Low-cost agroforestry technologies for climate change mitigation and adaptation in Sub-Saharan Africa: A review

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Photos 1.
Main agroforestry technologies in Sub-Saharan Africa:
a) *Vitellaria paradoxa* parkland after the harvest of a maize field;
b) Agrosilvopastoral relay system including livestock, sorghum field after harvesting in *Vitellaria paradoxa* parkland;
c) Intercropping of maize and groundnut crops with oil palm (*Elaeis guineesis*).

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RÉSUMÉ

Techniques agroforestières à faible coût pour l’atténuation du dérèglement climatique et l’adaptation à celui-ci en Afrique subsaharienne

L’agroforesterie englobe un large éventail de techniques et de pratiques ayant un potentiel pour améliorer la productivité des exploitations agricoles avec un minimum d’impact sur l’environnement, dans le contexte de l’atténuation du dérèglement climatique et de l’adaptation à celui-ci. Notre étude examine la pertinence des techniques et pratiques agroforestières en Afrique subsaharienne (ASS) pour l’atténuation et l’adaptation au dérèglement climatique. Nous avons inventorié 173 ouvrages scientifiques et 62 ont été examinés. Nos résultats indiquent que des techniques accomplies et bien développées sont utilisées dans les systèmes agroforestiers en Afrique subsaharienne. Elles peuvent être classées en quatre groupes principaux (cultures intercalaires, jachères améliorées, paillage et parcs) et sept sous-groupes (cultures de relais, cultures intercalaires de haies, boisements en rotation, jachères en taillis, régénération gérée par les agriculteurs, domestication d’arbres à la ferme par poly-propagation et paillage) en fonction de facteurs tels que l’origine et l’utilisation des arbres et les types d’association arbres-cultures. Notre étude a montré que l’effet positif maximal de l’agroforesterie en mode parc est obtenu lorsque la densité des arbres se situe entre 20 et 40 arbres/ha, puisque nos résultats indiquent une augmentation de la production végétale de 915,9 kg/ha. En outre, dans l’ensemble, la rentabilité du travail pour les techniques utilisant des arbres fertilisants dépasse de 17 % la rentabilité pour les jachères naturelles. Les techniques agroforestières contribuent grandement au programme REDD+, mais les meilleures techniques avec le meilleur rapport coût-bénéfice et un effet conséquent pour l’atténuation et l’adaptation semblent être les systèmes de culture intercalaire et de jachère améliorée. Cependant, nous avons constaté un manque de précision et de détail quant aux coûts économiques, sociaux et environnementaux spécifiques au contexte pour les différentes techniques. Pour que les agriculteurs puissent prendre des décisions utiles et rationnelles dans le cadre de l’adoption de l’agroforesterie, les recherches à venir doivent veiller à détailler les coûts économiques, sociaux et environnementaux de chaque technique dans chaque contexte spécifique.

Mots-clés : agroforesterie, innovation, impact, coût, Afrique subsaharienne.

ABSTRACT

Low-cost agroforestry technologies for climate change mitigation and adaptation in Sub-Saharan Africa: A review

Agroforestry encompasses a large set of techniques and practices that have the potential to improve farm productivity with minimum environmental impacts in the context of climate change mitigation and adaptation (CCMA). In this paper, we discuss the relevance of agroforestry technologies and practices for CCMA in Sub-Saharan Africa (SSA). We recorded 173 scholarly works and reviewed 62. Our findings indicate that comprehensive and well-developed technologies are used in agroforestry systems in SSA. They can be classified into four main groups (intercropping, improved fallows, mulching and parkland) and seven sub-groups (relay cropping, hedgerow intercropping, rotational woodlots, coppicing fallows, farmer-managed regeneration, on-farm tree domestication through poly-propagation and mulching) based on factors including the origins and uses of the trees and the types of tree-crop association. Our review showed that the maximum positive effect of parkland agroforestry is obtained when tree density ranges from 20 to 40 trees/ha, indicating an increase in crop production of 915.9 kg/ha. Furthermore, overall, the returns to labour of techniques involving fertilizer trees outperform those for natural fallows by 17%. Agroforestry techniques contribute substantially to the REDD+ program, but the best techniques with the highest cost-benefit- ratio and a substantial CCMA effect appear to be the intercropping and improved fallow systems. However, we observed a lack of detailed context-specific economic, social and environmental costs for the different techniques. For effective and rational decision-making by farmers in their adoption of agroforestry, further research should focus on filling in the detailed economic, social and environmental costs of each technology in each specific context.

Keywords: agroforestry, innovation, impact, cost, Sub-Saharan Africa.

RESUMEN

Técnicas agroforestales de bajo coste para la mitigación del cambio climático y la adaptación al mismo en el África subsahariana Revisión

La agroforestería engloba un amplio conjunto de técnicas y prácticas que pueden mejorar la productividad de las explotaciones con un impacto medioambiental mínimo en el contexto de la mitigación del cambio climático y la adaptación al mismo (CCMA). En este artículo se analiza la relevancia de las técnicas y prácticas agroforestales para la CCMA en el África subsahariana (SSA). Registramos 173 trabajos académicos y revisamos 62. Nuestras conclusiones indican que en los sistemas agroforestales del SSA se utilizan técnicas completas y bien desarrolladas. Se pueden clasificar en cuatro grupos principales (cultivos intercalados, barbechos mejorados, acolchados y zonas verdes) y siete subgrupos (cultivos rotativos, cultivos intercalados en setos, parcelas forestales rotativas, barbechos de brote de cepa, regeneración gestionada por el agricultor, domesticación de árboles en la explotación mediante polipropagación y acolchado) en función de factores como los orígenes y usos de los árboles y los tipos de asociación árbol-cultivo. Nuestra revisión mostró que el máximo efecto positivo de la agroforestería en zonas verdes se obtiene cuando la densidad de árboles oscila entre 20 y 40 árboles/ha, lo que indica un aumento en la producción de cultivos de 915,9 kg/ha. Además, en conjunto, los rendimientos del trabajo de las técnicas con árboles fertilizantes superan en un 17 % a los de los barbechos naturales. Las técnicas agroforestales contribuyen sustancialmente al programa REDD+, pero las mejores técnicas con el mayor ratio coste-beneficio y un efecto CCMA sustancial parecen ser los sistemas de cultivo intercalado y barbecho mejorado. Sin embargo, observamos una falta de costes económicos, sociales y medioambientales detallados y específicos de cada contexto para las distintas técnicas. Para que los agricultores tomen decisiones eficaces y racionales en su adopción de la agroforestería, la investigación futura debería centrarse en completar los costes económicos, sociales y medioambientales detallados de cada técnica en cada contexto específico.

