Scientific African 15 (2022) e01075

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Improving soil health and closing the yield gap of cocoa production in Ghana – A review

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ARTICLE INFO

Article history:
Received 7 July 2021
Revised 24 November 2021
Accepted 12 December 2021

Editor : H Karuri

Keywords:
Agroforestry
Cocoa
Nutrient cycling
Organic amendments
Soil ecological functions
Soil health

ABSTRACT

Ghana is the second largest producer of cocoa in the world and cocoa farming supports the livelihoods of 25-30% of Ghana's population. However, average yield is only about 30% of the potential yield. Cocoa farms established on recently cleared rainforest are initially productive, but then productivity declines as soils become depleted of nutrients. Further expansion of cultivated land by deforesting tropical rainforests is environmentally costly, socially unacceptable, and inherently unsustainable. Therefore, strategies are urgently required to maintain and restore the productivity of existing smallholder farms to close this yield gap and sustainably increase cocoa production to meet growing demand. In this narrative review we provide context to the issues and highlight recent advances that offer promising opportunities to restore the soil health of Ghana's cocoa farms and sustainably reduce the yield gap. The shade trees in traditional agroforestry farms help prolong productivity for longer by supporting soil ecological functions and this has sparked renewed interest in the establishment of sustainable agroforestry cocoa farms. The single rate and formulation of mineral fertiliser recommended to farmers nationwide fails to account for variability in the response of different soil types to inputs. Therefore, site-specific fertiliser recommendations that also quantify the benefits of organic amendments are emerging. Composting and returning cocoa pod husks to the soil offers a considerable opportunity to close nutrient cycles (particularly for P and K) on cocoa farms and to help build and maintain soil organic matter. However, research is required to overcome the risk that recycling cocoa pod husks may contribute to the spread of black pod disease. Soil health indicators that quantify the soil ecological functions provided by these sustainable land management practices require benchmarking to monitor the impact of these interventions.

Abbreviations: COCOBOD, Ghana cocoa board; FAOSTAT, Food and agriculture organisation of the United Nations statistics; CRIG, Cocoa research institute of Ghana; WRB, World reference base for soil resources; GIS, Geographic information system; SOM, Soil organic matter; CEC, Cation exchange capacity; CPH, Cocoa pod husks.

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https://doi.org/10.1016/j.sciaf.2021.e01075

Introduction

Cocoa is Ghana's major cash crop, providing employment to 800,000 smallholder farmers [103]and supporting the livelihood of about six million people representing 25-30% of Ghana's population [12]. Cocoa cultivation accounts for a large proportion of Ghana's economy and thereby contributes significantly to the nation's economic development. On-farm yields are highly variable [37] and often decline over time as the soil becomes depleted, which sometimes leads to farmers migrating to new lands and clearing forests to establish new farms.

In this narrative review article, we first provide background and context to cocoa farming in Ghana and outline the political, socioeconomic, and biophysical circumstances that have led to land management practices that increase the gap between actual and potential yields. We outline the evidence to support our assertion that soil health has been neglected during the drive to introduce innovations that rely on external inputs to achieve profitable yields and that improving soil health is key to closing the yield gap. Our objective was to focus on recent novel research advances that provide strategies to monitor and increase soil health on cocoa farms in Ghana with the aim of highlighting practices that could be implemented or promoted by policy makers to increase the sustainability of Ghanaian cocoa farms.

The key interventions that we critically review in our article that have the potential to increase soil health and elevate the sustainability of cocoa production systems in Ghana, and neighbouring countries, are (i) the re-establishment of agroforestry systems, (ii) the implementation of site-specific mineral fertiliser formulations and rates, and (iii) the use of cocoa pod husks (CPH) to create composts that return nutrients to the soil. We focus primarily on research outputs published in the last 10 years to illustrate the efficacy of these approaches, but occasionally cite older research to provide background and context. Improving the soil health of Ghanaian cocoa soils by implementing these interventions will help in addressing the United Nations sustainable development goals of zero hunger, decent work and economic growth, responsible consumption and production, and life on land.

Overview of cocoa production in Ghana

Cocoa production in Ghana is mainly concentrated in the forested areas of the country where the climatic conditions are favourable for growing cocoa [28]. Globally, there has been an increasing demand for cocoa since the early nineties and producing countries, including Ghana, have responded to this demand by putting measures in place to increase production [57]. In 1947, the Government of Ghana established the Ghana Cocoa Board (COCOBOD) which is the main agency that oversees the cocoa industry in Ghana [44]. In contrast to many major cocoa producing countries, where government involvement in the sector is minimal, COCOBOD has established structures which consist of rehabilitation programs for old cocoa farms, spraying programs to control pests and diseases, supply of subsidized fertilisers on credit, and improvements in extension systems to encourage adoption of new technologies and improved varieties [10,30,95].

