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SUSTAINABILITY OF AGROFORESTRY PRACTICES AND THEIR RESILIENCE TO CLIMATE CHANGE ADAPTATION AND MITIGATION IN SUB-SAHARAN AFRICA: A REVIEW

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Abstract

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Agroforestry is seen as a land management technique that can address many of the issues faced by smallholder farmers, such as climate change adaptation and climate change mitigation. Agroforestry helps farmers adapt to extreme weather events, create resilient microclimates for crops and livestock across regions, and help combat climate change. An important role of agroforestry in tackling climate change may be to reduce CO_2 emissions by actively sequestering carbon from the atmosphere. Soil stores the largest carbon stock (77%–92%) in agroforestry systems, with trees, herbaceous plants, and deciduous trees absorbing 7%–22% and 1%, respectively. Smallholder farmers in developing countries not only build resilient agroecological systems that actively absorb carbon, but also revert to more natural production systems that provide better ecological and social functions. By doing so, we can prevent climate change. Agroforestry not only reduces greenhouse gas emissions and improves the resilience of agricultural landscapes, but also can contributes to climate change mitigation and adaptation by promoting species migration to more favorable conditions and carbon sequestration. Climate projections could see production declines in much of sub-Saharan Africa, exacerbating food insecurity among citizens.

Key words: agriculture, food, carbon sequestration, climate, smallholder, sustainability

Introduction

Agroforestry has the potential to play a key role in reducing greenhouse gas (GHG) emissions into the atmosphere and helping smallholder farmers adapt to climate change around the world (Sanchez, 1995). Agroforestry systems have a limited role in adapting smallholder farmers to the projected climate change in the tropics, in general, and sub-Saharan Africa (SSA), in particular. As a result, tree densities in agricultural landscapes range from around 5% in the Sahel to more than 45% in the wet tropics, where agroforestry systems such as cocoa, coffee, and palm oil dominate (Zomer et al., 2009). Despite many efforts to model climate analogs and future climate impressions, the impacts of climate change on agroforestry systems are not fully understood (Luedeling et al., 2014).

Agroforestry has multiple economic and environmental benefits as it helps farmers adapt to rapidly changing weather patterns and combat climate change (IPCC, 2019a). Regardless of the reasons why countries want to expand their agroforestry systems and practices, there is a conflict between their goals and their ability to measure, report, and verify agroforestry actions and achieve climate benefits across the region (Rosenstock et al., 2019). The contribution of agroforestry to farm-level climate adaptation and landscape resilience can take many forms. As a result, agroforestry helps minimize air pollution and improve both warming and cooling of the environment, resulting in a more stable microclimate for crops and cattle across the region (Ellison et al., 2017).

Deforestation in the Gambia has resulted in a series of floods and droughts affecting the country's basic food supply, exposing farmers to food insecurity (Sonko et al., 2020). The Gambia's lowland terrain, heavy reliance on subsistence rain-fed agriculture, inadequate storm water drainage and management opportunities, and uncontrolled urban growth exacerbate the impacts of climate change (Garcia, Nakai, 2019; Manka, 2014; Sonko et al., 2020). Agroecology is defined as the application of ecological concepts, principles, and knowledge (i.e., interactions and descriptions of biodiversity, abundance, and activity) to the research, design, and management of sustainable agroecosystems. It is defined as "science and practice" (Bongarts, 2019), as a nature-based approach to building climate-resilient communities. Agroecology has the potential to help people build resilience and adapt to climate change. This is a practice that promotes sustainable use of ecosystems, selects native plants that are resistant to climatic stressors, and provides contextual responses to local problems (Kabore et al., 2019; Levard, 2018).

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Climate change and food security are two of the most important issues facing the world today. Furthermore, improving the resilience of agricultural systems, a key economic sector in most low-income developing countries, is important for adaptation to climate change (Adger et al., 2003; Conant, 2009; Parry et al., 2007). Rangelands, which include grasslands, scrublands, forests, and may also include post-harvest grazing arable land, constitute the majority of agricultural land in SSA (Homewood, Coast, 2004). Due to the vast amount of land covered compared to the amount that can be stored per unit area, rangelands can be an important source of carbon sinks (Conant, Paustian, 2002; Lal, 2016; Lipper et al., 2010; Smith et al., 2007). "Rangeland management" has the second highest technical potential for carbon reduction (Smith et al., 2007).

At the intersection of climate change adaptation and mitigation, the current problem of "climate-smart" agricultural systems arrives at and builds on previous agroforestry concepts (Carter et al., 2018; Kimaro et al., 2019; Rosenstock et al., 2019; Schöneberger et al., 2012). A new understanding of the importance of agroforestry and related activities to the climate change agenda is emerging as a result of the recent intergovernmental panel on climate change (IPCC) land use reports (IPCC, 2019b; Smith et al., 2020). Increasing yields of staple crops by shading trees to sustain the production of crops such as coffee, and by minimizing heat stress by reducing daytime temperatures, is an important aspect of agriculture in response to climate change. There are two agroforestry strategies that can improve performance (Rahn et al., 2014, 2018; Sida et al., 2018; Wangpakapattanawong et al., 2017). Farmers can substitute crops. Other livelihood alternatives can be explored and trees can be planted to change the local climate according to agricultural adaptation plans (Rippke et al., 2016).

Agroforestry reduces soil and water erosion, improves water management, and reduces crop yield variability, all of which contribute to adaptation (Ajayi et al., 2007, 2009; Franzel, 2002; Mercer, 2004). According to Noulèkoun et al. (2018), the climate parameters for predicting tree growth in the year of establishment (longest dry spell in rainy season) is different from those for the subsequent growth of trees with the established root system, i.e. overall balance of potential evapotranspiration and rainfall. Planting trees and shrubs increases the amount of carbon absorbed both above and below the ground, thereby helping to reduce GHG emissions (Verchot et al., 2007). Consequently, the overall aim of this review article was to assess the sustainability of agroforestry practices in SSA and their resilience to climate change adaptation and mitigation.