Palabras clave: agroforestería, innovación, impacto, coste, África subsahariana.

Introduction

Agroforestry is among the common agricultural systems in Sub-Saharan Africa (SSA) supporting more than 500 million people with a wide range of crops and livestock, and diverse cash income-generating activities. It is a system in which trees are sequentially or simultaneously integrated with crops and/or livestock with the intention of developing a more sustainable form of land use that can improve farm productivity (FAO, 2020; ICRAF, 2017; WOCAT, 2020). Yet, its potential contribution to local and national economies is generally under-estimated (Leakey, 2017).

The burgeoning population, land degradation, reduction in land cover that have been exacerbated by climate change have resulted in rapidly declining soil fertility and decreasing yields in agricultural systems of Sub-Saharan Africa. In Sub-Saharan Africa, soil fertility depletion is at alarming level, especially in small-scale land use system (FAO, 2020). Agricultural systems in Africa are particularly vulnerable to climate change because much of crop production is directly dependent on rainfall (Haile, 2005). For example, it was estimated that 89% of cereals in Sub-Saharan Africa are rainfed (Cooper *et al.*, 2008), thereby making climate a key factor in food security (Gregory *et al.*, 2005). Despite the progress made since the World Food Summit 1996, serious food insecurity persists, exacerbated by climate variability effects.

Thus, to maintain an appropriate balance between conservation and productivity, an optimized agroforestry system requires an integrated management with low-cost technologies and practices – maintaining soil fertility, increasing the yield, and household wellbeing with minimum environmental impacts in the context of climate change mitigation and adaptation.

This study, based on a literature review, discusses the relevance of different agroforestry technologies and practices for climate change mitigation and adaptation in Sub-Saharan Africa, with an emphasis on associated costs for biodiversity conservation, improvement of crops productivity, mitigation of environmental challenges and improvement of the wellbeing of the local population. Specifically, it aims to: 1) characterize successful technologies and practices developed in agroforestry for climate change mitigation and adaptation; 2) assess their socioeconomic and environmental impacts; 3) determine two technologies with the lowest economic cost. We aim to answer the following research questions: 1) How successful are agroforestry technologies and practices developed in Sub-Saharan Africa for the mitigation and adaptation to climate change? 2) Does the adoption of agroforestry technologies and practices for climate change mitigation and adaptation depend on the social, environmental, or economic costs of their implementation?

Method

Study area

Sub-Saharan Africa refers to African countries and territories that lie fully or partially south of the Sahara and encompasses four sub-regions mainly delineated based on their climate and vegetation: Eastern Africa, Middle Africa, Southern Africa, and Western Africa (figure 1). Sub-Saharan Africa has a wide variety of climatic zones or biomes with generally a dry winter season and a wet summer season. These include the Sahel (hot semi-arid climate, e.g. Mali, Niger, Chad and Sudan), savannas (West and East Sudanian savannas), tropical rainforests (West and Central Africa), woodlands, savannas, and grasslands mosaics (Eastern Africa), Afromontane forests, grasslands, and shrublands (Eastern Africa), the Western and Southern Congolian forest-savanna mosaic (transition zones between the tropical forests and the miombo woodland belt), the Namib and Kalahari Deserts (South-Western Africa), and the Cape Floristic Region at Africa’s southern tip (subtropical and temperate forests, woodlands, grasslands, and shrublands).

The population of Sub-Saharan Africa was estimated at 1.094 billion in 2020 and projected to double by 2050, reaching 2.118 billion, with a growth rate of 2.65% between 2015-2020 (World Population Prospects, 2019). Countries with the fastest growth rate (> 3%) are mostly from Middle Africa (i.e., Angola, Chad, Democratic Republic of the Congo, and Equatorial Guinea), in contrast to Southern Africa’s countries. In the other sub-regions, Niger (Western Africa), Burundi and Uganda (Eastern Africa) also have a higher growth rate (>3%) than the regional average.

Agriculture in Sub-Saharan Africa represents 15.3% of total Gross Domestic Product (GDP) and employed more than half of the total workforce in 2019 (World Bank, 2020). Most agricultural activity is subsistence farming, making this activity highly vulnerable to climate change. Maize is the most important staple crop across Sub-Saharan Africa, and other important staples include rice (Eastern and Western Africa), potatoes (Eastern and Central Africa), sweet potatoes (Eastern Africa), cassava (Western and Eastern Africa) and plantains (Eastern and Central Africa) (OECD/FAO, 2016). Livestock production systems is also largely extensive, with poultry contributing a substantial share of livestock production value across the entire region (12% in Eastern Africa to 45% in Central Africa and Southern Africa) (OECD/FAO, 2016). Other significant contributions include pasture based ruminant production in semi-arid areas and game meat in Central Africa.

Concept clarification

In this article, the expression “agroforestry technology” is used to designate all the procedures and methods used in agroforestry.

