Potentials of bamboo-based agroforestry for sustainable development in Sub-Saharan Africa

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Potentials of bamboo-based agroforestry for sustainable development in Sub-Saharan Africa: a review

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Abstract:	There is widespread assertion among scientists, government and development experts that bamboo agroforestry could contribute to sustainable rural development in sub-Saharan Africa (SSA). However, there is limited available data to verify the suitability of the system in the region. In addition, the current state of knowledge and adoption of agroforestry in SSA offers very little guidance as to which type of agroforestry systems bamboo could be integrated. Here, we reviewed the potential socioeconomic and environmental benefits of bamboo agroforestry and accentuate implications on sustainable rural development in SSA. In addition, we analysed potential research areas that could be intensified, so that future developments and scaling-up of bamboo agroforestry can be rooted in robust scientific findings rather than the intuitions of governments and development actors.
Response to Reviewers:	Please see attachment

International Network for Bamboo and Rattan (INBAR)
Kumasi
Ghana
7th October 2016

Editor in Chief
Agricultural Research

Dear Sir or Madam

Response to review Comments on AGRI-D-16-00177: Bamboo agroforestry for sustainable development in sub-Saharan Africa: review of potentials and research needs

We have considered the rather minor concerns of the two anonymous reviewers and revised our manuscript accordingly. The revised sections and additions have been highlighted in yellow in the main manuscript. In the below table, we also provide responses to the most applicable comments.

Reviewer	Comment	Response
1	The title may be revised to, "Potentials of bamboo-based agroforestry for sustainable development in sub-Saharan Africa: a review"	Agreed! Title of the paper duly revised
1	Section 2, Agroforestry-general overview and development in SSA is unwarranted as this has nothing to do with bamboo-agroforestry. It must be deleted.	Agreed! Section 2 removed
1	In the text there remain many grammatical mistakes, which must be taken care of while revising the manuscript. For example, line 25-there must be comma (,) after word vegetation; on the same page line 30, portion (the yellow type) must not be italic; same is true with word and when used between species at many places; in line 30, shift word and after word strictus	Revised as suggested. Revision highlighted in yellow.
1	At many places, two synonyms of same species are used using word or in between, keep one only. For example, page 7 line 28 and page 11, line 60 plant cited as Bambusa bambos or B. arundinacea; these are synonym, keep the 1st and delete the 2nd. It is true with many other species also.	Revised as suggested. Revision highlighted in yellow.
1	While mentioning many species together as is the case on page 7, need not to mention full generic name for time and again for each species of the same genus, rather club these species together. For example, all species of Dendrocalamus in this paragraph may be written as Dendrocalamus brandisii, D. latiflorus, D. membrenaceous, D. strictus and so on; similarly, Bambusa edulis, B. oldhanmii, B. textilis, and so on…	Revised as suggested. Revision highlighted in yellow.
1	Page 8, instead of writing long figure US$ 133,650,000 it may be mentioned as US$ 133.65 million	Revised as suggested. Revision highlighted in yellow.

1	Page 9, line 5, use sub-script in CO2 mentioning as CO_2	Revised as suggested. Revision highlighted in yellow.
1	Other general formatting issues	These have been duly corrected
2	The manuscript is very general one in nature about the scope of bamboo agroforestry in sub Saharan Africa. It does not include anything about the productivity potential, economic returns to the farmers, rotation age, bamboo crop interactions. The paper simply mention about some bamboo species introduction in the region. The productivity potential and returns to the farmers needs to be mentioned.	Literature on bamboo agroforestry is limited. We have included section 3.5 that discusses the potential contributions of bamboo agroforestry to poverty reduction. This should address the weakness of the paper in addressing the potential economic returns to the farmer. In this same section, we highlighted areas that may also require investment from the farmer and also contributions to food security and nutrition in sub-Saharan Africa (SSA). Section 2 is also improved to include aspects of bamboo productivity and rotation cycle.

We hope the concerns of the reviewers are duly addressed.

Thank you.

Yours faithfully

Signed

Samuel T. Partey, PhD
Corresponding author

Potentials of bamboo-based agroforestry for sustainable development in Sub-Saharan Africa: a review

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Abstract

There is widespread assertion among scientists, government and development experts that bamboo agroforestry could contribute to sustainable rural development in sub-Saharan Africa (SSA). However, there is limited available data to verify the suitability of the system in the region. In addition, the current state of knowledge and adoption of agroforestry in SSA offers very little guidance as to which type of agroforestry systems bamboo could be integrated. Here, we reviewed the potential socioeconomic and environmental benefits of bamboo agroforestry and accentuate implications on sustainable rural development in SSA. In addition, we analysed potential research areas that could be intensified, so that future developments and scaling-up of bamboo agroforestry can be rooted in robust scientific findings rather than the intuitions of governments and development actors.