The yield gap of cocoa production in Ghana

Ghana and Côte d'Ivoire, together produce around 60% of the world's cocoa, and neighbouring Cameroon and Nigeria (who are the third and fourth largest producers in Africa) share similar climatic conditions. As depicted in Fig. 1 [45], it is clear that increases in production over time have been driven largely by an increase in the area of cultivated land.

In Ghana, an increase in the area of cultivated land contributed to increases in production from 2002 to 2004, but the area declined from two million hectares in 2004 to 1.8 million hectares in 2006 (Fig. 1). This decrease may be due to farmers succumbing to production constraints and growing less capital-intensive crops or selling their lands to illegal miners (known locally as "Galamsey") to use as capital for more profitable ventures. Illegal small-scale mining has been identified as a factor contributing to recent decline in cocoa productivity due to almost irremediable damages to farms and water bodies [28]. However, the area of land used to grow cocoa in Ghana has remained fairly constant since 2006 and, despite increases from 400 kg per hectare in 2006 to 550 kg per hectare in 2012, yields have since plateaued, resulting in stagnated national production at around 870,000 tonnes per year (Fig. 1). Similar trends of stagnant or declining yields are observed in other cocoa growing nations in West Africa (Fig. 1).

Cocoa cultivation has gradually taken over about 14–15 million ha (1.5 million ha in Ghana) of tropical forests globally. Since forestland is limited and rapidly disappearing, further expansion is environmentally costly, socially unacceptable, and inherently unsustainable. Deforestation has become a global environmental concern and is pushing cocoa buyers and consuming countries to commit to reducing deforestation associated with cocoa production by developing strategies to increase yields on existing farmlands. Therefore, increasing cocoa production to meet growing demand, without expanding the area cropped, has become a global challenge [98]. Increasing the sustainability of cocoa production in Ghana depends largely on reviving production in the Ashanti, Central, and Eastern regions where soil quality is most degraded [58] before moving to other regions, such as the Western, Brong Ahafo and Volta regions to prevent these soils from facing the same declines.

The national average yield in Ghana between 2015 and 2019 of 525 kg ha^{-1} [45] was only 30% of the yield potential of 1,889 kg ha^{-1} estimated by Aneani and Ofori-Frimpong [10], resulting in a large yield gap between the actual and potential yields. There is a need to understand the reasons for the yield gap to realise yield potential [23]. Factors identified as determinants of cocoa yields in Ghana and elsewhere include the varieties grown, soil fertility, pest and diseases, and