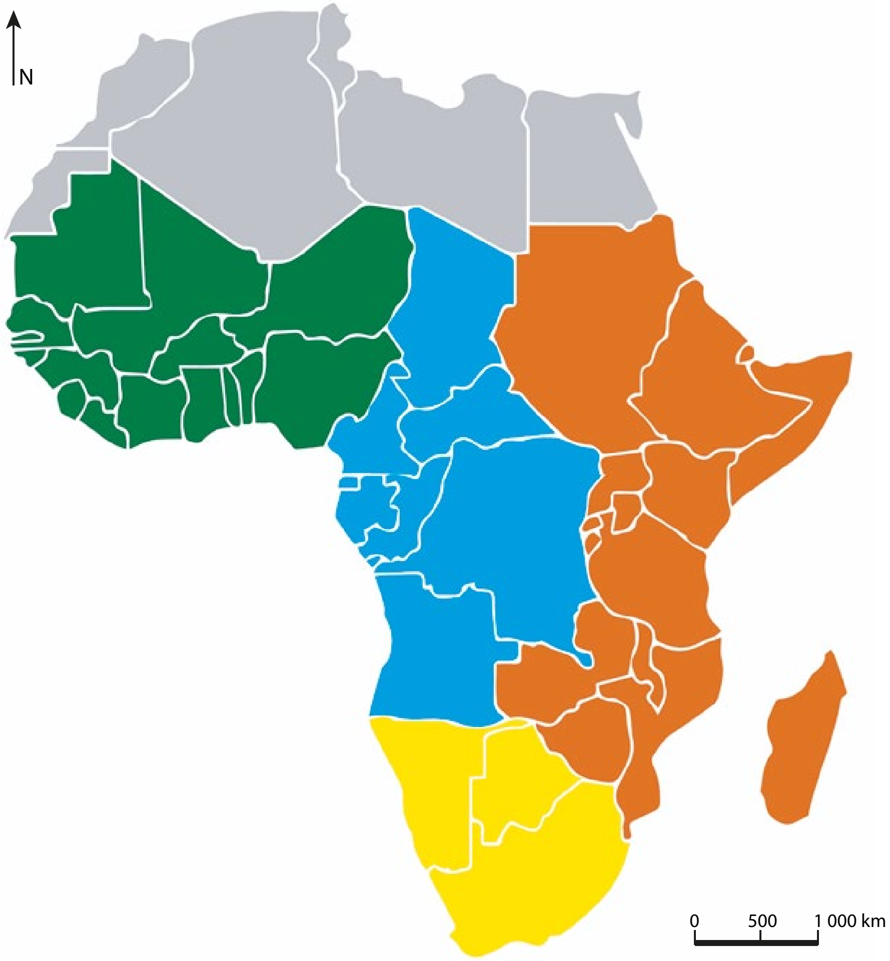

Figure 1.
Geographical map of Sub-Saharan Africa showing the four sub-regions: Eastern Africa (orange), Western Africa (dark green), Middle Africa (blue), and Southern Africa (yellow). Note: The United Nations geoscheme for Africa excludes Sudan from Sub-Saharan Africa, whereas the African Union's definition includes Sudan but instead excludes Mauritania. Both are included in this map. Source: The Statistics Division of the United Nations.

Data collection and analysis

Bibliometric data and publications on Technologies in agroforestry of Sub-Saharan Africa was collected using the Scopus search engine in August 2020. Scopus includes a wide range of journals (Leydesdorff *et al.*, 2010) and represents one of the largest databases on scientific literature (Djalante, 2018). It provides wide-ranging access to bibliographic and citation information (Wraith *et al.*, 2020). The different components of a bibliographic record are authors, author affiliation, keywords, year of publication, and journal in which the document is published (Noyons, 2001). We first searched for relevant publications using a combination of syntax: "Agroforestry technologies" AND "Sub-Saharan Africa" AND "Impact" in their titles, abstracts or keywords, without restriction to the publication period. However, the search results were restricted to publications concerning the 46 members states of Sub-Saharan Africa, written in English or French. Publications that did not relate to agroforestry technologies were excluded. Duplicate files were ultimately removed (Wraith *et al.*, 2020). Results were downloaded in BibTeX format for further processing and analysis. This database was expanded with search results from Google Scholar search engine using the same key words (Halevi *et al.*, 2017; Younger, 2010). All reference lists included in the selected documents were considerate for additional potentially relevant information. The recorded Bibliometric data was analysed using CADIMA tools (Kohl *et al.*, 2018) following three steps: 1) definition of selection criteria, 2) relevant file selection based on the titles, abstract and full text screening, and 3) data extraction from the selected full texts.

We recorded 173 publications (133 and 40 from Scopus and Google Scholar, respectively). We eventually selected 62 for this study, including 72% research articles, 10% books or book chapters and 18% reports (grey literature) from the retrieved literature. The selected literature encompasses the last 28-year period, starting from 1992 to 2020. The majority of the publications (93%) focused on the description of at least one technology, the impact on crop yield and soil fertility replenishment (52%), climate change mitigation and adaptation (25%), and the factors affecting the adoption (11%). Only 5,3% of the publication really addressed the Benefit-Cost Ratio (BCR) of the technologies developed in Sub-Saharan Africa.

The overall finding was synthetized and categorized into characteristics, impacts and successful technologies. The implications for conservation were developed from the analysis of the main finding. Within the characteristic category, we were interested in the description and classification into homogenous groups of the technologies, and tree species commonly involved. Tree species names were updated and confirmed on the platform iNaturalist

(Schmidt *et al.*, 2016). The impacts included environmental effect especially on climate change mitigation and adaptation, social effect and economic value. Available Meta-data were collected from recorded literature to compute a comprehensive graph on the total cost, Net Present Value (NPV), and the BCR of technologies. Because of the lack in detailed information on the economic, social, and environmental costs of each technology regarding specific context, we only focused on comparing the implementation cost and the BCR of the technologies in different context.

In the results of this review, we did not specifically present differences in agroforestry technologies between SSA sub-regions because of the limited number of available studies that meet the inclusion criteria. Thus, despite the differences in terms of climate and vegetation that characterize the four sub-regions of SSA, a consistent trend did not emerge to justify the presentation of the results per sub-region or a comparison between the sub-regions. Instead, we proceeded by grouping agroforestry technologies (see table I) that share alike characteristics across SSA, based primarily on the origin and uses of the tree, and the types of tree-crop association. Such a grouping also defines their social, economic and environmental functions and was guided by the nature of the study research questions.