Climate change resilience and sustainability of agroforestry practice

Agroforestry is defined as effective land use practices that increase productivity while maintaining ecosystem stability. A rigorous scientific definition of agroforestry should emphasize two characteristics that distinguish all types of agroforestry from other land uses. Group or line up the planned tree and shrub developments next to the crops and/or animals in the sample area. Some types of agroforestry require little external input (for the poor), have high recycling rates, and are well integrated with trees, crops, and animals, making them sustainable livelihoods and climate resilient. They have been excellent candidates for achieving both goals of Koohafkan et al. (2012).

Climate change refers to extreme changes in climate and the consequences of these changes in other parts of the world. Climate change, whether caused by natural or anthropogenic factors, can change the likelihood and severity of extreme weather and/or climate events. Changes in the concentration of radioactive GHGs, a major driver of global climate change, are also important indicators (Forster et al., 2007; Menon et al., 2007). Large long-term changes in the predicted typical weather patterns for a region (or for the entire planet) over a significant period of time are called climate change.

Adaptation and mitigation of climate change are two different concepts. Mitigation measures are measures to reduce and contain GHG emissions, while adaptation methods are based on reduced sensitivity to the impacts of climate change. All human interventions aimed at reducing emissions or improving sinks of GHGs such as carbon dioxide, methane, and nitrous oxide are considered mitigation. In the context of climate change, adaptation is the process that occurs in natural or human systems in response to actual or projected impacts of climate change, with the aim of minimizing harm and maximizing benefits. Scientific and political interest in adaptation has increased dramatically since the IPCC third assessment report (TAR) showed that humans are at least partially responsible for climate change, and that some consequences can no longer be prevented (Burton et al., 2002).

Sustainability is "the convergence of environmental health, social justice, and economic vitality to create vibrant, healthy, diverse, and resilient communities for present and future generations." In the context of climate change, terms such as "sustainable economy" and "sustainable energy system" are used to describe ways in which energy, transportation, and other systems can be transformed, so that they do not contribute to global warming. As a result, evolutionary pathways will influence the severity of climate impacts not only through changes in exposure and sensitivity, but also through changes in system adaptability. This includes disaster risk reduction and resource management at the local level and broader social elements such as governance, community involvement and rights, and levels of education (Jung, 2005; Tompkins, Neil Adger, 2005).

The basic elements of green spaces are woody plants, which have varying functions and longevity depending on their species characteristics and specific environmental conditions. These conditions can be highly variable even in small areas, as noted by Anastasijević and Vratuša (1997). However, planting native tree species that are adapted to the microclimate conditions of the environment can increase the resilience and functional importance of urban green spaces. By doing so, designated areas of cities can achieve a greater effect in terms of urban planting. In addition, the effects of mostly dry temperate habitats in which urban green spaces are developed are often very detrimental to individuals of particular tree species. Several recent studies have emphasized the importance of allochthonous input as the primary source of carbon used for food in forest streams (Cummins, 1974; Minshall, 1967). The conditions under which a species grows affect its growth dynamics and achievement of specific developmental stages, as well as its persistence. Sustainable development measures and climate protection policies, especially adaptation, can reinforce each other (Munasinghe, Swart, 2005; Swart et al., 2003) (Fig. 1).

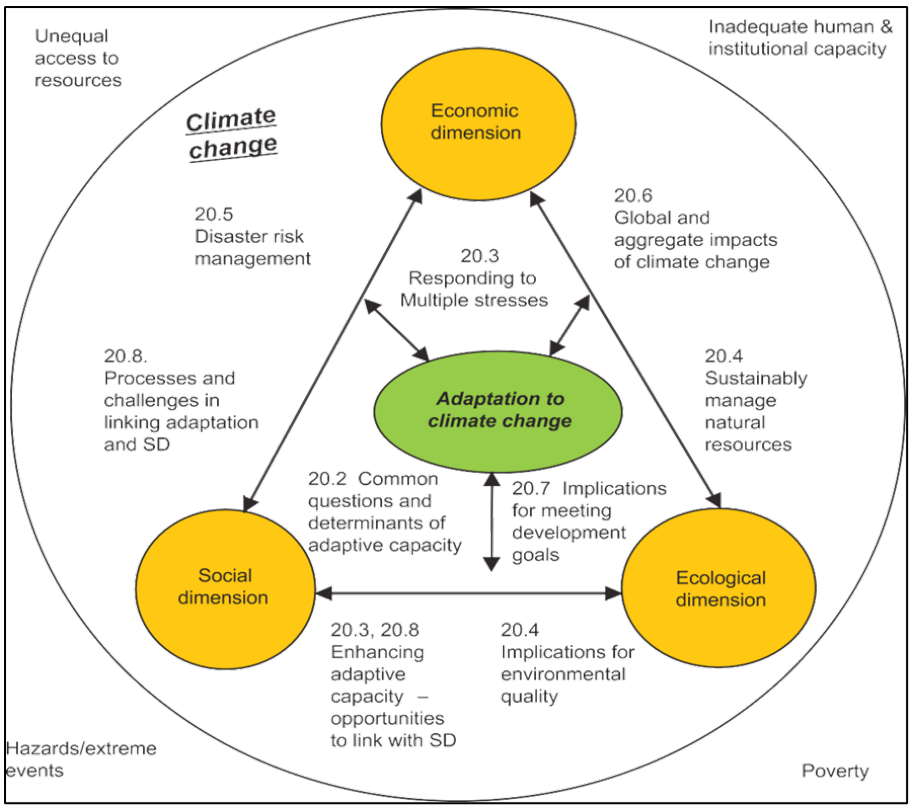


Fig. 1. Climate change adaptation and sustainable development (Munasinghe, Swart, 2005).

Agricultural sustainability is described as "the effective management of agricultural resources to meet changing human needs while maintaining or improving environmental quality and conserving natural resources" (Lal, 2011). Sustainable land-use systems provide satisfactory levels of production without long-term depletion of natural resources, are locally flexible, and ensure conservation of natural resources through equitable distribution of inputs and outputs (Conway, 1994; Neher, 1992; Torquebiau, 1992).