Keywords: agroforestry, deforestation, land use systems, ecosystem services, bamboo, sustainability, Africa

1. Introduction

Agriculture is the mainstay of most national economies of sub-Saharan Africa (SSA) and its development has significant implications on food security and poverty reduction as highlighted in the United Nation's Sustainable Development Goals (SDGs). One focus of the SDGs is enhancing global agriculture to meet the food security needs of ever increasing population [13]. This is particularly critical in developing countries where food production is not keeping pace with increasing population [46, 50]. Although an economic booster, improvements in SSA's agriculture sector are increasingly hampered by land tenure issues, declining soil fertility, poor markets, inadequate funding and poor infrastructural development [25, 63]. Moreover, these challenges are expected to be further exacerbated by climate change which has emerged as one of the major threats to development in Africa and its agriculture sector [15, 38]. Furthermore, SSA's quest to meet the SDGs will equally be challenged in years to come as its growing human population will inevitably lead to catastrophic consequences particularly in relation to ecosystem degradation, declining agricultural productivity, and changing environment [68, 74]. In order to sustainably develop in the future, it is essential to find solutions to these problems, particularly with regard to ensuring food security and coping with the changing environment [8]. Recent advances in global agricultural research have been focusing on the questions of increasing the resilience (against drought, erosion, fertility loss, etc.) and productivity of agricultural systems, which are directly related to increasing the adaptive capacity of farmers. The concept of climate-smart agriculture (CSA) dwells on this development agenda and aims at fostering the development and implementation of agriculture innovations that (1) sustainably increases agricultural productivity to support equitable increases in incomes, food security and development; (2) adapts and builds resilience to climate change from the farm to national levels; and (3) develops opportunities to reduce greenhouse gas emissions from agriculture compared with past trends [18, 31]. Research shows that agroforestry (a landuse system that combines trees/shrubs and other perennials with crops and/or animals) can contribute substantially in this direction through its multiple benefits and ecosystem services. According to Verchot et al. [78] agroforestry provides a set of innovative practices that are designed to enhance productivity in a way that often contributes to climate change mitigation through enhanced carbon sequestration, and also strengthen the system's ability to cope with adverse impacts of changing climate conditions [11, 20, 34]. In addition, agroforestry options may provide a means for diversifying production systems and increasing the 'sustainagility' (allowing farmer's agility to continue) of smallholder farming systems [20].

In SSA, bamboo resources constitute one of the largest non-timber forests products identified to be a suitable complement to timber usages such as building and construction, pulpwood, flooring, panel products and furniture [48, 62]. In comparison with forest timber species, bamboo has a short gestation period of five years and has huge range of socio-economic and environmental benefits [37]. In many parts of SSA, bamboo is currently being promoted for forest plantation developments to reduce the natural forests for timber and wood fuels [33, 52, 83]. However, sscientists will agree that sole bamboo plantation developments may impact negatively on food security except they are arguably established on degraded lands. This makes the integration of bamboo into indigenous cropping systems (via agroforestry) agronomically interesting and necessary to meet both socioeconomic and environmental needs. While experiences from Asia and other countries demonstrate that the integration of bamboo within agricultural systems is a suitable approach for increased productivity of food crops and non-food biomass [55, 56], there is limited available data to verify the suitability of the technology in SSA (and Africa in general) and elucidate the ecological principles by which the system works. In addition, the current state of knowledge on bamboo agroforestry offers very little guidance as to how investments into the land use system may contribute to sustainable rural development in SSA. Here, we reviewed the potential socioeconomic and environmental benefits of bamboo agroforestry and accentuate implications on sustainable development in SSA. In addition, we analysed potential research areas that could be intensified, so that future developments and scaling-up of bamboo agroforestry can be rooted in robust scientific findings rather than the intuitions of governments and development actors.