Results

Technologies in agroforestry systems in Sub-Saharan Africa

The tree-crop combination can be either in temporal rotation or spatial mixture stand. Comprehensive and well described technologies were developed and used in the agroforestry system in SSA (AF-SSA). Despite a great variation in the terminologies, authors agreed on the main content of each technology (Dallimer *et al.*, 2018; Nyasimi *et al.*, 2017; Ouédraogo *et al.*, 2019; WOCAT, 2020). These technologies can be classified into four main groups and seven sub-groups based on factors including the origin of the tree, the objective of its use in the system, the technique of biomass introduction in the crop field and the types of tree-crop association (photos 1, figure 2 and table I).

Table I presents a summary of the main characteristics of the technologies developed and used in agroforestry system of Sub-Saharan Africa (TAF-SSA). Although the tree species used did not greatly vary from one technology to another, they were context specific and related to the main objective of farmers. Thus, an analysis of the available literature clearly identified two groups: leguminous tree species (where the focus is to reclaim degraded land

Table I.
Summary of the main characteristics of the technologies used in Agroforestry systems in Sub-Saharan Africa (TAF-SSA).

Agroforestry technology	**Other terminologies**	**Description**	**Key tree species**	**Authors**
Fertilizer tree system	• Fertilizer tree technologies	Technology using introduced N_2-fixing trees essentially for soil fertility replenishment. It includes: • Intercropping • Improved fallows • Mulching		Toth *et al.*, 2017
Intercropping	• Alley cropping • Hedgerow intercropping	Farming system with crops in alleys formed by leguminous trees to provide mulch and green manure: It includes: • Relay cropping: strip intercropping between tree rows • Hedgerow intercropping: planted hedgerows of widely spaced leguminous tree species with food crops either between the hedges, or around the edges. Trees are regularly coppiced at about 0.75 m above ground to reduce below ground competition and shading	• *Gliricidia sepium* (Jacq.) Walp. • *Leucaena leucocephala* (Lam.) de Wit • *Elaeis guineensis* Jacq. • *Senna siamea* (Lam.) Erwin and Barneby • *Acacia auriculiformis* A. Cunn. ex Benth. • *Acacia mangium* Willd. • *Acacia tumida* Benth. • *Albizia lebbeck* (L.) Benth. • Fruit trees (cocoa, coffee)	Kang, 1997; Kant *et al.*, 2012; Mafongoya *et al.*, 2006; Nyasimi *et al.*, 2017; Vaast and Somarriba, 2014
Improved fallow	• Improved bush fallow system • Sequential tree fallow	Involve deliberately planted tree/shrub species – usually legumes – as integral components in a crop-fallow rotation (of two years for example). Usually called by the tree used, (Example: "*Gliricidia fallows*"). It includes: • Rotational woodlots: involves non-coppicing leguminous tree species • Coppicing fallow: involves leguminous tree species capable of re-sprout when cut back at the end of the fallow period	• *Gliricidia sepium* • *Sesbania sesban* (L.) Merr. • *Tephrosia Vogelii* Hook. f. • *Tephrosia candida* DC. • *Cajanus cajan* (L.) Millsp. • *Calliandra calothyrsus* Meissner • *Senna siamea*	Mafongoya *et al.*, 2006; Partey *et al.*, 2017a; Swamila *et al.*, 2020
Mulching	• Biomass transfer	Consists of incorporating a range of plant materials, a layer of biomass (dry or wet leguminous tree leaves) to the ground to stimulate the activity of soil biota to improve soil fertility	• *Gliricidia sepium* • *Leucaena leucocephala* • *Acacia tumida*	Bayala *et al.*, 2011; Ibrahim *et al.*, 2015
Parkland	• Conservation agriculture • Fodder tree technology • Evergreen agriculture	An anthropogenic vegetation assemblage derived from slow process of indigenous trees selection and density management by farmers. It includes: • Farmers manage regeneration • On farm tree domestication through poly-propagation	• *Adansonia digitata* L. • *Borassus aethiopum* Mart. • *Faidherbia albida* (Del.) Chev. • *Hyphaene thebaica* (L.) Mart. • *Lannea microcarpa* Engl. & K. Krause • *Parkia biglobosa* (Jacq.) R. Br. ex G. Don • *Pterocarpus erinaceus* Poir. • *Pterocarpus lucens* Lepr. ex Guill. & Perr. • *Sclerocarya birrea* (A. Rich.) Hochst. • *Tamarindus indica* L. • *Vitellaria paradoxa* C. F Gaertn. • *Ziziphus mauritiana* Lam.	Bayala *et al.*, 2011; FAO, 2020; Maranz, 2009

