving crop productivity. Agroforestry, a key component of CSA projects in southern Malawi, increased maize yields by 20% in a droughty year (Amadu et al. 2020). Agroforestry trees like *Mucuna pruriens*, *Leucaena trichandra*, *Crotalaria ochroleuca*, and *Calliandra calothyrsus* have been used in Central Highlands of Kenya to improve soil fertility and maize yields (Mugwe et al. 2009; Mucheru-Muna et al. 2014).

Trees in the agroforestry ecosystem play multiple roles, both productive and protective, such as the production of food, feed, firewood, and timber and improve soil fertility. The trees bind soil particles together and act as windbreaks. This reduces the chances of fertility loss through run-off and wind, leading to a resilient and adaptive production system that yields more and diverse food that sustains rural livelihood during adverse weather conditions occasioned by changing climate. As demonstrated by Nyberg et al. (2020), high tree density on agricultural land was more market-oriented and self-sufficient in Kenya. This can act as an enabling environment or incentive for the farmers to adopt climate-friendly agricultural practices. Trees in the system shield the crops and regulate micro-climate within the farm, thereby protecting the crops and livestock against high temperatures which could otherwise negatively impact crops and livestock productivity because they are sensitive to water stress and high temperatures (Tschora and Cherubini 2020).

The use of leguminous agroforestry trees like *Dalbergia sissoo*, *Derris indica*, *Diphysa robinoides*, *Enterolobium cyclocarpum*, *Erythrina abyssinica*, *Erythrina poeppigiana*, *Gliricidia sepium*, *Inga edulis*, *Inga vera*, *Lespedeza bicolor*, and *Leucaena trichandra* among others has been tested and approved by numerous International Institute of Tropical Agriculture (IITA) projects across subtropics and tropics SSA. For example, Nigeria has effective species that improve soil fertility by biologically fixing atmospheric N into the soil. Moreover, pruning provides the cropped land with green manure that improves SOC and N leading to improved crop yields. Historically, the contribution of N from *Leucaena* used as mulch on maize productivity (grain yield) equated to roughly 100 kg ha $^{-1}$ per each 10 t ha $^{-1}$ of pruning (Nair et al. 1984).

Trees are an important element in sustaining agroforestry production systems. However, the general efficiency of the system needs vital information such as the types of trees to incorporate the spacing and arrangement of the trees, crops, and livestock units within the farm. If well organized, agroforestry has massive potential to holistically provide solutions to climate change challenges in a simultaneous way. Agroforestry contributes to climate change adaptation and mitigation through, but is not limited to:

- Promoting rural development
- Promoting conservation of biodiversity
- Carbon sequestration
- Improving soil fertility
- Escaping from food price destabilizations caused by climatic events

Soil and Water Conservation

The pressures of the intertwined effects of climate change and anthropogenic activities cause severe water and wind erosions in agricultural lands in SSA. The depletion of soil and water reduces agricultural productivity leading to massive food insecurities and poverty (Sileshi et al. 2019). As such, soil and water conservation (SWC) measures have prominently come out in key development policy agendas in SSA countries to curb food insecurity (Adjepong et al. 2019). The measures improve agricultural economic efficiency which can lead to a ripple effect on climate change mitigation and resilience. Crops are more vulnerable to extreme rainfall events compared to grasses or forests; therefore, SWC measures can enhance the resilience of the crops during drought and heavy rainfall, increase biomass production, and enhance plant C stock and sequestration.

Soil and water conservation is a global poverty-oriented and sustainable strategy for the management of natural resource. It encompasses a wide range of practices undertaken at the local level to maintain or improve land productive capacity in areas susceptible to degradation. The strategies aim to prevent or reduce soil salinity, erosion, and salinity, conserve or drain water, and maintain or improve soil fertility. The most important salient feature of the strategies is that they must be adaptable to local conditions. Therefore, based on farm characteristic, labor availability, financial capital, climatic and geological conditions, vegetation type, and landscape, smallholder farmers across SSA have practiced including but not limited to (1) physical SWC measures such as check dams, contour tillage, minimum tillage, half-moon, soil bunds, stone bunds, tied ridges, and zai pits; (2) agronomic SWC like cover crops, intercropping, crop rotation, mulching, row planting, and strip cropping; and (3) biological SWC measures such as agroforestry and planting grass or Napier grass on hedges or terraces. Farmers in Techiman Municipality, Ghana, incorporate compost manure, animal manure, and chemical fertilizers as SWC measures (Adjepong et al. 2019).