2. Bamboo resources and utilization in SSA

Bamboos are fast-growing woody grasses belonging to the grass family Gramineae and sub-family Bambusoideae [22]. Bamboos grow mostly in the tropics and subtropics in mixed forests or as pure stands, and are cultivated in plantations, on homesteads and on farms [37] with a total area of covering 31.5 million hectares globally, thus accounting for about 0.8 percent of the world's total forest area in 2010 [21]. There are over 1,500 bamboo species recorded worldwide, ranging in height from a few inches (cm) to over 100 ft (30 m), with stem (culm) diameters of 1/8 inch (3 mm) to over 10 inches (25 cm). In SSA, over 3 million hectares of bamboo forest was reported for seven countries (Ethiopia, Kenya, Ghana, Nigeria, Uganda, the United Republic of Tanzania and Zimbabwe) [45]. In Ethiopia, Nigeria and Ghana, bamboo covers about 6.5%, 14% and 5% their total forest vegetation respectively [45, 59]. Common bamboo species in SSA include: *Arundinaria alpine*, *Bambusa multiplex*, *B. vulgaris*, *B. bambos*, *B. pervariabilis*, *B. vulgaris var vitata* (the yellow type), *Oxythenanthera abyssinica*, *Dendrocalamus strictus* and *Oxytenanthera braunii*. Although most bamboo resources grow naturally, greater attention has been paid in recent years to the establishment of planted bamboo. In most of SSA, planted bamboo is generally established to provide raw material and to avoid depletion of naturally regenerated stands. Some of the planted bamboos are introduced species from Asia. In Ghana about eighteen foreign bamboo species were introduced from Asia by the Forestry Commission. These include: *Gigantochloa albociliata*, *Bambusa edulis*, *Dendrocalamus brandisii*, *B. oldhanmii*, *D. asper*, *Guadua angustifolia*, *D. strictus*, *G. chacoensis*, *D. membrenaceus*, *Thyrosostachis siamensis*, *D. latiflorus*, *B. textilis*, *B. ventricosa*, *and B. burmanica* [22]. In Kenya, over 20 bamboo species including: *B. brandisii*, *B. vulgaris* var. *striata*, *B. arundinacea*, *B. tulda*, *D.*

membranaceus, *D. strictus*, *D. brandisii*, *D. asper*, *O. abyssinica*, *Phyllostachys heterocycla* var. *pubescens* and *Thyrsostachys siamensis* were introduced from Asia [61]. Several uses of bamboo are identified in SSA but in contrast with exploitation and utilization of many timber species it remains one of the region's valuable under-utilized resources [54]. Bamboo production is a major source of livelihood for several millions in SSA and remains an important part of small to medium enterprises that deals in crafts and charcoal production [16]. It is an important raw material for building construction [48, 62] and has been used as substrate for the African catfish, *Clarias gariepinus* [4] and the construction of bicycle frames [3] in Ghana. Bamboo leaves reportedly have antibiotic properties and is good medicine for curing fever [59]. Biomass productivity of bamboo varies based on ecologies, bamboo species, age and management. In most of SSA, the total dry matter production of a 4-year bamboo under optimum condition ranges from 80 to 120 Mg ha^{-1} yr^{-1} with a rotation cycle of 3-4 years [59].

3. How could SSA benefit from bamboo agroforestry?

The definition of agroforestry by Leakey [44] demonstrates a key feature of agroforestry as a land use system that is designed to meet both environmental and socioeconomic needs for land users at all levels. However, the achievement of such socioeconomic and environmental benefits is normally dependent on the woody component which is the most integral of agroforestry systems. Below, we analyze certain socioeconomic and ecological needs in SSA which could be met through bamboo agroforestry.

3.1 The deforestation menace and increased household energy needs

Roughly 2.8 billion people worldwide, including the world's poorest and most marginalized burn wood to satisfy their basic energy needs [7]. Historically, most rural households in SSA hugely depend on wood fuels to meet their household energy needs. Statistically, 81% (about 653 million people) of SSA's population rely on traditional biomass fuels for cooking and heating which is even projected to increase to 720 million in 2030 [79]. Besides the conversion of forest lands into farmlands and bush fires, available literature points to fuelwood consumption as one major anthropogenic cause of deforestation in SSA [19]. In countries such as Ghana, rated among the top one percent of West African countries with high consumption and demand for wood, the country is set to lose a gross revenue of US$133.65 million equivalent to 2.6% of its 2008 agricultural sector Gross Domestic Product due to forest loss [14]. It is projected that increased degradation of forest resources due to fuelwood consumption and charcoal production could have catastrophic consequences on many national economies of SSA and forest fringe communities who derive their livelihoods from non-timber forest products [29, 35]. In addition, the limited electrification of many regions of SSA is expected to have serious demand implications on the region's wood fuel resource base, which is already threatened by the high deforestation rate [2]. The International Network for Bamboo and

Rattan (INBAR) has demonstrated that using bamboo to make charcoal can take pressure off other forest resources and avoid deforestation. Bamboo's characteristics of fast growth and high renewability make it an efficient and renewable substitute resource for charcoal production. With a calorific value (6959 cal g^{-1}) comparable to that of wood and almost half that of petroleum by weight, bamboo charcoal produces fewer pollutants than either and reportedly lasts longer [37]. In most countries in SSA, sustainable forest management has been made a priority, and government and scientists are now advocating the use of bamboo to reduce pressure on major commercial timber species sometimes sourced for household energy needs. With about 30% yield rate, SSA has a strong potential to produce about 9 million tons of bamboo charcoal on a sustainable basis which could potentially replace 64% of the region's wood consumption for charcoal production [59].