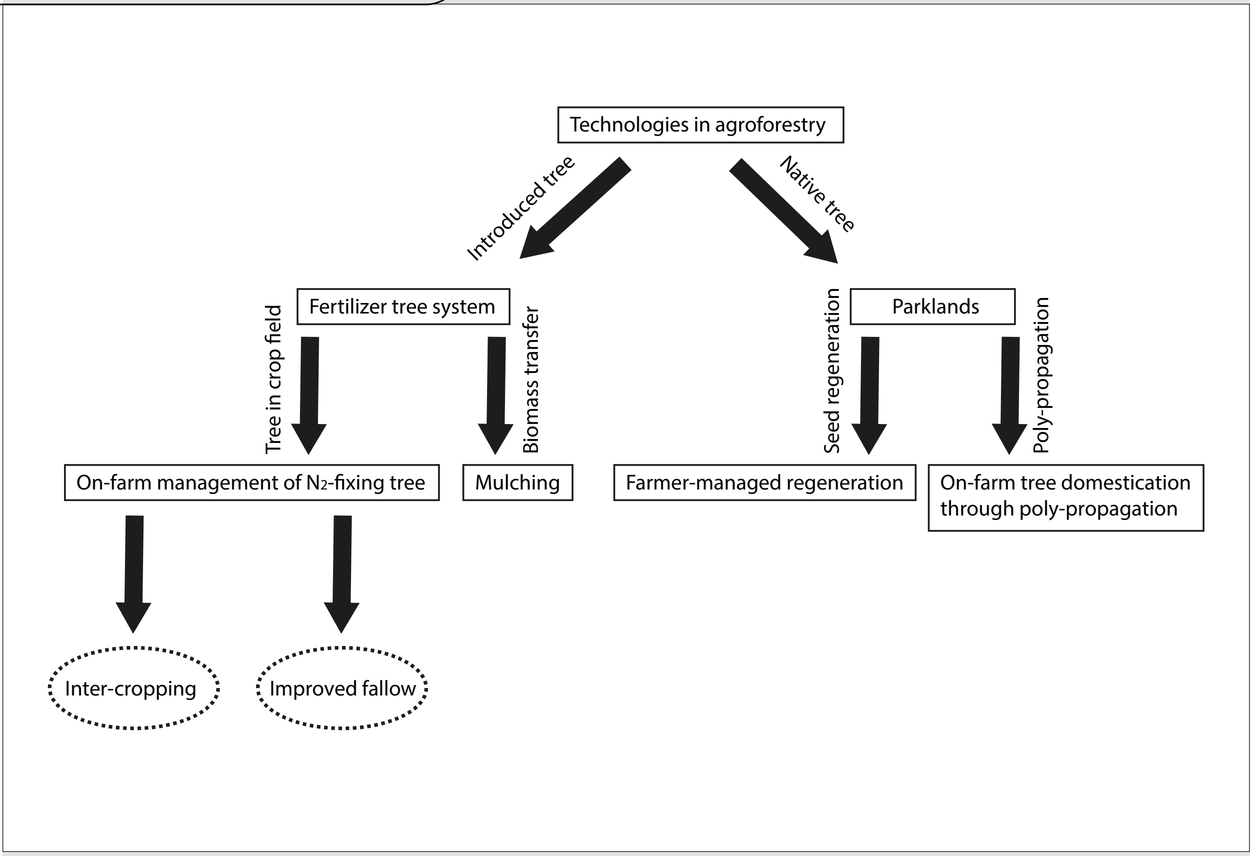

Figure 2.
Classification of the technologies used in agroforestry systems in Sub-Saharan Africa.

through replenishment of soil fertility) and multipurpose tree species, mainly indigenous tree species purposely left in the field by farmers. The focus in the latter is to provide farmers with food, additional income, fuelwood, etc. (Binam *et al.*, 2017; Swamila *et al.*, 2020).

Impacts of technologies and innovative agroforestry systems

Social impact

The trade-off between agroforestry practices and impacts often revolves around social benefits. For instance, a combination of chemical fertilizers with improved fallows was the most socially profitable technology (Maithya *et al.*, 2006). One clear observation from the production systems in Sub-Saharan Africa is that agroforestry with indigenous fruit trees enhanced both better diet and health of the local population, while improving farmers' knowledge and capacity of practicing and managing local diversity (Tchoundjeu *et al.*, 2010). The social benefits that accrue from the usage of the eco-garden system include the improvement in the local livelihoods through its potential to support diets by providing food and nutrition security and reducing poverty by creating employment opportunities (Materechera and Swanepol, 2013; Nyasimi *et al.*, 2017; Partey *et al.*, 2017b). An analysis of survey results in West Africa showed that after the threshold of 20 trees/ha, an increase in the number of trees kept and managed on farms may increase the food consumption score (Binam *et al.*, 2017). However, there have also been several negative impacts derived from agroforestry systems. A conflict was observed between herders and farmers with the establishment of trees on cultivated lands. Fields that hitherto were "common property" and on which livestock would freely graze became more privatized. Thus, fodder previously available for livestock especially in dry season became limited requiring extra labour in herding animals (Ajayi *et al.*, 2011).

Economic impact

Agroforestry through its economic value could be seen as a means of improving farmers' livelihoods (Materechera and Swanepol, 2013). Economic analysis of pigeon peas (*Cajanus cajan*) fallows and *Gliricidia sepium* (gliricidia) fallows over six years in West Africa showed the profitability of the technology compared to natural fallows (Swamila *et al.*, 2020). The technology clearly increases the maize and groundnut yield by 200% and 350%, respectively. Globally, the returns to labour in fertilizer tree technologies outperform (17%) those in natural fallow (Degrande, 2001). In the Sahel, there is an optimal number of trees to be kept on the farm. The maximum positive effect is obtained when tree density ranges from 20 to 40/ha, indicating an increase of crop production by 915.9 kg/ha (Binam *et al.*, 2017). In a condition of water shortage, *Sesbania sesban* (sesbania) fallow increased grain yield and dry matter production of subsequent maize per unit amount of water used. The average maize grain yields in sesbania fallow, and in continuous maize cropping without fertilizer were 3, and 1 Mg/ha with corresponding water use efficiencies of 4.3 and 1.7 kg/mm/ha, respectively (Phiri *et al.*, 2003). Total yield after two-year sesbania fallow in four cropping seasons was 12.8 t/ha compared to 7.6 t/ha for six seasons of continuous unfertilized maize (Partey *et al.*, 2017a).

The maize yield in tree-based systems is up to double (29 to 113%) in the first three years (Chirwa *et al.*, 2003; Nyadzi *et al.*, 2003). In agrosilvopastoral relay system, several studies especially in East Africa have confirmed that shrubs have an impact on milk production. The overall impact of the woodlot in terms of additional net income from milk was reported to be high, at US$ 19.7 to US$ 29.6 million over 15 years (Place *et al.*, 2009). There is evidence that an agroforestry system also provides off-farm incomes from the marketing of agroforestry tree products such as non-timber forest products, fuelwood and fodder for livestock, compared with subsistence agriculture (Binam *et al.*, 2017; Dallimer *et al.*, 2018; Nyasimi *et al.*, 2017; Ouédraogo *et al.*, 2019; Thorlakson and Neufeldt, 2012). An optimum of 40 trees/ha is recommended in the Sahel (Binam *et al.*, 2017). The domestication of a local fruit tree can provide an average household income of US$ 242 a year for farmers in East Africa (Kalaba *et al.*, 2010; Tchoundjeu *et al.*, 2010). Selling of *Adansonia digitata* in Burkina Faso can generate up to US$ 300 in three months for farmers engaged in agroforestry (Sawadogo, 2011).