The literature amasses practical examples where physical, biological, and agronomic SWC measures are combined for sustained farming activities. The integrative approach improves the utilization efficiencies of each element as opposed to a singular application. The Ethiopian and Ghanaian governments encouraged their farmers to use improved seeds alongside SWC measures in order to increase the productivity of the cultivated land, reduce air pollution, lower on-farm costs, prevent contamination of surface and ground waters, and stop land degradation (Adjepong et al. 2019). Soil and water conservation measures enhance soil resilience by improving soil and moisture storage conservation benefits. As stated by Zougmoré et al. (2014), SWC measures like half-moons, zai pits, and stone bunds when combined with organic and/or mineral fertilization could be the potential technologies to promote the resilient agricultural system in semi-arid West Africa. Mulch, tied ridges, and minimum tillage reduced sediment nutrient loads and improved maize yield stability in different on-station experiments set up in semi-humid and dry parts of Central Highlands of Kenya (Okeyo et al. 2014). Soil and water conservation technologies like rock bunds, zai pits, filter walls, agroforestry, and half-moons are widespread in north-western Burkina Faso, are reinforced with organic inputs, and have continued to contribute to secured livelihoods and reduced poverty and susceptibility to drought and famine in the region. Another study (on-station study) reported that half-moon could vary sorghum yields from 1400 to 2000 kg ha^{-1} (Sawadogo 2011). The advantages of integrating cover crops, intercropping, and crop rotation in the physical SWC structures include those that have been discussed in various sections above.

The above examples demonstrate ways in which various SWC measures increase agricultural productivity and adaptability against the backdrop of the continued threat posed by climate change. In summary, the physical SWC strategies are protective against soil erosion and moisture depletion, while biological and agronomic SCW measures improve soil fertility. Functioning as a unit, these measures increase food production per unit cultivated land. Biological SWC practices such as intercropping with leguminous crops reduce consumption of mineral fertilizers at farm level leading to increased SOC and reduced emission of GHGs. It is thus imperative that SWC technologies' adoption is scaled up if its impacts on climate change are to be realized on a large scale. Therefore, incentive and policy environments should be strengthened together with enhanced extension services to capacitate SSA farmers to adopt these technologies.

Knowledge Gaps in the Present Understanding of How ISFM Addresses the Three Pillars of CSA and the Mechanisms

The understanding of how ISFM addresses the three pillars of CSA has rather been elusive despite the rich literature including empirical and simulated evidence. This is possibly because quantitative studies have not explicitly discussed the impact of ISFM in light of CSA. The current literature is devoid of ISFM studies that holistically investigate all the three pillars under one study. Instead, there are enormous stand-alone studies that demonstrate the capacity of ISFM to improve food security through enhanced agricultural production (e.g., Mhango et al. 2012; Muyayabantu et al. 2013) and promote mitigation by cutting down on emissions (e.g., Antoni et al. 2015; Raji and Dörsch 2020) or via C sequestration (e.g., Morugán-coronado et al. 2020). Consequently, the understanding of ISFM in the context of CSA is unclear. This may misinform policy and developmental interventions. Recent attempts to place ISFM in addressing food security, adaptation, and mitigation in light of CSA highlighted trade-offs resulting from singular soil fertility management components that make up ISFM (Descheemaeker et al. 2020). However, considering ISFM as a system, the highlighted trade-offs are neutralized by several co-benefits of integrating improved germplasms with inorganic and/or organic sources of soil fertility inputs. The discussions that follow seek to demonstrate how ISFM discussed in this paper fits in handling changes associated with climate change while addressing food security, adaptation, and mitigation pillars of CSA.

Climate change is likely to affect agriculture as a consequence of increasing temperature, fluctuating rainfall patterns, more climatic variability, and frequency of occurrence of extreme events (Descheemaeker et al. 2020). ISFM handles these climatic changes in various mechanisms while meeting food security, adaptation, and mitigation requirements of CSA. For instance, ISFM (e.g., combination of inorganic and organic fertilizers, intercropping, cover crops, and agroforestry) increases agricultural productivity through increased soil fertility, protection against adverse hot temperatures, conservation of soil moisture, and reduced erodibility. Intercropping and agroforestry executed in an integrated system ensure diverse food production that can be utilized during adverse seasons occasioned by bad climatic events. Furthermore, increased income associated with ISFM (Pypers et al. 2011) through reduced cost of production (cutting down on inorganic fertilizer use) and sale of surplus produce brought about by the use of ISFM directly contributes to food security at the household level. The farmers may use the increased income to purchase more food (e.g., processed food) during droughty seasons.