Sub-Saharan Africa

Geographically, SSA is part of the sub-Saharan African continent. This includes all countries and territories in SSA Africa, in whole or in part, according to the United Nations (Kazzah et al., 2022). The United Nations Africa Geoscheme excludes Sudan from its definition of SSA, while the African Union definition includes Sudan but not Mauritania. The harsh climate of the sparsely populated Sahara created an effective barrier separating the Sahara from SSA, breached only by the Sudan Nile, but Nile navigation was hindered by the Sud and river cataracts (Claussen et al., 1999; Desertification, 2014). Overall, SSA covers about 17% of the world's land area, accounts for 1% of the world's gross domestic product (GDP) in US dollars, and supports a population that accounts for about 12% of the world's population. Nevertheless, the region's GDP per capita is $2546.37, one-fifth of the world's average of $12,820.29.

SSA is one of the most vulnerable regions for climate change on earth (IPCC, 2014b). Rain-fed farming systems, which account for more than 95% of the agricultural area used by SSA, are particularly vulnerable (Serdeczny et al., 2017). The resilience of subsistence farmers is intrinsically related to the health and resilience of the soils they cultivate. Smallholder farmers practice farming in over 80% of their SSA land and produce 80% of the food supply (Wangpakapattanawong et al., 2017). Climate change is having a major impact on SSA, especially in relation to agricultural production. Climate change projections for this region point to a warming trend, particularly in the inland subtropics; frequent occurrence of extreme heat events; increasing aridity; and changes in rainfall with a particularly pronounced decline in southern Africa and an increase in East Africa. The currently high malnutrition and infectious disease rates in SSA are projected to increase compared to a no climate change scenario. Rain-fed agricultural systems, on which much of the region's population currently depends, are particularly vulnerable to these climate changes.

Smallholders, who cultivate less than 1-10 hectares of land, include pastoralists, foresters, and fishermen. They are characterized by family-oriented motivations, such as mainly using family labor for production and part of the products for family consumption, in order to promote the stability of the peasant household system. These smallholder farmers prioritize family needs over commercial production. Agriculture is the backbone of the Ethiopian economy, contributing to about 50% of the country's GDP and over 80% of its exports (Stellmacher, Kelboro, 2019; Temesgen et al., 2009). Moreover, it is one of the most important employment sectors, as about 80% of the country's population

depends on the agricultural sector for their livelihoods (Njeru et al., 2016). Ethiopia's agricultural sector is dominated by small farmers (Aweke, 2017). Smallholder farms are less than 2 ha and are operated mainly by family labor (Rapsomanikis, 2015). In Ethiopia, about 95% of major crops (cereals, legumes, oilseeds, vegetables, root crops, fruits, cash crops, etc.) are produced by smallholders (Aweke, 2017).

Agroecology potential promises a third way between shared global agricultural trade-offs, such as food production and conservation, environmental sustainability, and ecosystem services (Bongaarts, 2019; WWF, 2020). However, the most successful examples of agroecology mainstreaming come from small family farms, which occupy only about 30% of the world's agricultural land. Large-scale agriculture, which occupies most of the world's agricultural area, is defined here as highly mechanized commercial crop-growing and animal husbandry activities on land owned or leased by individual farmers, companies, or family businesses. The sector is responsible for 70% of current deforestation, the largest share of agriculture-related GHG emissions and agricultural water use, and habitat destruction leading to biodiversity loss ((Bongaarts 2019).

Climate Change in SSA

In the low-emission scenario RCP2.6 representing a 2 °C world, African summer temperatures increase until 2050 at about 1.5 °C above the 1951–1980 baseline and remain at this level until the end of the century. In the high-emission scenario RCP8.5 representing a 4 °C world, the warming continues until the end of the century, with monthly summer temperatures over Sub-Saharan Africa reaching 5 °C above the 1951–1980 baseline by 2100. By contrast, the higher aridity index in East Africa is correlated with higher rainfall projected by global climate models, while high rainfall savannahs' can be replaced by forests in less than 20–30 years (Bond and Parr, 2010).

Groundwater is the only source of safe drinking water in many rural areas of SSA (MacDonald et al., 2009). Most of the SSA, with the exception of Congo, parts of Angola, and southern Nigeria, has low permeability, small aquifers, and several larger aquifer systems (MacDonald et al., 2012). At 2 and 3 °C above pre-industrial levels, groundwater recharge rates are projected to decrease by 30–70% in western southern Africa and increase by about 30% in parts of eastern Africa and Southeast Asia (Döll, 2009).

Agricultural Impacts of SSA

The IPCC concludes that the overall impacts of climate change on yields of major cereal crops in Africa are likely to be negative with a high probability, with large regional variations (Niang et al., 2014). Worst case (fifth percentile) projections show losses of 27–32% for maize, sorghum, millet, and peanuts by the mid-20th century, assuming an increase of about 2 °C above the pre-industrial levels (Schlenker, Lobell, 2010). Using the output of 14 Coupled Model Intercomparison Project Phase 3 - Global Climate Models and Decision Support System for Agrotechnology Transfer (CMIP3-GCMs and the DSSAT) harvest model, we estimate an average yield loss of 24% in maize and 71% in beans when the temperature reaches 4 °C (Thornton et al., 2011). Maize, one of the most commonly grown crops in SSA, has been found to be remarkably sensitive to temperatures above 30 °C during the growing season. Geographically, most (90%) of the currently planted maize acres are expected to be adversely affected. Crop losses in these locations are primarily due to shortened harvesting periods and heat stress during the crop breeding season (Cairns et al., 2013; Thornton et al., 2009). Considering nitrogen stress, they show a further 10%–20% decrease in maize yield in various sub-Saharan regions (Rosenzweig et al., 2014). Annual mean temperatures in SSA are already above ideal temperatures for wheat growth, and this trend is expected to continue (Liu et al., 2008).