3.2 Contribution to climate change mitigation through carbon sequestration

Agricultural fields remain one of the major contributors to greenhouse gas emissions. Statistical information provided by Smith et al. [71] showed that agriculture accounted for an estimated emission of 5.1 to 6.1 $GtCO_2$-eq yr^{-1} in 2005 (10-12% of total global anthropogenic emissions of greenhouse gases (GHGs). With agricultural lands covering about half of the earth's land surface, reducing CO_2 emissions could have huge implications on meeting targets set by the Intergovernmental Panel on Climate Change [78]. In comparison with monocultured crop lands, the incorporation of trees or shrubs into cropping systems (through agroforestry) is often recognized as a unique opportunity to mitigate climate change through carbon sequestration [51]. Agroforestry has been cited as a key land use system in landscape-scale mitigation schemes under the REDD+ (Reduction Emissions from Deforestation and forest Degradation) and AFOLU (Agriculture, Forestry and other land uses) concepts. Of all the land uses analyzed in the Land-Use, Land-Use Change and Forestry report of the IPCC, agroforestry offered the highest potential for carbon sequestration in non-Annex I countries [78]. Considering the woody perennial (tree, shrub, palm and bamboo) is the integral component of an agroforestry system, most of the system's ability to sequester carbon is dependent on the woody perennial. Like most trees used in agroforestry, the integration of bamboo into cropping systems is one mainstream opportunity to mitigate climate change. Bamboo grows relatively fast and its high annual regrowth and renewability after harvesting, may give bamboo agroforestry a high carbon storage potential especially when the harvested culms are transformed into durable products [73]. Measurements of carbon sequestration in bamboo agroforestry are limited but estimates from bamboo plantations and forests are highly documented (particularly in Asia) and have been shown to vary depending on the type of plantation system, species composition, age of component species, geographic location, environmental factors, and management practices. In a mixed patch of three village bamboo species (*B. cacharensis*, *B. vulgaris and B. balcooa*) in the agroforestry system of northeast India, Nath and Das [55] found the carbon pool in the aboveground biomass ranged from 21.69 Mg ha^{-1} during 2003 to 76.55 Mg ha^{-1} during 2006. Allocation of carbon was found to be more in culm components (85 - 89 %) than in branch (8 - 10 %) and leaf (3 - 4 %). The rate of aboveground C sequestration was 18.93 - 23.55 Mg ha^{-1} yr^{-1} with the mean of 21.36 Mg ha^{-1} yr^{-1} [55, 56]. In Japan, Song et al. [73] found the total carbon stock of *Phyllostachys bambusoides* bamboo stands to be 165.1 Mg $ha^{–1}$, whilst that of *Dendrocalamus strictus* bamboo stands was 75.4 Mg $ha^{–1}$. Reviews by Song et al. [73] and findings of Zhou and Jiang [85] found that the total carbon storage capacity in a typical bamboo ecosystem, including in the soil, was 106.36 Mg $ha^{–1}$, of which the aboveground green vegetation stored 34.3 Mg $ha^{–1}$, accounting for 32.3% of the total, and that the forest floor and soil (0 to 60 cm in depth) stored 72.2 Mg $ha^{–1}$, accounting for 67.7% of the total. Further, a study conducted in Bangladesh found that the total carbon stock of a 5 year old *B. vulgaris* was quite high (15.53 Mg $ha^{–1}$ $yr^{–1}$) in comparison to some fast growing tree species like *Acacia auriculiformis* (recording 10.21 Mg $ha^{–1}$ $yr^{–1}$ after 11 years) and *Eucalyptus camaldulensis* (recording 10.12 Mg $ha^{–1}$ $yr^{–1}$ after 18 years) recommended for the clean development mechanism (CDM) project [72]. This high annual rate of carbon accumulation means that bamboo agroforestry could be one of the most efficient land use systems for carbon fixation. Additionally, the increased lifespan of durable bamboo products made through modern technology can ensure that the sequestered carbon will not return quickly to the atmosphere, thereby prolonging the carbon storage by bamboo [73]. Considering the large extent of degraded croplands and pasturelands in SSA and the potential to improve them using bamboo agroforestry, there is enormous potential to sequester additional carbon in such systems. In an agroforestry system with 50% of the plantation density or 30% of the plantation density, the system level C sequestration potentials are promising for SSA, along with annual and tuber crops.