ISFM addresses the second CSA pillar (increasing resilience of the agricultural systems by adapting to adverse climatic changes). The mechanisms in which ISFM satisfies this pillar are variant and include (1) adapting crop cultivar; (2) adapting pests, diseases, and weed control; (3) adapting via diversification of income portfolio; (4) changing cropping patterns; (5) altering planting dates and post-harvest storage; (6) adjusting fertilizer application rates; and (7) diversification of crops. Evidence has shown that different ISFM components improve soil water content. This capacity renders the cropping system adaptable to less and erratic rainfall events (Descheemaeker et al. 2020). Furthermore, crop residue management, agroforestry, and intercropping regulate soil temperature and evaporation and protect soils and crops from the direct impact of raindrops. These ISFM components buffer temperature fluctuations and hence can protect the production systems from rising temperatures and frequent heat and water stresses associated with climate change. Agroforestry and conservation tillage make it possible to flex the planting date because of the reduction of tillage operations. This enhances the adaptive capacities of the production systems by allowing timely sowing depending on the occurrence of rains which results in reliable and improved yields occasioned by better utilization of in-season rains (Descheemaeker et al. 2020).

Similarly, ISFM mitigates the effects of adverse climatic changes through different mechanisms. The approach addresses this by reducing GHG emissions. Empirical studies have shown that N_2O emission can be reduced by improving N use-use efficiencies as advocated for by the principles of ISFM. Adopting improved germplasm together with combining inorganic and organic fertilizers optimizes the nutrient use efficiency of the applied inputs (Vanlauwe et al. 2014). On the other hand, CH_4 can be effectively managed by proper storage and use of animal manure within the farm in a crop-livestock production system (Nampoothiri et al. 2018; Raji and Dörsch 2020). The second mechanism is increased C sequestration in soil and biomass production, primarily achieved by promoting the build-up of SOM. ISFM increases biomass production leading to increased SOM while protecting it from rapid decomposition through improved soil structure. Occluded SOM is protected within soil micro-aggregates and thus inaccessible to microbial degradation leading to SOM build-up. ISFM components such as intercropping, agroforestry, and conservation tillage considerably reduce farm operations (mechanization) meaning that CO_2 emissions are also lowered by optimizing energy use efficiency of farm mechanization. In fact, it can be argued that often GHG emissions and C sequestrations are simultaneously achieved via ISFM.

We end this discussion by pointing out that ISFM stands to greatly benefit in its vital role in meeting the triple wins if there is an effective coordinated approach to its implementation and evaluation. The benefits of such approach include, but are not limited to, (1) shared successes and limitations of ISFM, thereby lowering experimentation and evaluation costs; (2) availability of consistent database of ISFM information to support and inform policy formulation at national, regional, and global level; (3) strengthened collaborative relations and trust; and (4) increased acceptance and adoption of research findings. Nonetheless, the biggest impediment to coordinated approach to ISFM research in SSA is the existence of numerous inconsistent land and input use regulations and policies at intra- and intergovernmental levels coupled with underfunding of research endeavors.

Conclusions and Way Forward

The discussions emerging from this chapter strongly show greater capabilities of ISFM to simultaneously address the three pillars of climate-smart agriculture, namely, food security through improved productivity, adaptation, and mitigation of GHG emissions. However, the missing link in understanding mechanisms through which ISFM promotes or compliments CSA lies in the current lack of studies that concurrently investigate the effects of ISFM on food productivity, adaptation, and mitigation of GHG emissions under single experimental set-up or simulation model. Such studies will further vindicate the strong positive relationship between ISFM and pillars of CSA. For this to be achieved, with a positive impact on farmers, there is a greater need for rural development agencies and relevant stakeholders to formulate actionable land and resource use policies and institutionalized information dissemination strategies that promote the adaptation and use of various ISFM components by smallholder farmers.

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