Climate change also threatens livestock production in SSA. Livestock are a valuable source of food (meat, milk and other dairy products), animal products (such as leather), money, and crop insurance (Seo, R.O.M., 2007). Drought makes livestock vulnerable, and there is a clear link between drought and animal deaths, especially if they are dependent on local biomass production (Masike, Urich, 2008; Morton, 2012; Sallu et al., 2010; Thornton et al., 2009). Land degradation reduces the productivity of agricultural systems, income and food security, and the resilience of ecosystems and populations. It is estimated that land degradation costs SAA 7% of its agricultural GDP, or nearly $4 billion, each year.

Agroforestry Resilience's Scope Climate Change and Agriculture in sub-Saharan African countries

At the local level, agricultural intensification and food production have significant environmental impacts on soils and biodiversity, as well as negative impacts on climate, food security, and farm incomes (Krausmann et al., 2013). Smallholder farmeers in less developed countries can combat climate change by reverting to more natural production systems that provide better ecological and social services, while meeting the needs of farmers. Adaptation and building resilient agroecological systems that actively absorb carbon (Jonsson et al., 1999; Lott et al., 2009; Neupane and Thapa, 2001). The scarcity of mineral fertilizers combined with the ineffectiveness of current agricultural policy has shifted attention from food security to sustainable agroforestry methods (Kiptot, 2012; Muchena et al., 2005; Tschakert)

The scarcity of mineral fertilizers combined with the ineffectiveness of current agricultural policy has shifted attention from food security to sustainable agroforestry methods (Kiptot, 2012; Muchena et al., 2005; Tschakert, Tappan, 2004). The estimated global potential for total GHG sequestration in agriculture is 1500–4300 Mt CO2 per year, of which about 70% comes from developing countries; 90% of this potential lies in restoring soil carbon and preventing net release of soil carbon (Smith, Wollenberg, 2011). Tree densities in agricultural landscapes range from about 5% in the Sahel to more than 45% in the humid tropics with cocoa, coffee, and oil palm agroforestry systems (Zomer, 2009).

Farmers' perceptions of climate information services

Farmers can make better decisions based on information from climate systems, such as cultivar selection, pro-

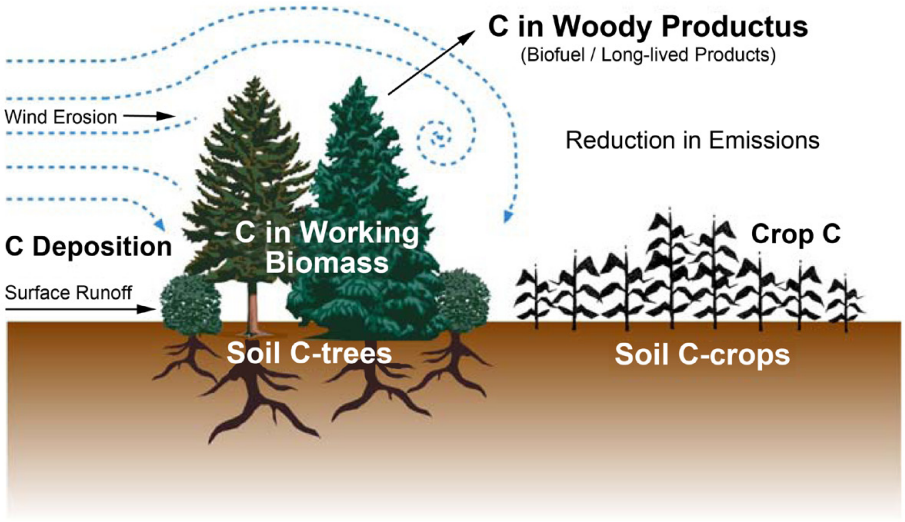


Fig. 2. Accumulation of forest carbon sinks and sources is affected by field windbreak (Schoeneberger, 2008).

duction methods, and sowing dates, all of which can improve yields (Lal, 2011). Climate education programs will provide farmers with information about possible ways to better cope with climate change. This new knowledge has the potential to increase farmers' willingness to use financial facilities and enable them to adopt more efficient agricultural technologies. This has the potential to build economic resilience by compensating farmers if bad weather results in poor harvests (Lal, 2011).

Effects of climate change on diversification of livelihoods

As the effects of climate change continue to unfold, farmers increasingly need to diversify their sources of income beyond agriculture. It is a powerful tool for poverty alleviation for poor farmers in rural Nigeria. Off-farm diversification helps farmers maintain or increase their income, allowing them to invest more in agriculture (Asfaw et al., 2017). Diversifying activities along the value chain is an important adaptation strategy. For instance, cassava farmers in southern Nigeria, as well as millet and peanut farmers in northern Nigeria, can process their products into value-added items before selling and marketing them. Snail farming and beekeeping are also viable options. By engaging in these additional tasks, farmers can enhance their productivity and income levels (Nzegbule et al., 2019).

Agroforestry's contributions to climate change adaptation

Agroforestry contributes to weather exchange mitigation in three approaches, which include sequestering carbon in biomass and soils, lowering GHG emissions, and warding off emissions via decreased fossil gas and power utilization on farms. For a windbreak (Fig. 2), forests are crucial terrestrial C sinks because they store a huge quantity of C in vegetation and soil and interact with atmospheric tactics through the absorption and respiration of CO_2 (Li et al., 2015; Pan et al., 2004; Xu et al., 2012).

At the same time, the device emits fewer greenhouse gases, such as nitrous oxide, because trees absorb more nutrients and less area is fertilized. Forests are significant carbon sinks, and urban trees and harvested timber also contribute to natural carbon sequestration (Flanary, Keane, 2020). As a result, less fossil fuel and energy are used in agricultural activities since some land is not cultivated. Additionally, the energy used in cotton production is mainly derived from fossil fuels, with diesel being the most direct energy input, followed by fertilizer and equipment as indirect energy inputs (Yilmaz et al., 2005). Agroforestry could be a win-win solution to the challenging decision between reforestation and agricultural land use because it enhances carbon storage and can also improve agricultural production (Chavan et al., 2016; Unruh et al., 1993).