3.3 Sustainable fodder supply for livestock

In SSA, the livestock sector employs at least 100 million poor people including women [41, 58]. In the Sahelian zone, the sector accounts for about 35% of Gross Domestic Product (GDP) and supplies about 30% of the revenue in the agriculture sector [75]. In addition, livestock provide draught power, skins, transport and manure, and fulfill various socio-cultural functions such as payment of dowry, establishment and reinforcement of relationships and source of prestige within the pastoral society [49, 84]. As a sector employing more than 60% of rural households in West Africa, investment in the livestock sector is critical in the quest to alleviate rural poverty and enhance food security. Among other factors, access to sustainable feed supply is one of the industry's key constraints. As most livestock are kept on a free-range system, forage of fair nutritive value is normally scarce in the dry season. During pasture scarcity periods, livestock are stall-fed on cereal crop residues and low-quality rangeland hay. These low quality forage based diets impede livestock productivity due to a lower dry matter (DM) intake, and lower digestibility and nutritive value of ingested feed. In most cases, livestock severely lose body weight, and the small-scale subsistence farmers often sell their animals at lower prices to avoid further production losses. The problem is further exacerbated by the inability of most farmers to provide supplementary feed sources [53], minerals and energy-rich feeds that optimizes microbial fermentation of low quality fibrous feeds in the rumen that in turn increases total dry matter intake and improves animal productivity [27, 40, 65]. In this regards, tree leaves have received increasing attention, due to many advantages such as supply of good quality green fodder during the dry periods, and high crude protein and minerals contents [28, 39]. Considering this need, evergreen bamboo, which produces year-round litter production and has relatively high nutritive characteristics, may provide a valuable supplementary source of feed. In India, bamboo leaves are already used as fodder for ruminants, particularly when there is scarcity of pasture. In Himachal Pradesh and Uttarakhand during winter months, bamboo (*Dendrocalamus hamiltonii*) and dwarf bamboo leaves are extensively used as green fodder. All species of bamboos used as fodder have shown positive effects on cattle, particularly young calves, and reportedly increased milk production [76]. Furthermore, leaves of 27 species of bamboo analysed for their nutrient content were found to be rich in crude protein (9-19%) and low in crude fibre (18-34%) [70].

3.4 Land restoration and soil conservation

Land degradation is a major biophysical problem in SSA normally contributed by the removal of vegetation through unstainable agricultural practices and illegal mining operations (Kusimi 2008; Kusimi 2015). Like most trees, bamboo has the propensity to improve soils as it grows on marginal soils with low fertility. In Brazil, bamboo species such as *Bambusa blumeana* and *Phyllostachys pubescens* are used in controlling soil erosion, preventing nutrient loss and improving soil structure [24]. The valuable features of bamboo for controlling soil erosion are its extensive fibrous root system, connected rhizome system, the leafy mulch it may produce on the soil surface, its comparatively dense foliage which protects against beating rains, and its habit of producing new culms from underground rhizomes which allows harvesting without disturbing the soil [10]. In China, a 5 year field experiment conducted showed an average surface soil runoff per month in bamboo forests of only 0.10 $m^3 \cdot ha^{-1}$, which is equivalent to only 77% of the rate for the Chinese fir forest and 35% of the rate for the *Pinus massoniana* forest [80]; the resulting sediment delivery rate was 0.18 kg ha^{-1}, amounting to only 42.8% of the rate for the Chinese fir forest and 23.6% for the *P. massoniana* forest [73]. In order to restore degraded agricultural lands in central India, Behari et al. [9] developed successful seven agroforestry models with three bamboos (*B. bamboos*, *B. nutans* and *D. strictus*). The inter crops were: Soybean (*Glycine max*), Moong (*Phaseolus aureus*), Wheat (*Triticum aestivum*), Urad (*Phaseolus mungo*), Pigeon pea (*Cajanus cajan*) and Mustard (*Brassica campestris*).