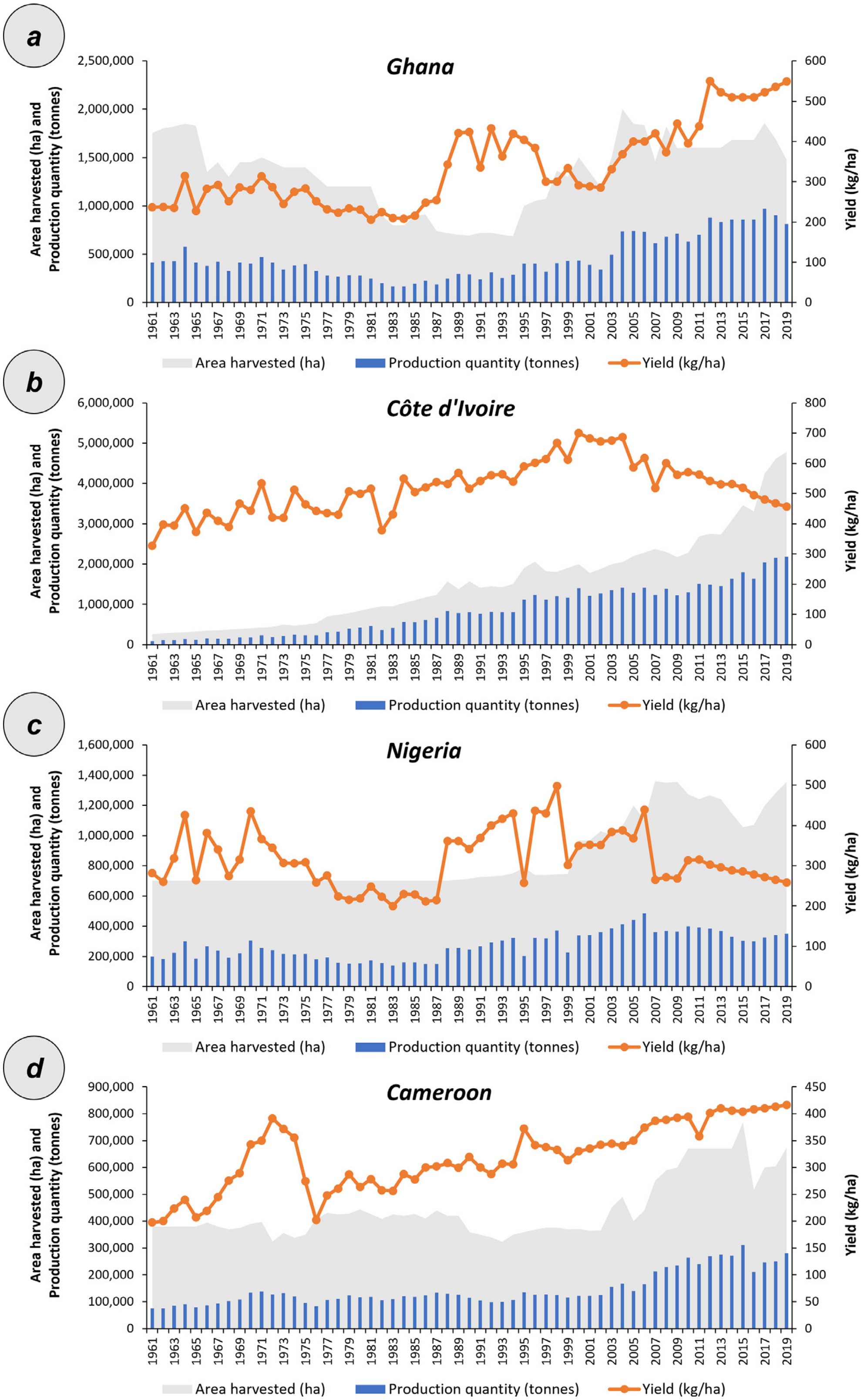

Fig. 1. Temporal trends in area harvested, production quantity, and yield of cocoa in the major West African cocoa producing countries of Ghana (a), Côte d'Ivoire (b), Nigeria (c), and Cameroon (c) between 1961 and 2019. Data source: [45].

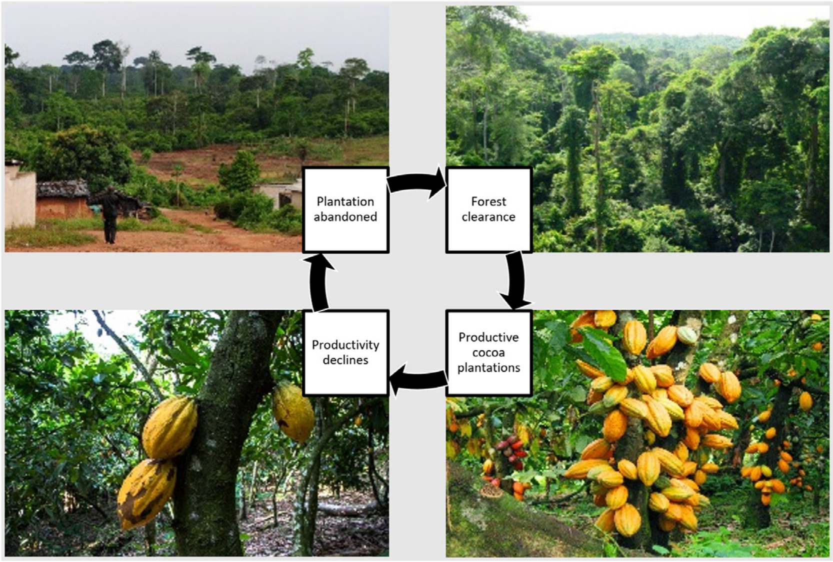

Fig. 2. Depiction of the unsustainable cycle of cocoa production systems in Ghana whereby virgin forest is cleared to establish cocoa farms which are initially productive, but then decline in productivity, eventually leading to abandonment and further clearance of more virgin forestlands.

maintenance and agronomic practices; the latter of these can be linked with access to credit, and infrastructure [3]. Research directed towards addressing these challenges, to bridge the huge yield gap identified in the cultivated areas, should be exploited to ensure sustainable cocoa production in Ghana. We make this recommendation because meeting demand by continuing to expand the area of cocoa cultivated is inherently unsustainable.