Table II.
Percentage in soil organic carbon (SOC) and nitrogen (N) in various tree-based technologies in Sub-Saharan Africa.

Variable	Technology	Percentage (%)	95% confidence intervals	
			Lower	Upper
SOC	Alley cropping	20.6	6.8	34.4
	Fallow	22.8	8.6	37.1
	Mulching	39.5	20.7	8.2
	Parkland	35.5	25.1	45.9
Nitrogen	Alley cropping	32.1	8.6	55.5
	Fallow	15.3	12.1	42.7
	Mulching	32.4	4.8	60.0
	Parkland	35.5	17.2	53.8

SOC: Soil Organic Carbon. Adapted from Bayala *et al.* (2018).

Environmental impact

Environmental benefit reported from tree on farm varied with the technology (including both tree species and density). Generally, farms under agroforestry technology are more protected against severe wind and drought and are resilient to climatic variability (Kimaro *et al.*, 2016, 2019). In Tanzania, gliricidia agroforestry technology is reported to improve soil fertility, moisture retention and control soil erosion (Ouédraogo *et al.*, 2019; Swamila *et al.*, 2020). In the 2017 drought, farmers engaged in gliricidia agroforestry saved up to 75% of their crop yields (Kimaro *et al.*, 2016, 2019). Trees in parklands contribute to soil organic carbon (SOC) and carbon sequestration via photosynthesis while increasing soil fertility, air humidity and the reduction of greenhouse gas (GHG) emissions. These were demonstrated in findings of more than 100 peer-reviewed research studies on the intercropping and improved fallow with nitrogen-fixing green fertilizers, including trees and shrubs (Bayala *et al.*, 2018, 2014; Cheesman *et al.*, 2016; Partey *et al.*, 2017b; Thierfelder *et al.*, 2017). The SOC increased in the AF technologies with the best results from mulching and parkland (table II). In fact, AF has been recognized by IPCC as an important component in climate change mitigation (GIEC, 2007). Conservation Agriculture including tree-based cropping can contribute to 1.3-6.4 GtCO2-eq/year by 2030 (Pachauri and Reisinger, 2007).

In most parts of SSA, agroforestry acts as a viable alternative to inorganic fertilizers in improving soil fertility. The residual effect from a short duration of improved fallow may last one to two seasons, but the effect of an eight-month fallow can last for one or more seasons, depending on the level of degradation of the soil (Amadalo *et al.*, 2003). A well-managed improved fallow system may contribute between 100 kg N/ha/year and 200 kg N/ha/year (Amadalo *et al.*, 2003). Under nutrient poor conditions, total N and SOC increased by 6–14 kg/ha/year and 2.6-194 kg/ha/year respectively (Masikati *et al.*, 2014).

Successful and low-cost agroforestry technologies for climate change mitigation and adaptation

The success of a cropping technology is evident from its adoption by farmers, and the adoption is context and site-specific. In general, the uptake of technologies is more complicated than that of annual crops (Mercer, 2004) because of the multi-components shaping farmers' decision. Despite the variety in factors determining farmers' engagement, three major constraints were highlighted to influence a rational decision-making of farmers for whatever the technology is in AF-SSA (Swamila *et al.*, 2020):

- the shift in productivity,
- the increase in profit,
- the learnability and input accessibility.

There have been few studies that focused on assessing the economic aspect of using a tree-based technology in AF-SSA. Factors affecting the adoption (including the

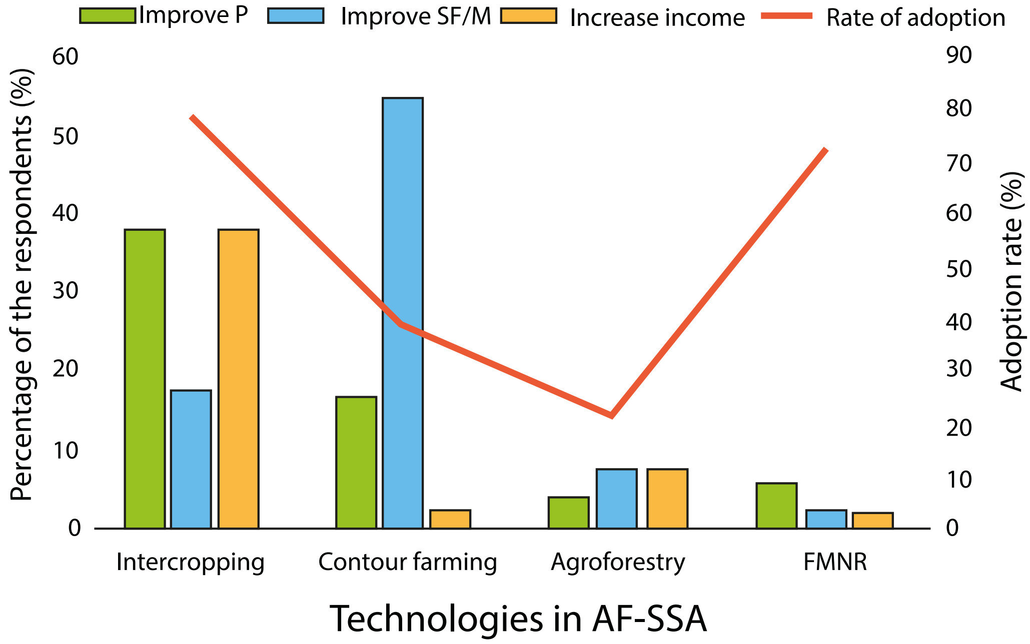

Figure 3.
Adoption rate and factor affecting the adoption of the most successful technologies in agroforestry system to mitigate climate change effects. AF-SSA: Agroforestry in Sub-Saharan Africa. Improv P: Improve productivity; Improve SF/M: Improve Soil Fertility/Moisture; FMNR: Farmer Managed Natural Regeneration. Adapted from Ouédraogo *et al.* (2019).

assessment of the cost of various inputs) of developed technologies in AF-SSA were mainly assessed through local perception. From farmers' perception, these factors vary with the technology. The figure 3 shows that soil fertility replenishment is the main factor determining the adoption of contour farming, while improving the yield and farmers income are the determinant factors for intercropping adoption. The adoption rate of the technologies decreases from the intercropping to the agroforestry (which recorded the best adoption rate), then rise to Farmer Managed Natural Regeneration.