3.5 Poverty reduction and food security

In SSA, bamboo-based agroforestry systems are now developing and available literature on their economic feasibilities are limited. However, with livelihoods in SSA mostly tied to agriculture and forestry, investments in bamboo-based agroforestry systems may contribute to rural poverty reduction and improved livelihoods in the region. Like most agroforestry systems, bamboo-based agroforestry systems are expected to open new income streams by diversifying agroecosystems and offering multiple economic benefits from the sale of grains and vegetables from short-duration crops (integrated with bamboo), supply of fodder for livestock, and the sale of processed bamboo culms as wood fuels, charcoal, timber or industrial raw materials [51]. In most of SSA, it is common for rural households to diversify income streams as a pathway to reduce vulnerability to the failure of their primary income generating activities [6, 17]. In addition to vulnerability reduction, market opportunities also influence many households to indulge in other activities that sustainably generate income within shorter periods [47]. For this reason, charcoal production during the dry seasons is common among farmers as a secondary income generating activity. As regional and national environmental policies are likely to favour bamboo agroforestry in future as a major source of wood biomass for charcoal and firewood due to high rates of forest degradation, bamboo agroforestry will provide new vistas of income opportunities for charcoal producers. Income from charcoal sales will (1) provide safety-nets in times of shortfalls in incomes derived from arable farming, livestock or fisheries; (2) support current charcoal/wood fuel consumption; and (3) serve as a potential pathway out of poverty [1, 82]. With a projected rise in the consumption of wood fuels and charcoal by 2030, economic returns from bamboo-processed wood fuels and charcoals are also expected to rise. Bamboo is already contributing to household income security in SSA. In Ethiopia, a survey of 345 households showed bamboo income contributed up to 11% of the annual cash income of households [52] which shows investment in bamboo production could be a poverty reduction strategy for many SSA countries. While bamboo agroforestry could be economically prosperous, households will have to meet the financial and social capital requirements to engage in the production and marketing of potential saleable products [81].

Besides contributions to household income, bamboo agroforestry could also contribute to the food security and nutritional needs of SSA. The shoots of bamboo have good profile of minerals and nutrients such as protein, fiber, sugar, amino acids, inorganic salts etc. Table 1 shows the nutrient components of some bamboo species in SSA compared with some of the common vegetables widely grown and eaten in SSA. In many parts of Asia, Europe, Australia and the United States of America, bamboo shoots are widely eaten as important part of meals. In SSA, there are many bamboo species that produce edible shoots. However, they are not known to many due to limited awareness. With increased purchasing cost of many high value vegetables in SSA, bamboo shoots could be a viable cost-effective source of protein, vitamin and mineral for many households.

4. In which agroforestry system could bamboo be used?

Several agroforestry systems in SSA are characterized and their designs are matched to ecologies and farmers' needs in this section. In addition, the design of an agroforestry system may be dependent on the associated non-woody component (crop or livestock) as well as the morphological and physiological characteristics of the woody perennial. In the case of bamboo, sympodial and monopodial forms may have different agroforestry recommendations. In sympodial bamboos, new culms develop from buds on elongated culm necks (pseudorhizomes) rather than from buds on rhizomes. Generally, monopodial bamboos are native to temperate climates with cool, wet winters, and sympodial bamboos to tropical climates with a pronounced dry season [55, 57]. In SSA, most of the available bamboo species are sympodial and are highly concentrated in the forest agroecological zones. Such bamboo species may be suitable for boundary planting, windbreak and shelterbelt systems or as planted fallows on degraded lands. Similar agroforestry systems with sympodial bamboo species have been successfully developed in India [32]. The development of any of the aforementioned agroforestry systems with bamboo species such as *B. multiplex*, *B. vulgaris (the green type), B. bambos*, *B. pervariabilis, B. vulgaris var vitata*, *O. abyssinica* or *D. strictus* could be an opportunity to develop a sustainable bamboo biomass resource base for firewood and charcoal. In addition, boundary planting and windbreak systems with bamboo could reduce risks of crop failure and demarcate farm boundaries to minimize land litigations. Considering natural stands of bamboos (e.g. *B. vulgaris*) are found around water bodies in SSA, this could be a unique opportunity to manage them for riparian buffer agroforestry developments around major water bodies. Riparian buffers are importance for water resource conservation and serve other ecosystem services (such as provision of habitat for wildlife) [26, 69]. Including the aforementioned systems, monopodial bamboos may be most suitable for intercropping systems. In such intercropping systems, bamboo can be planted at varied spacing of 4 m × 4 m to 8 m × 8 m, depending on the clump size of the species. In India, crops such as finger millet, cowpea, bottle gourd, turmeric, sesame, and sweet potato were found to be more suitable [32]. Bamboo intercropping systems are rare in SSA with the latest being an INBAR-led bamboo agroforestry pilot project in the dry semi-deciduous zone of Ghana where different cropping systems with maize, cowpea and cassava are planted between the rows of *B. balcooa* and *O. abyssinica* in the quest to develop a model bamboo-based agroforestry system. While shading effects beyond three years of bamboo establishment may restrict crop integration, other shade tolerant crops like ginger could still form part of such an integrated land use system. Furthermore, with relatively high nutritional composition of bamboo leaves, bamboo silvopasture systems could be developed and scaled up in SSA particularly in the Savannah/Sahel areas where livestock production is a major livelihood activity. This implies that even at stages where major food crops could not be integrated with bamboo due to canopy closure, bamboo fodder could supplement the nutrient requirements of livestock particularly during the dry seasons where fodder of optimum nutritional quality are often scarce.