Cocoa shifting cultivation systems

Cocoa farms in Ghana were traditionally established under a carefully cleared canopy of typical primary or secondary forest, or under that of established shade trees, close to the natural conditions under which the cocoa plants are adapted to survive [42]. Traditional land preparation involves slash and burn, which returns nutrients from the forest biomass, in the form of ash, to the soil [34]. Cocoa grown on cleared virgin forestlands, or even secondary forest, produces higher yields than cocoa grown on previously cropped or deforested lands due to a phenomena known as the “Forest Rent” [84]. This refers to the rich nutrients readily available to the cocoa crops when grown on cleared forestlands, thereby reducing the requirement for farmers to purchase and apply fertilisers. Farmers therefore prefer to acquire virgin forestlands to start cocoa production rather than rehabilitating old unproductive farms, which require higher inputs such as labour (especially for clearing old crops and controlling weeds) and fertiliser [84, 102]. This preference, however, is not ecologically sustainable since the “Forest Rent” eventually becomes exhausted after 20-30 years [34] when productivity declines and production is maintained by clearing another area of virgin forest (Fig. 2). Whilst the focus of this paper is on cocoa production in Ghana, issues of soil degradation are applicable to many other countries where cocoa is grown, such as Côte d’Ivoire [67], and so the focus here on Ghana represents a case study of a global issue.

The traditional agroforest cocoa production system, utilising remnant forest or planted shade trees, has been promoted to compensate for the deforestation caused by cocoa expansion [20,21,59]. Cocoa agroforestry provides a range of environmental benefits, including carbon storage [19,63], biodiversity [20,96], soil fertility [98], and greater economic security to farmers through the provision of forest products that are of commercial and domestic value [11]. However, the introduction of early yielding cocoa varieties that are suited to low or no canopy shade has facilitated the growing of cocoa trees in full sun or with fewer shade trees [102]. This development therefore results in a variety of practices along a spectrum that spans two extreme circumstances; (i) the traditional extensive production with low inputs and mostly shaded farms, and (ii) the more intensive production using hybrid varieties with little or no shade trees. Farms can therefore be categorised according to their shade levels and the species richness of shade trees [83].

Higher yields have been observed under full sun cocoa production with fertiliser applications [3] than under shaded systems. On-station trials formed the basis for adoption of the no-shade intensive cultivation system, which has been well adopted (especially in the Western Region), but with insufficient (or without) use of fertiliser [3,49,71]. Consequently, on-farm yields fall short of the theoretical yields based on the on-station trials. Other studies have reported the greater yield on unshaded cocoa farms to be short-lived, compared to shaded farms. Yield in unshaded farms has been observed to decline after 10 to 15 years, and farms become virtually unproductive after 18 to 29 years whereas, in the traditional shaded system, yield only starts to decline after 25 years [3,71]. Furthermore, the short-term benefits of full sun cocoa cultivation in Ghana

Table 1
Physical and chemical properties and recommended management of World Reference Base for Soil Resources (WRB) reference soil groups cropped with cocoa in Ghana. Compiled and modified from: [18,24,82,104]. CEC = Cation Exchange Capacity

WRB reference soil groups	Physical properties	Chemical properties	Management
Acrisols	High subsoil clay content Topsoil has low aggregate stability	Low CEC (< 24cmol kg^{-1} clay) Base Saturation <50% at 25-100cm Low pH (5.66) Low nutrients	Prevent erosion Preserve organic matter Regular fertilisation required Agroforestry recommended for low input farming
Lixisols	High subsoil clay content Topsoil has low aggregate stability	Low CEC (< 24cmol kg^{-1} clay) Base Saturation <50% within 25-100cm Low pH (5.88) Fairly leached Low nutrients	Prevent erosion Preserve organic matter Regular fertilisation and liming required
Luvisols	High subsoil clay content	High CEC (>24cmol kg^{-1} clay) Base Saturation > 50% at 50-100cm Fertile soils	
Nitisols	Clayey subsurface horizon Low activity clay, with iron oxides High aggregate stability Deep well drained soil Fair water holding capacity High organic matter	P-fixation Fertile soil, rich in Fe	Application of slow release P fertilisers
Ferralsols	Deeply weathered, red or yellow soils of the humid tropics dominated by kaolinite and iron / aluminium oxides Good soil depth and permeability Stable microstructure	Low pH (5.01) and water holding capacity Poor chemical fertility Strong P-fixation	Manuring, mulching and/or adequate fallow periods or agroforestry practices Application of slow release P fertilisers
Fluvisols	Developed in alluvial deposits Poorly drained	Severe acidity and high levels of Al toxicity	Water management required Drought stimulates microbial activity and organic matter mineralization