Agricultural output in many African countries, significantly for subsistence farmers and in SSA, is heavily reliant on rainfall for irrigation. Due to a lack of rainfall, lots of agricultural land might be misplaced due to weather trade, with shorter growing seasons and reduced yields. Moreover, most subsistent plants, which include sorghum in Sudan, Ethiopia, Eritrea, and Zambia, maize in Ghana, millet in Sudan, and groundnuts in Gambia, will suffer from climate trade (Fischer et al., 2002).

Adoption of Sustainable Climate-Smart Agriculture by Small-Scale Farmers in Sub-Saharan Africa

Farmers in SSA, especially smallholder farmers with limited resources, face multiple challenges in coping with climate change and variability (Andrieu et al., 2017; Mugi-Ngenga et al., 2016). Climate-smart agriculture encompasses agricultural approaches that can deliver the triple benefits that are the pillars or core goals of the concept: increased production over time, improved livelihoods and ecosystem resilience, and reduced or eliminated GHGs (Mango et al., 2018). Climate-smart agriculture also

Table 1. Characterization of minimum and maximum temperatures of the different regions.

Region of Kenya	Minimum (night) temperature		Maximum (day) temperature	
	Trend	Magnitude/°C	Trend	Magnitude/°C
Western	Increase	0.8–2.9	Increase	0.5–2.1
Northern	Increase	0.7–1.8	Increase	0.1–1.3
North Eastern	Increase	0.7–1.8	Increase	0.1–1.3
Central	Increase	0.8–2.0	Increase	0.1–0.7
South Eastern	Increase	0.7–1.0	Increase	0.2–0.6
Coast	Decrease	0.3–1.0	Increase	0.2–2.0

Note: (Kenya, 2010, 2012).

includes better weather forecasts, early warning systems, and climate risk insurance (Murray et al., 2016). Many researchers have been involved in the development and commercialization of low-cost technologies suitable for small-scale agriculture in SSA over the last 30 years (Schaafsma et al., 2018). In recent years, however, attention has focused on solving problems such as reduced productivity, poor soil fertility, degraded countryside, food shortages, and increased risks to agricultural production, all of which are exacerbated by climate change. Cereal diversification, cereal–legume rotation, stress and drought crops, agroforestry, and conservation agriculture are examples of techniques that meet this criterion today (Schaafsma et al., 2018).

Climate-smart agriculture and smallholder integrated crop–livestock farming systems

Agriculture plays a key role in the Kenyan economy in terms of food security, promoting industrial growth, money generation, employment generation, foreign exchange earnings, and poverty reduction. Small-scale farming is common in Kenya, with approximately 75% of total agricultural production produced on rain-fed agricultural lands with farms varying in size from 0.3 to 3 ha (Kenya, 2012). Agriculture–livestock systems, crop–crop systems, crop–livestock systems, integrated rice–fish systems, and fish–poultry systems are also options for small-scale integrated crop–livestock systems in Kenya. In the face of increasing population pressures, especially in densely populated areas of Kenya, integration is a method of increasing productivity and maintaining incomes (Thorpe et al., 2000).

Trends of rainfall and temperature variation

According to Jaetzold (2010), a review of temperature trends, rainfall patterns, extreme events, and slow-onset events in Kenya revealed substantial evidence of climate change, with a clear indication that temperatures have typically risen throughout the country (Table 1).

This affects, among other things, evaporation, soil moisture, and water availability. However, it is less variable than precipitation (Jaetzold, 2010). Seasonal rainfall in western Kenya shows a general increasing trend, with first rains decreasing and second rains increasing. However, the general trend in Central and Eastern Kenya is downward.

The Overview of Agroforestry systems

Agroforestry increases the productivity and economic stability, while providing many benefits to smallholders vulnerable to climate change (Lin, 2014). Agroforestry is a dynamic, ecologically oriented natural resource management method that diversifies and supports smallholder agricultural production to increase social, economic, and environmental benefits by combining trees with farms and pastures (Leakey, 2017). The vulnerability of households to climate change was assessed using natural (soil erosion intensity, wood, and land resources) and physical (fuel wood energy) capital components. Agroforestry assets (yield per hectare, land, trees, and animals), income, and household adaptability were used to assess household flexibility (income diversification) (Nair et al., 2021). Agroforestry is the intentional planting of woody perennials on the same land unit with agricultural plants and/or animals, or in some spatial mixture or in such a sequence that woody and non-woody system components must have significant interactions (positive and/or negative ecological and/or economic). Research describes agroforestry systems based on their structure, function, socioeconomic nature, level of management, and environmental spread (Nair et al., 2021) (Fig. 3). Agroforestry is a direct source of food and fruit and complements the wood and fuel sectors (Current et al., 1995). In addition, keeping trees on the farm is the best form of insurance and strategy for various climate change situations (Chavan et al., 2016).

Agroforestry Practices' Contribution to Climate Change Adaptation and Mitigation via Carbon Sequestration

Agroforestry strategies can reduce GHG emissions by increasing carbon storage in the aboveground and belowground biomass and soil organic carbon stocks (IPCC, 2019b). Agroforestry integrated with crop and livestock systems can significantly increase carbon sequestration. Human activities lead to burning of fossil fuels and coal and destruction of forests, all of which contribute to global climate change (Ripple et al., 2020). Climate change affects local temperatures and terrestrial ecosystems and poses a threat to life and human livelihoods. Due to increased exposure to climate hazards, existing vulnerabilities, and reduced adaptive capacity, the effects of climate change have been more severe and destructive in some areas (Tucker et al., 2015).