5. What can constrain bamboo agroforestry adoption in SSA?

Although agroforestry is often viewed as a sound land use system well adapted to the social and ecological environment of SSA [64], large scale landscape adoption of agroforestry is relatively low.

Referring from the reviews by Franzel [23] and Place and Dewees [66], several factors are likely to influence adoption of bamboo agroforestry innovations: (1) biophysical adaptation of the innovation – the ability of the innovation to adapt and be adapted successfully to the farm environment; (2) profitability of the innovation – in a broad sense to include consideration of returns to labour and land as well as financial profitability; (3) farmers' awareness of the innovation; (4) access to land, labour, and water; (5) access to social capital, particularly where group action is needed; (6) availability of essential inputs, particularly seed; (7) access to financial capital; and (8) degree of risk and uncertainty. Like most agroforestry systems, bamboo-based agroforestry systems are also likely to be faced with (9) the lack of effective and efficient land tenure systems that provide a long-term guarantee of benefit from up-front investments [42, 43].

6. Research needs for bamboo agroforestry development in SSA

Giving bamboo agroforestry is relatively new in SSA, it is imperative that research on the socioeconomic and biophysical aspects of it is intensified, so that future developments and scaling-up can be rooted in robust scientific findings rather than the intuitions of governments and development actors. In sub-sections 6.1 to 6.3 we highlight some relevant areas of research for bamboo agroforestry development in SSA

6.1 Ethnobotany and socioeconomic aspects of bamboo agroforestry

The woody perennial of an agroforestry system technically defines its socioeconomic importance. It is therefore imperative that one assesses the local knowledge of bamboo within the intended agroecological zone of establishment. Assessment of local knowledge of bamboo may involve determining local bamboo use, ecological distribution as well as taboos and belief systems about its cultivation and utilization. Local knowledge of bamboo may reveal new vistas of bamboo use as well as constraints that may restrict its adoption by farmers. A major methodology to achieving this is the administration of questionnaire interviews and field observations that emphasize on the aforementioned areas and offers the platform to clear doubts and enigma through knowledge sharing. Considering the dynamic and changing nature of agricultural practices in SSA, understanding the factors that drive changes within the intended locality may also help guide strategies to promote sustainable bamboo agroforestry. The drivers of changes could be natural or human induced factors that directly or indirectly bring about changes in any agricultural production systems [30]. As these factors are more related to needs and profitability, it will be crucial to investigate the advantages bamboo could potentially contribute to meeting the subsistent and/or commercial needs of farmers. Further, the competitive advantage of bamboo (in terms of costs and benefits) would have to be assessed and compared with trees or shrubs that offer comparable use and importance.

6.2 Ecological processes and component interaction within bamboo agroforestry

According to Ong et al. [60], the success of any agroforestry system is dependent on the interaction between the woody perennial and associated components. Such interactions may occur aboveground or belowground. Competitive and complementary interaction within a bamboo agroforestry system may be dependent on the arrangement of the components, planting density and the level of technical management [5, 77]. The study of interactions in bamboo agroforestry may require the examination of complex ecological processes. Table 2 provides a summary of typical tree-soil-crop interaction processes that could be expected within a tropical bamboo agroforestry system. Experimental designs with different planting spacing and density of bamboo and crops may be crucial in defining the best cultural practices applicable to specific bamboo species and agricultural crops. In addition, quantifying the spatio-temporal scales of the processes enumerated in Table 2 would inform management decisions and investment options that promote the productivity and sustainability of bamboo agroforestry [36].

6.3 Testing bamboo fodder for a wide range of livestock

In the quest to develop bamboo-based silvopasture systems, it will be imperative to (1) determine integrated tree/crop-livestock production systems in an intended locality; (2) identify predominant livestock feeding practices; (3) document priority fodder species and assess farmers' ethnobotanical knowledge about the species; (4) determine the nutritional and mineral profile of the prioritized livestock feed sources; (5) assess the consumption patterns and digestibility of prioritized fodder species in comparison with bamboo; and (6) evaluate the growth and health (using haematological indicators and serum biochemistry) of livestock fed with fodder from common species in comparison with bamboo. In SSA, bamboo generally grows throughout the country although mostly concentrated in the forest agroecologies. The development of bamboo-based silvopasture systems will be a unique opportunity for farmers in the Savannah/Sahel agroecological zones where livestock production is a major livelihood activity.