are largely due to the initially fertile forest soils [3]; especially in the Western Region which is the youngest cocoa growing region, still benefiting from the “Forest Rent”.

Shaded cocoa competes with shade trees for nutrients, water and sunlight, which may affect its yield during the first few years following establishment. However, in the long term, the trees in the shaded cocoa system can create an environment similar to that of a secondary forest and maintain important soil processes that improve soil quality [31,36]. Although both intensive and extensive cultivation systems could benefit equally from the “Forest Rent”, it seems that the traditional agroforestry cocoa is better able than the full sun system to self-regulate soil fertility in the absence of fertiliser application. These ecosystem functions provided by the shade trees could explain why the shaded system has a longer production period.

Traditional cocoa agroforestry systems with the optimal shade species mix and density can be a more sustainable option for cocoa production in Ghana since smallholder farmers who cannot afford fertiliser (a major requirement for productive full sun cultivation) produce the majority of the country’s cocoa. Notwithstanding, the majority of farmers, unaware of this fact, are still driven by the short-term benefits of full sun cultivation. However, the economic benefits of other forest products derived from the traditional shade system remains the motivation behind some farmers’ decision not to shift to full sun cultivation. There are risks and costly production constraints induced by ecological stresses on the cocoa plants when grown without the shade.

In this opening section we have provided context that outlines the challenges facing cocoa production in Ghana and made the case for why a stronger focus on the health of soils is required to close yield gaps. These observations have led to a renewed interest (both national and international) in the establishment of sustainable shaded cocoa.

The quality and health of cocoa soils in Ghana

The majority of Ghana’s cocoa is grown in the semi-deciduous forest agroecological zone on six soil classes recognised as suitable for cocoa production; Acrisols (66%), Lixisols (18%) and Luvisols (7%) and about 7.5% on Nitisols, Ferralsols and Fluvisols combined [89] (Table 1). Cocoa adjusts to a wide range of soil classes and types, but good yield depends on the soil’s quality. In the case of cocoa farms, it is the ability of the soil to sustain cocoa yield while maintaining environmental quality within the ecosystem. An increasing recognition of the importance of soil health and quality has led to the development of myriads of soil quality indexes and assessment frameworks [5,13,79]. In cocoa production systems, soil physical and chemical properties are commonly used as indicators of soil quality. However, while biological properties as indicators have gradually been explored, this has seemingly not yet been applied in Ghana. To determine the soil quality of cocoa soils in Ghana, we need a better understanding of how soil properties, particularly the underexplored soil biological properties, vary in space and time, are impacted by land management, and how they relate to crop yield.

Physical and chemical properties as indicators of cocoa soil health

Most Ghanaian soils cropped to cocoa are formed from heavily weathered parent materials (with kaolinitic clay mineral components) and thus have low pH (5.35 ± 0.027), low cation exchange capacity (< 24 cmol kg^{-1}), and low organic carbon content (0.39 ± 0.009 g/100 g) with nitrogen and phosphorus being the most limiting nutrients [82,104] (Table 1). The transition from forests to cocoa farms, especially the no-shade systems, impacts soil physical and chemical properties. The cocoa plant adapts very well to many soil types but soils cropped to cocoa should have sufficient available nutrients to meet the minimum nutrient requirements, have a soil depth of about 1.5m that allows good root development without any obstructions, and preferably a texture of approximately 30 % clay, 50 % sand, and 20 % silt [90]. Nutrient availability and absorption are primarily affected by soil water availability, acidity, aluminium toxicity, and the organic matter content of soils [22,90]. Cocoa is sensitive to both droughty (sandy) and waterlogged (clayey) soils, and since production in Ghana is purely rainfed, well drained soils that hold enough water to make nutrients available is essential. Water deficit has been estimated to account for about 50% of the cocoa yield gap [105].