Agricultural practices such as conservation tillage, grassland management, and in-crop grazing can also help reduce carbon

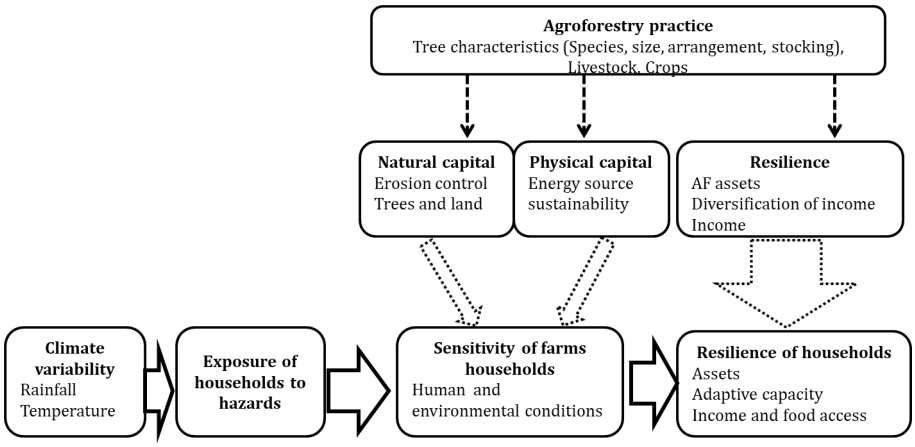


Fig. 3. The research's conceptual framework explaining farmers' vulnerability to the consequences of climate variability (Turner et al., 2003; Modified by Mabel Nabunya, 2017).

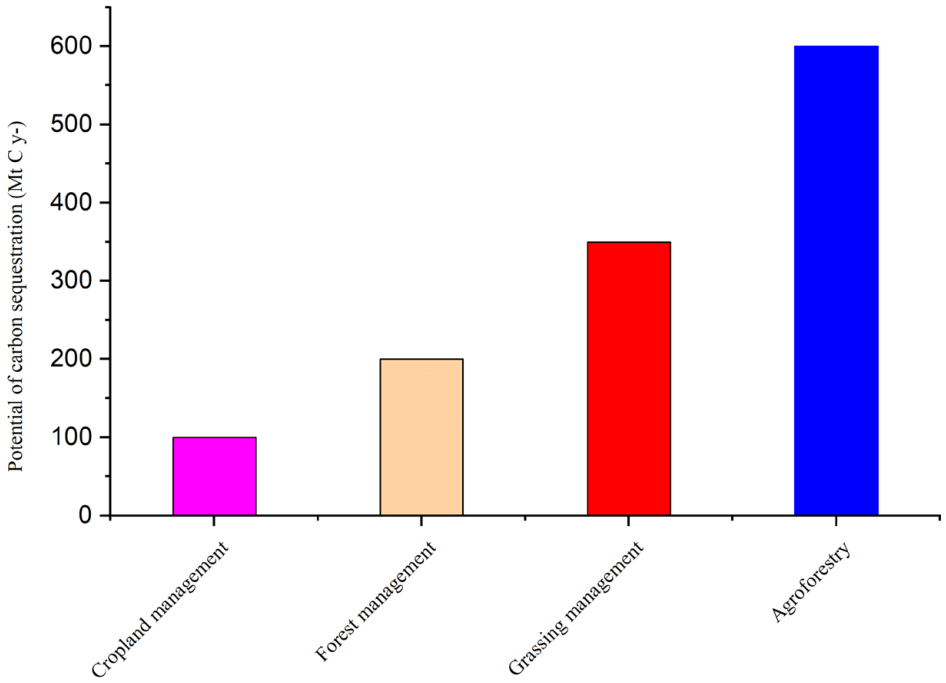


Fig. 4. Carbon sequestration potential from different land-use systems (Yohannes, 2016).

losses and improve carbon storage on agricultural land. Soil carbon sequestration is an important ecological service provided by grasslands and can be enhanced by optimal grazing strategies (Griscom et al., 2017). These approaches reduce CO_2 emissions from cultivation, such as conventional cultivation and organic agriculture. However, there is still much uncertainty about how soil carbon changes over time in managed grasslands (Desjardins et al., 2012; Olson et al., 2017; Paustian et al., 2016), and there may be limitations to soil carbon storage due to carbon and nitrogen cycles, such as soil nitrogen limitations (Van Groenigen et al., 2017). Therefore, when evaluating alternatives, the net effect of different management strategies on all three biogenic GHGs must be assessed (Del Grosso et al., 2005; Robertson et al., 2000). One of the most important effects of agroforestry, in general, is the ability to respond to climate change by sequestering carbon in aboveground plant biomass and soil (Kaonga, 2005; Unruh et al., 1993; Verchot et al., 2007). National and global surveys of terrestrial carbon sinks have identified two main benefits of agroforestry (Wise, Cacho, 2005).

Implementation of global agroforestry systems could remove 1.1–2.2 × 1015 g C from the atmosphere over the next 50 years, according to an analysis of global C stocks (Albrecht, Kandji,

Table 2. Climate change adaptation and mitigation are aided by agroforestry functions (Schoeneberger et al., 2012).

Climate change activities	Major climate change functions	Agroforestry functions that support climate change mitigation and adaptation
Adaptation Action that reduces or eliminates the negative effects of climate and takes advantage of positive effects	Reduce threats and enhance resilience	• Alter microclimate to reduce the impact of extreme weather events on crop production
		• Alter microclimate to maintain the quality and quantity of forage production
		• Alter microclimate to reduce livestock stress
		• Provide greater habitat diversity to support organisms (e.g., negative pollinators, beneficial insects)
		• Provide greater structural and functional diversity to maintain and protect natural resource services
		• Create diversified production opportunities to reduce risk under fluctuating climate
	Facilitate species movement to more favorable conditions	• Assist in plant species movement through planting decisions
Mitigations Activities that reduce the GHGs in the atmosphere or enhance the storage of GHGs in the ecosystem	Sequester C	• Accumulate C in woody biomass
		• Accumulate C in soil
		• Reduce fossil fuel consumption
		➢ with reduced equipment runs in areas' trees
		➢ with reduced farmstead heating and cooling
		• Reduced N_2O emission
		➢ by greater nutrient uptake through plant diversity
		➢ by reduced N fertilizer application in tree component
		• Enhance forage quality, thereby reducing CH_4

Notes: C – carbon; CH_4 – methane; GHG – greenhouse gas; N – nitrogen; N_2O – nitrous oxide.