7. Conclusions

The Food and Agriculture Organization (FAO) recently recommended the adoption of agroforestry practices (tree-based farming practices) for food security in all Sub-Saharan African (SSA) countries, and the need of SSA country governments to incorporate agroforestry into their national agricultural policies. Presently, agroforestry innovations are encouraged as a sustainable approach to food security in the UN Sustainable Development Goals. The socioeconomic and ecological importance of bamboo are not farfetched particularly with the provision of huge biomass source for renewable energy, potential for restoring degraded forestlands and also as a sustainable carbon sink. By incorporating bamboo into mixed-use agroforestry complexes, we can maximize its functionality while integrating it with other production crops. As a relatively new innovation, it is imperative that research on the socioeconomic and biophysical aspects of it is intensified, so that future developments and scaling-up can be rooted in robust scientific findings rather than the intuitions of governments and development actors.

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Table 1 Comparative account of various nutrients present in freshly emerged juvenile bamboo shoots and some common vegetables (adapted from Chongtham et al. [12])

Species	Amino acids (g 100g^{-1})	Protein (g 100g^{-1})	Carbohydrates (g 100g^{-1})	Starch (g 100g^{-1})	Fat (g 100g^{-1})	Vitamin C (mg 100g^{-1})	Vitamin E (mg 100g^{-1})	Ash (g 100g^{-1})	Moisture (g 100g^{-1})	Dietary fiber (g 100g^{-1})
Bamboo										
Bambusa bambos	4.0	3.6	5.4	0.3	0.5	1.9	0.6	1.4	89.8	3.5
Bambusa vulgaris	3.6	3.6	6.5	0.3	0.5	4.8	0.5	1.0	90.6	4.2
Dendrocalamus asper	3.1	3.6	4.9	0.4	0.4	3.2	0.9	1.0	89.4	3.5
Dendrocalamus brandisii	3.0	2.3	4.9	0.5	0.2	1.6	0.4	0.6	89.8	4.0
Dendrocalamus membranaceus	3.5	3.4	5.4	0.2	0.4	1.6	0.7	0.6	89.3	2.9
Dendrocalamus strictus	3.1	2.6	6.2	0.3	0.3	2.4	0.6	0.7	90.1	2.3
Gigantochloa albociliata	3.5	3.1	4.6	0.3	0.5	1.0	0.6	0.7	89.2	4.2
Common vegetables										
Brassica olarecea var. capitata	0.3	1.8	5.6	-	0.1	2.6	32.2	0.7	91.9	1.0
Daucus carota	0.2	0.9	10.6	-	0.2	1.2	3.0	1.1	86.0	1.2
Solanum tuberosum	0.2	1.6	22.6	15.4	0.1	0.4	19.7	1.1	74.7	0.4
Abelmoschus escalentus	0.3	1.9	6.4	-	0.2	1.2	13.0	1.1	88.3	1.2
Cucumis sativus	0.1	0.6	2.5	0.1	0.1	0.7	3.2	0.4	96.3	0.4
Phaseolus vulgaris	0.3	18.8	20.1	-	2.0	4.6	-	4.3	10.8	1.8
Solanum melongena	0.2	1.4	4.0	-	0.3	1.3	12.0	0.8	92.7	1.3

- = data unavailable

Table 2 Possible tree-soil-crop interaction processes in tropical bamboo agroforestry systems (adapted from Rao et al. [67])

Nature of interaction	Process
Soil fertility: Chemical	
Carbon	Increases in active pools of soil organic matter through litterfall, root turnover and incorporation of tree prunings and crop residues
Nitrogen	Increased soil N supply through deep soil N capture and reduced leaching
Phosphorus	Transformation of less available inorganic P forms into readily plant-available forms
Cations (Ca, Mg, K)	Relocation in soil profile, organic acids binding Al, localized Al detoxification
Soil fertility: Physical	improved soil aggregation, porosity and pore connectivity, reduced bulk density, break up of hardpans/compacted soil layers
Soil fertility: biological	Build-up of soil macrofauna and microbial populations, reduced/increased soil insect pests and pathogens
Competition	Sharing of growth resources: light, water and nutrients by trees and crops
Microclimate	Shading (reduced soil and air temperature); shelter (protection from wind); rainfall interception and re-distribution
Conservation	Reduced soil erosion, reduced leaching
Biological:	
Weeds	Reduced weed population, shifts in weed species, decreased viability of perennial weed rhizomes, decay of annual weed seek bank
Pests and diseases	Reduced/increased pest-parasite/predator populations
Allelopathy	Release of growth affecting chemicals into soil environment

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