Likewise, the social impacts of a technology are not always estimated by existing studies, though more valued sometimes by farmers. Despite the increasing positive agroecological impacts of technologies in AF-SSA, their adoption has been dismally low across all sub-Saharan African because of the sensitiveness of trialability (Mafongoya *et al.*, 2006). In general, tree-based agroforestry technologies are more negatively affected by land tenure, one of the major issues affecting agriculture in SSA (Bambio and Agha, 2018; Lawin and Tamini, 2019). Nevertheless, improved adoption rate of agri-environmental practices for climate change mitigation in the southern and western Africa were reported because of the participatory approach used (Akinnifesi *et al.*, 2008; Ouédraogo *et al.*, 2019). Intercropping (especially with *Gliricidia sepium, Sesbania sesban* and *Maesopsis eminii* intercropping) and improved fallows were reported with the best result both in productivity (figure 4), climate mitigation, and adoption rate (figure 3) in the SSA irrespective of the local specific conditions (Corbeels *et al.*, 2019; Haider *et al.*, 2018; Kaba *et al.*, 2017, 2019; Kaba and Abunyewa, 2021; Sileshi *et al.*, 2020; Swamila *et al.*, 2020).

Implications for sustainable agroforestry under climate change

The concept of sustainability applies to a wide range of human activities, and particularly to agriculture because of its capacity to contribute to the development and its substantial impact on the environment. It refers to a system in which the needs of the present are met without compromising the ability of future generations to meet their own needs, with reference to the environment, economic and social domains. Thus, sustainable agriculture involves the production of goods and services (economic function), the management of natural resources (ecological function) and the contribution to rural dynamics (social function) (Latruffe *et al.*, 2016). Sometimes, political sustainability is added as a fourth dimension of sustainability to capture aspects related to governance, law and justice, communication, and ethics, etc. Sustainability is also occasionally assessed through the lens of viability (i.e., the capacity to survive in the long term) and durability (the capacity to be transferred across generations) (Latruffe *et al.*, 2016).

To understand the potential contribution of agroforestry to a sustainable development in SSA, it is important to recall its connection with climate change. The adverse

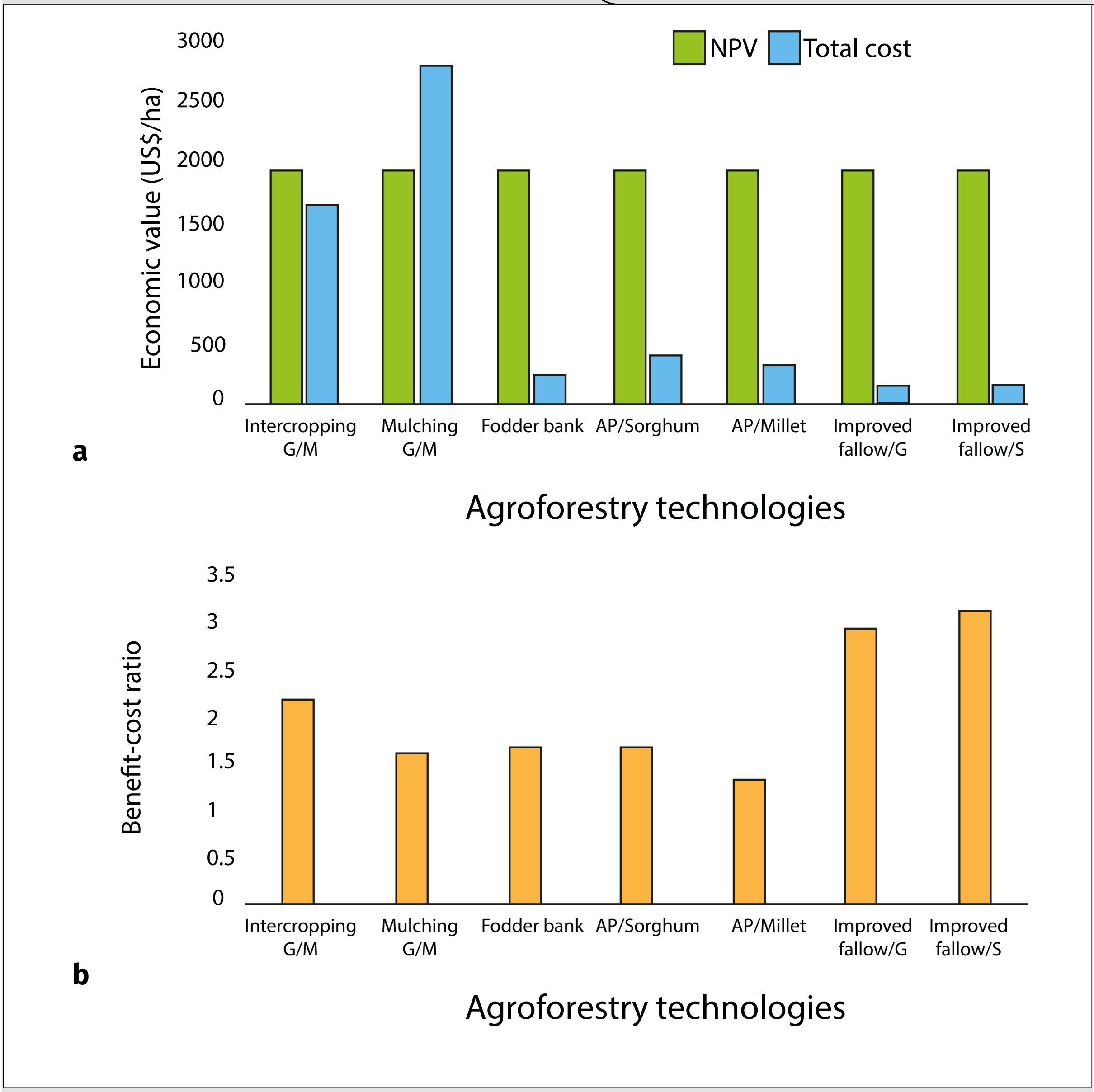

Figure 4.
Economic analysis of agroforestry technologies: a) NPV and Total Cost; b) Benefit-Cost Ratio. NPV: Net Present Value; G: *Gliricidia sepium*; S: *Sesbania sesban*; M: Maize; AP: Agroforestry Parkland. Adapted from Ajayi *et al.*, 2005; Fahmi *et al.*, 2018; Rao and Mathuva, 2000; Takimoto *et al.*, 2008.