High rates of Al saturation in cocoa soils negatively affects the growth of cocoa. Aluminium reduces root and shoot growth and, subsequently, nutrient uptake. Soil Al concentration is negatively correlated with pH; the lower the pH, the higher the Al availability to plants. Cocoa growing soils in Ghana have low pH, with 83.3% of soils surveyed across all cocoa growing regions having pH lower than 5.5, indicating that they are suboptimal for cocoa farming [82]. Soil pH is lowest in the southwestern part of Ghana [82] and these soils are thus most susceptible to Al toxicity. Acidification may be occurring due to the application of nitrogenous fertilisers without concurrent applications of liming agents to compensate for the decrease in pH that accompanies plant root uptake of ammonium.

Soil nutrient status and diagnostic methods for assessing cocoa nutrient requirements

There have been many studies on the nutrient status of cocoa-growing soils and the use of mineral fertilisers in cocoa production, as reviewed by Snoeck et al. [90], but few on the use of organic fertilisers [4]. Most studies supported the requirement for mineral fertiliser application to maintain sustainable yields, but recent findings indicate that different soil types require site-specific fertiliser formulations instead of the nationwide fertiliser formulation recommended across all cocoa growing regions [40]. In Ghana, a single fertiliser formulation (N:P:K 0:22:18 + 9CaO + 7S + 6MgO) referred to as 'Asaase Wura' is recommended at a rate of 375 kg ha^{-1} by the Cocoa Research Institute of Ghana (CRIG) to cocoa farmers across all cocoa growing regions despite the fact that the cocoa growing regions vary in soil properties [89].

Recommended fertiliser formulations and application rates in most cocoa producing countries have been based on fertiliser response trials (to determine the required nutrient thresholds), the nutrients retained in the crop, the nutrient balance (between supply and export through harvest), and a soil nutrient status assessment [90,99]. Site-specific fertiliser formulations in Ghana can be developed using a soil diagnostic tool to calculate the fertiliser needs of cocoa. This tool was first developed by Jadin and Snoeck [54], and updated much later by Snoeck et al. [87], based on numerous fertiliser trials [90]. The diagnostic tool compares actual and optimal soil nutrient levels and calculates the quantity of key nutrients needed to rectify any nutrient imbalance [40]. This approach has been used to diagnose soil nutrient deficiencies and calculate the nutrients required to balance nutrient loss after harvesting [39,40,67].

Snoeck et al. [89] developed a method that maps the nutrient requirements of cocoa to the soil nutrient status in all growing regions in Ghana by combining Geographic Information System (GIS) technology with soil diagnostic modelling. Through this study it was discovered that the fertiliser formula recommended by CRIG suits only 6% of the land cropped to cocoa. This discovery may imply that the fertiliser programme promoted by COCOBOD to improve soil quality and boost production is not optimised in 94% of the area over which it is adopted. It was recommended in the study that at least 30 different location-specific fertiliser formulations are required; this recommendation was based on soil nutrient thresholds and ratios of some specific nutrients. However, the recommendation is still yet to be adopted.

Biological indicators of quality and health of cocoa soils

Biological indicators of soil quality have gained research attention quite quickly even though little evidence has been provided to link the indicators to aboveground productivity. Similar to their physical and chemical counterparts, no single biological parameter can be used in isolation to holistically represent soil quality or health [47]. Factors frequently measured are soil microbial biomass and activity, nitrogen mineralisation, rate of litter decomposition and soil organic matter content. Soil organic matter (SOM) represents a key indicator for soil quality, and its importance is well understood by Ghanaian cocoa farmers [6]. SOM is the main determinant of biological activity because it is the primary food source for soil organisms and has a major influence on the physical and chemical properties of soils; this makes it a key integrated indicator of soil degradation [70].

SOM provides an important link between biological and physico-chemical indicators that needs to be considered for sustainable fertility management of cocoa soils. Land use change from forests to cocoa farms affects soil functional biodiversity and ecological processes such as the decomposition of organic residues and nutrient cycling [29,36,50]. Evidence of historic nutrient mining and SOM depletion can be observed in cocoa growing regions across Ghana [82]. However, higher carbon storage capacity has been observed in cocoa agroforests than in unshaded cocoa [63].