2003). In semi-arid, sub-humid, humid, and temperate climates, the average carbon stock of agroforestry systems with manure trees as an integral part was calculated to be 9, 21, 50, and 63 Mg C ha^{-1}, respectively (Montagnini, 2004). Agroforestry can indirectly affect carbon sequestration by reducing the burden on natural forests that act as natural carbon sinks. Sileshi and Mafongoya (2006), argue that the ecosystem benefits of agroforestry-based land-use practices are not understood, so little attention has been paid to accelerating and generalizing their adoption in agriculture and natural resources. Using environmental economics and externality theory, the application of contingency incentive mechanisms was investigated as an alternative strategy to promote the adoption of fertilizer trees/shrubs in South Africa (Ajayi et al., 2007; Ajayi, Matakala, 2006).

Carbon Stock in the Forest

The contents of carbon emission are greater from deforestation and forest degradation (Nair, 2012). Conversely, this can be managed through the sustainable management of land and forest. The enhancement of forest C stocks through agroforestry can be considered as one of the main options for reducing greenhouse gases in the atmosphere. For instance, the U.S. produces about 25% of global CO_2 emissions from burning fossil fuels (Morgan and Jack, 2010). The main role of agroforestry in terms of climate change could be to reduce carbon dioxide emissions by actively sequestering carbon from the atmosphere. From an agroforestry perspective, C sequestration mainly means the assimilation of atmospheric CO_2 during photosynthesis and the transfer of fixed C to vegetation, litter, and soil pools for "safe" (long-term) storage (Labata et al., 2012; Morgan et al., 2010).

In addition, agroforestry techniques helped to restore 35 °C of the original C acre in the destroyed forest, compared to only 12 °C in cultivated land and pastures in the tropics (Palm et al., 1999). Compared to agricultural land management, which can only store 100 million tons of carbon per year by 200, agroforestry systems can capture 600 million tons of carbon per year by 200 (Fig. 4). According to a carbon stock assessment study conducted in the Philippines (Peichl et al., 2006), agroforestry systems sequestered carbon in the following order. In addition, carbon was stored in the following order: soil (77–92 °C) > trees (7–22 °C) > herbaceous vegetation and litter (1%) (Labata et al., 2012).

Agricultural Landscape in Transition, with Agroforestry's Contribution to Climate Change Mitigation and Adaptation

Agroforestry has the potential to contribute to climate change mitigation and adaptation by reducing threats and improving agricultural landscape resiliency, facilitating species movement to more favorable conditions, sequestering carbon, and reducing GHG emissions, according to available evidence (Table 2). One

Table 3. Perceived best and implemented adaptation methods to climate change (Komba, 2012).

Adaptation method	Perceived best by	Implemented by
Irrigation	156 farmers, 28.1%	31 farmers, 5.6%
Short-season crops	147 farmers, 27.0%	131 farmers, 24.1%
Crops resistant to drought	83 farmers, 15.5%	93 farmers, 17.3
Planting trees	61 farmers, 11.7%	37 farmers, 7.4%
Changing planting dates	38 farmers, 7.4%	60 farmers, 11.3%
No adaptation	49 farmers, 10.4%	182 farmers, 34.4%

of the advantages of agroforestry is the possibility of providing integrated and synergistic adaptation and mitigation services (Duguma et al., 2014)mitigation and adaptation measures are handled separately, due to differences in priorities for the measures and segregated planning and implementation policies at international and national levels. There is a growing argument that synergistic approaches to adaptation and mitigation could bring substantial benefits at multiple scales in the land use sector. Nonetheless, efforts to implement synergies between adaptation and mitigation measures are rare due to the weak conceptual framing of the approach and constraining policy issues. In this paper, we explore the attributes of synergy and the necessary enabling conditions and discuss, as an example, experience with the Ngitili system in Tanzania that serves both adaptation and mitigation functions. An in-depth look into the current practices suggests that more emphasis is laid on complementarity-i.e., mitigation projects providing adaptation co-benefits and vice versa rather than on synergy. Unlike complementarity, synergy should emphasize functionally sustainable landscape systems in which adaptation and mitigation are optimized as part of multiple functions. We argue that the current practice of seeking co-benefits (complementarity.

Smallholder Farmers' Climate Change Adaptation

Agriculture is the most important sector in SSA and is expected to be most affected by climate change (Deressa, 2007; Hassan, Nhemachena, 2008; Mano, 2006; Molua, 2012; Moussa, 2006). Although climate change may affect the agricultural sectors of many countries, it is particularly important for smallholders whose main source of income is agriculture. Füssel, Klein (2006) found that adaptation is the most effective strategy for farmers to mitigate the negative effects of climate change. Tanzania is one of the countries in South Africa where agriculture is the main economic sector. Agriculture is Tanzania's main source of food, accounting for 5% of GDP, 60% of merchandise exports, 75% of rural household income, and 80% of employment (Andersson, Slunge, 2005, Gbetibouo, 2009). The way farmers frame their future climate expectations of changing weather conditions is a critical factor influencing their adaptive capacity in the Limpopo Basin of South Africa. If there were no limitations, a higher percentage of farmers would adjust their irrigation access by 28.1% (compared to the current 5.6%), plant short-term crops by 27% (compared to the current 2.1%), and plant trees by 11.7% (compared to the current 7%) (Table 3). Therefore, irrigation is the most common adaptation option that farmers would like to use to respond to climate change, but current conditions make this difficult.