effects of climate change are the modifications of the physical environment or the biota (as a result of changes in the physical environment), which can have significant harmful effects on the composition, resistance or productivity of natural and managed ecosystems, and on the functioning of social and economic systems, or on human health and well-being (CCNUC, 1992). GIEC (2007) warned that, beyond the climate itself, the consequences of climate change are more complex and include for example: a possible extinction of 20 to 30% of animal and plant species if the temperature rises by more than 2.5 °C, and of more than 40% of species for a warming greater than 4 °C. This would have important consequences for societies, including conflicts and migrations linked to food crises, health hazards, and environmental hazards. In such a context, to increase agricultural productivity (at least in the short run), farmers might turn either to shifting cultivation or to very intensive agricultural practices, including the application of mineral fertilizers, pesticides, insecticides, and herbicides at higher rates than ever. In the long run, these practices would be detrimental to the soil and crop productivity.

Agroforestry can contribute substantially to a sustainable development in SSA through its capacity to increase yields and food consumption, provide off-farm incomes from the marketing of agroforestry tree products, reduce communities' dependence on forests, build resilience to climatic variability, protect against environmental hazards (e.g. severe wind, drought, soil erosion) and contribute to climate change mitigation through carbon sequestration (Partey *et al.,* 2017a). Yet, because agroforestry practices were primarily designed for improving soil productivity and soil protection, social and other economic aspects are not always estimated by existing studies in contrast to environmental impacts (e.g. nutrients dynamics, carbon sequestration, etc.). Social impacts of a technology could include for example: education, working conditions (working time and workload, including pain), and quality of life or well-being (Partey *et al.,* 2017a), more valued sometimes by farmers. Even for environmental sustainability, Leakey (2017) criticized the current view of agroforestry as "a set of distinct prescriptions for land use" and recommended instead the integration of various agroforestry practices into a landscape, with increasing scale, so as to maximize benefits from the formation of a complex mosaic of patches that "farmers can manipulate and manage".

Despite its potentials for a sustainable development, large-scale landscape adoption of agroforestry is relatively low (Partey *et al.,* 2017a) due to several constraints. Firstly, owing to their tree component, agroforestry technologies are generally more negatively affected by land tenure, which is far from secure in many SSA countries (Bambio and Agha, 2018). Secondly, a conflictive environment was developed because a freely graze areas became more privatized. Thirdly, farmers' livelihood priorities are prone to frequent shifts because of the challenges and opportunities brought about constantly by modernization and growing resource needs. Finally, the accessibility (costs, inputs, learnability, etc.) of the technologies can be a major constraint in the adoption and upscaling of agroforestry technologies. All these challenges are exacerbated by the increasing human population in SSA, projected to double by 2050 with subsequent food demand (Tabutin *et al.,* 2020). The increase of population has implications on food security resulting in agricultural expansion with more farmlands. The immediate consequence is usually removal of trees from farmlands along with agriculture intensification and/or agriculture expansion into non-agricultural lands. However, at country level, a large-scale adoption of agroforestry technology and practices can still provide food security and mitigate ecological challenges (Kiyani *et al.* 2017; Jahan *et al.,* 2022). In order for agroforestry to fully contribute in the attainment of Sustainable Development Goals (SDGs), and help in climate change mitigation and adaptation in SSA, future research and development efforts should address the constraints of population growth, new agroforestry technologies development, and their adoption.

Additionally, a clear differentiation in developed technologies across SSA defined by sub-regions with associated socioeconomic emphasis could not be established from this review. It is worth noting that many forms of agroforestry are practiced in SSA, associated with a great variety of climatic conditions and land-use options. These agroforestry technologies are also characterized by a wide variability in tree species, density, temporal and spatial organization, as well as management practices (Unruh *et al.,* 1993). Analyzing such differences would inevitably require more data that are not readily available across SSA. Besides, similarities exist in the needs, uses and main drivers of change in woodland resources by local populations across SSA (Assèdé *et al.,* 2020). Still, a fine scale analysis of the differences in agroforestry technologies between SSA sub-regions could be addressed in future studies so as to provide more context specific and tailored recommendations for the successful development of agroforestry in SSA.

Conclusions

Technologies developed and used in the agroforestry system in Sub-Saharan Africa (AF-SSA) can be classified into four main groups and seven sub-groups based on factors including the farmers' objective, the biomass introduction technique in the crop field and the tree-crop association types. In parkland agroforests, indigenous fruit trees enhanced both diet, health, with an average household income of US$ 242 a year in East Africa. Globally, the returns to labour in fertilizer tree technologies outperform (17%) those in natural fallows. The maize yield in tree-based systems is up to double (29 to 113%) in the first three years. A well-managed improved fallow system may contribute between 100 kg N/ha/year and 200 kg N/ha/year. However, the best agroforestry technologies with the highest benefit-cost ratio associated with climate change mitigation effects in Sub-Saharan Africa would be the intercropping and improved fallows systems. Up-front investment and frequent shift in farmers' priorities can be a real barrier to the adoption of certain AF-SSA. Further research should focus on filling the gap in detailed economic social and environmental costs of each technology regarding specific context for effective rational decision-making by farmers in the adoption of AF-SSA.

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