Research linking the ecological functionality of cocoa soils with the soil biota within Ghanaian cocoa production systems is lacking. However, a few studies have quantified changes in carbon and nutrient stocks with time under cocoa systems, either via chronosequences or the monitoring of long-term plots [3,15,34,53,75]. Some studies have observed that the rate of litter decomposition in cocoa farms decreases following forest conversion because litter quality changes [34,75]. Soil fauna play a major role in converting cocoa litter into useable forms of nutrients for plants. In Bahia, Brazil, the adoption of cocoa agroforestry systems has increased the abundance and diversity of soil and litter fauna [33]. However, experiments to understand how cocoa management systems in Ghana influence the abundance, diversity, and activity of soil fauna are lacking.

In this second section of the review we have provided context for the soil physical, chemical, and biological properties of Ghanaian cocoa soils and highlight the need for a greater focus on soil biological properties. The consequences of a failure to develop site-specific fertiliser formulations and the use of acid-forming fertilisers on soils susceptible to acidification has resulted in very low pH (<5.5) in the soils of some cocoa growing regions, particularly in southwest Ghana [82]. Organic inputs are required to build SOM and encourage nutrient cycling in Ghanaian cocoa farms.

Relationships between shade, litter, and soil quality

Research is currently being undertaken to devise shade management strategies designed to both increase productivity and optimise ecological benefits [4]. While little evidence exists to quantify the ecological benefits of shade trees, the functional benefits to cocoa are known to include favourable microclimate, erosion control, and soil quality improvement [3,14,86,97]; these benefits are particularly important to farmers during long severe dry periods in Ghana. The quantitative effects of shade on cocoa yield have been established in most cocoa producing countries [2,26,64], including Ghana [4,14,16,17,90]. The consensus is that well managed agroforestry farms with the appropriate levels of shade have long term positive effects on yield; possibly because of enhanced delivery of ecosystem services in the shaded farms, compared to monoculture farms. The density of shade levels adopted by farmers in Ghana has been categorised as low, medium or high, by different researchers using a range of metrics, such as canopy cover, tree density, and tree diameter at breast height [3]. CRIG recommend shade cover (defined as percentage light interception) of 40% [77]. However, Abdulai et al. [1] highlight the need for recommendations of optimum shade levels to be climate region specific.

The ability of cocoa agroforestry systems to survive with little or no fertilisation is attributed to enhanced nutrient cycling through the decomposition and mineralisation of nutrients entering the soil from litter fall. Both litter quality and decomposer diversity decrease with decreasing shade [27,33,36,42,48,101]. In Ghana, litter quality (C/N ratio) is decreased when native forest is converted to shaded farms. This decline in litter quality correlates with a reduction in litter decomposition rate [35]. Likewise, changes in soil quality along a chronosequence of cocoa agroforestry systems has been observed in a number of studies. The release of nutrients from litter in older cocoa farms (35-55 years old) was reported to be enough to recover the nutrients extracted by the cocoa crop [80]. Litter decomposition rate and Cation Exchange Capacity (CEC) was significantly greater in a >25-year-old cocoa agroforestry system than in 1–4 year old farm, and vesicular arbuscular mycorrhizal fungi spores were twice as abundant and more diverse in the older farms [88]. These findings demonstrate that shade and litter are important drivers affecting soil quality, and more studies are required to quantify their contribution to improving the physical, chemical and biological properties of cocoa soils in Ghana.

This third section has highlighted the vital role that shade trees, and in particular, shade tree litter, play in maintaining soil health in cocoa farms. We demonstrate the negative consequences that the introduction of hybrid varieties grown in monoculture have had on soil health and nutrient cycling. Mitigating these negative consequences will be difficult because uncertainties about the optimum species and density of shade trees and tenure rights represent barriers to agroforestry adoption [68]. Other soil management strategies that are easier and faster to adopt are required to achieve sustainable management of cocoa production in Ghana.

Soil management strategies for sustainable cocoa production in Ghana

Poor soil fertility in cocoa soils worldwide has been a major concern for all stakeholders. Research for sustainable production has called for a shift away from soil management strategies that exclusively provide inorganic fertiliser application rates towards strategies aimed at improving soil structure and supporting soil ecological functions while reducing negative environmental impacts. The gradual reduction in the rates of inorganic fertilisers use and the introduction of organic fertilisers is being researched in several cocoa producing countries [46,66,93]. Organic fertilisers increase SOM content; an important soil attribute that has a major influence on soil properties and ecological functions such as soil water conservation and nutrient cycling [9,32,69].