Climate Change Adaptation Mechanisms

According to Connor, Mínguez (2012) and Sayer, Cassman (2013), adaptation to climate change is urgently needed to ensure global food security and environmental quality. Farmers in different regions have different understandings of climate change and adaptation strategies. Farmers' perspectives on climate change are important not only in adaptation plans, but also in policymaking and in the integration of scientific and indigenous knowledge for climate change adaptation (Ayal, Leal Filho, 2017; Juana et al., 2013; Woods et al., 2017).

Some adaptation methods used in African countries include changing planting dates, fertilization, irrigation applications, cultivar characteristics, livestock species selection, mixed and multiple cropping, agroforestry with mitigation benefits, and livelihood diversification (Nyong et al., 2007). Pastoralists use emergency food, slaughter of weak animals for food, and multi-species livestock composition as adaptation methods during drought to cope with extreme climatic conditions. During drought, most pastoralists and farmers switch from animal husbandry to sheep and goat rearing, as the latter's need for fodder has decreased (Seo, 2006).

Contributions of Agroforestry to Food Production and Climate Change

Low soil fertility is a major problem for food production and one of the main biophysical barriers to increasing agricultural growth in SSA (Kwesiga et al., 2003; Monerie et al., 2020; Vanlauwe, 2006). In addition, sub-Saharan African soils are expected to consume 22 kg/ha of nitrogen, 2.5 kg/ha of phosphorus, and 15 kg/ha of potassium per year (Smaling et al., 1997). After the end of fertilizer subsidies and the disintegration of national production input distribution networks, the problem of fertilizer availability became even more urgent. Fertilizer trees/shrubs are an agroforestry-based soil fertility restoration strategy that originated in South Africa in the late 1980s in response to declining soil fertility and low levels of macronutrients in several sub-Saharan African countries. In Malawi, it is estimated that more than 6.6 million USD of nutrients are lost annually due to soil erosion (Bojö, 1996). It is accepted in the literature that compost trees/shrubs are long-lasting, technically sustainable, and environmentally friendly.

Climate Change's Economic Impact

Global temperature increases have been unprecedented and are projected to continue. Because past emissions persist in the atmosphere, even extreme reductions in GHGs can only reduce

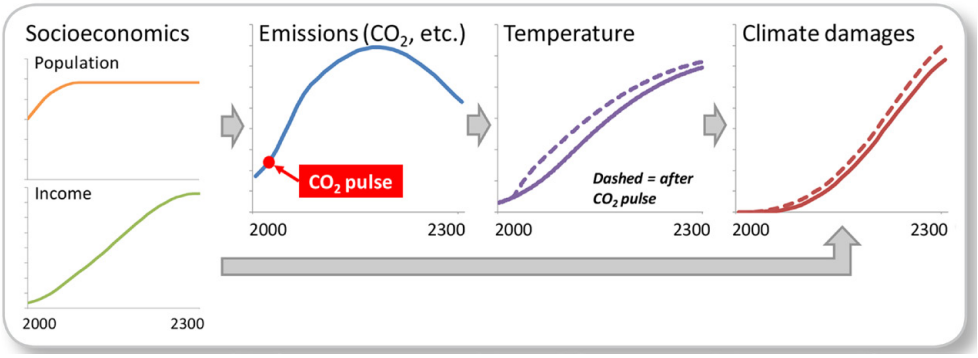


Fig. 5. Causal chain in integrated assessment models (Rose et al., 2014).

temperature increases (IPCC, 2018). The capacity of Indian agroforestry systems to store carbon is influenced by both environmental and socioeconomic factors (Peichl et al., 2006). In addition, it is more difficult for poor countries to adapt to climate change (Adger, 2006; Alberini et al., 2006; Smit, Wandel, 2006). Climate change has a greater impact on poor countries, especially on agriculture and water supply. Climate change would have a major impact on the environment. Temperature and precipitation affect plants and animals directly and indirectly through interactions with other creatures. Changes in distribution and abundance, invasions, and local and global extinctions are all consequences of climate change (Gitay et al., 2001).

Climate Change's Impact on Agriculture

Agriculture is the most vulnerable sector of the industry because its productivity is completely dependent on climatic variables such as temperature, rainfall, humidity, and so on. Extreme weather events have exposed and affected the productivity potential of agriculture. Due to its geographic importance, poor income, and greater dependence on the climate-sensitive agricultural sector, Bangladesh is one of the most vulnerable countries in the world to climate change (Mandal, 2016; Rahaman et al., 2020). Climate change is seriously affecting agricultural production and food security in Bangladesh. Climate change is already affecting food production in several ecologically sensitive areas, such as coastal areas, drought areas, and flood-prone parts of the country (Hoque, Haque, 2016).

According to the Intergovernmental Panel on Climate Change, rice and wheat production in Bangladesh could decrease by 8% and 32%, respectively, by 2050 compared to the base year of 1990, potentially leading to acute food insecurity (IPCC, 2019 a). Integrated assessment models (IAMs) are models that combine emission pathway projections with a simple climate model with a damage function that translates changes in surface temperature, precipitation, and sea level into economic losses (Fig. 5).

Conclusion

Climate change is expected to have the greatest impact on SSA's agricultural sector, especially smallholder farmers. Climate is a key factor controlling several stages of the life cycle of organisms, such as plant germination and flowering. Agroforestry's contribution to climate change adaptation at the agricultural scale has come through increased landscape resilience across regions. Participatory multidisciplinary techniques, integrated animal husbandry systems, and climate-friendly farming practices can be employed to maintain and improve production efficiency while reducing emissions rates, resulting in superior cost-effectiveness. In semi-arid, sub-humid, humid, and temperate climatic zones, average carbon stocks by agroforestry systems, in which fertilizer trees are an integral part, are calculated to be 9, 21, 50, and 63 Mg C ha^{-1}, respectively. The practice of agroforestry can significantly contribute to the reduction of CO_2 emissions by effectively sequestering carbon from the atmosphere. To ensure the sustainability of agroforestry and its resilience to climate change, it is crucial for the agricultural advisory units of governments in SSA to raise awareness among farmers and encourage the adoption of agroforestry for both climate change adaptation and mitigation purposes.

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