The use of both organic and inorganic fertilisers as an integrated nutrient management strategy is gaining research attention in cocoa production systems. However, information on the dynamics of the types of organic amendments, their application rates, and their effects on soil quality in cocoa cropping systems is very much limited. Organic fertilisers offer an important opportunity to enhance the sustainability of cocoa production, particularly in Ghana where soils cultivated with cocoa have low SOM content [82], and nutrient stocks [62], due to many years of nutrient mining through harvesting. Knowledge regarding the benefits of organic fertilisers to cocoa soils in Ghana is mostly confined to the use of poultry manure and the ash from burnt cocoa pod husks, which is an option recommended by CRIG to Ghanaian cocoa farmers [77].

Cocoa pod husks (CPH), a major source of organic matter on cocoa farms, contain 1000 mg N kg^{-1}, 3000 mg P kg^{-1}, and 48571 mg K kg^{-1} [90]. Their use as a soil amendment has revealed significant improvements in soil properties and plant growth [7, 46,65,66,74,92]. Yet, the potential to use CPH as an organic fertiliser in cocoa farms has been underexplored in Ghana; largely because it is believed that spreading husks may contribute to the spread of black pod disease (*Phytophthora* spp.) [7,77], and so CPH are treated as farm waste that must be disposed of. However, there is evidence to suggest that application of CPH-based compost reduces black pod disease both by reducing *Phytophthora* spores and by raising the nutrient status of the cocoa plants to induce resistance [41].

Research into the valorisation of CPH for alternative off-farm uses [61], such as feedstock for bioenergy [51,73,85,94], animal feed [72], traditional soap making [78], chemical extracts for pharmaceutical and food processing [100], and as biosorbent and bioremediation agents [38,60,76] has attracted far more interest than research into the use of CPH as a soil organic amendment. The little research that is undertaken has focused more on the use of CPH composts as organic amendments on arable and horticultural fields rather than on cocoa farms where it may be of greatest use to return the nutrients mined to grow the husks. Since husks are generally piled up on farms and not returned to soils as an organic fertiliser, the nutrients that they contain, particularly K, are susceptible to leaching and loss during rainfall events [52]. Thus, there is an urgent need for fundamental research on the suitability of CPH-based soil amendments that combines nutrient management with integrated pest and disease management in Ghanaian cocoa farms.

Composting, one of the most conventional and environmentally suitable means of valorising agricultural and household waste, has been suggested as a means for farmers in Ghana to recycle CPH into organic fertilisers [77,99]. However, this has not been widely adopted in Ghana, unlike in Indonesia, Papua New Guinea, and Cameroon, where an increase in on-farm composting of CPH has been observed [66]. The application of CPH composts could considerably reduce inorganic fertiliser use, thereby saving costs and improving soil quality and health.

Composting CPH without any co-amendments results in reduced N availability through immobilisation. Therefore, some studies have looked at the effects of various co-amendments to CPH-based compost on soil nutrient fluxes. Co-composting CPH with other amendments such as poultry manure or nitrogen rich green leaves (such as Neem, Tithonia, and Moringa) enhances the fertilising potential of CPH [43,56,66]. Poultry manure performs better than the leaves since the former is richer in nutrients, especially N, P and K. Nutrient release from compost is slower than inorganic fertilisers and, therefore, is not made immediately available to plants [25,99]. In some situations (such as on a typical Ghanaian cocoa farm) sourcing these co-amendments is challenging as they are not widely available. Some studies have assessed the efficacy of CPH enriched with inorganic fertilisers. The growth of cocoa seedlings was enhanced when CPH compost was used as a potting media than when NPK 15-15-15 was added to topsoil or to the CPH compost [74]. However, when CPH was composted with urea or triple superphosphate, the former supressed plant height while the latter improved growth [46]. The emphasis for future research on organic amendments for cocoa farms in Ghana should be on finding the optimal balance of nutrients in terms of their release and plant availability. Therefore, the study of integrated organic (CPH) and inorganic fertility management in cocoa production systems is needed to find the optimum proportions that combine to increase the sustainability of cocoa production.

In this section we highlight a key 'low hanging fruit' that could enhance the soil health and fertility of cocoa farms. The widespread adoption of CPH compost across all cocoa growing regions of Ghana could help to return nutrients to soils. The use of organic amendments for integrated soil fertility management is more likely to occur on older (21-30 years) monocrop farms and can be encouraged by disseminating information, providing education, and raising awareness [81]. The authors are engaged in such activities as part of a Global Challenges Research Fund project; 'Remediation of Cocoa Soils in Ghana as a Route to more Sustainable Cocoa Production'.

Conclusions

Ghanaian cocoa soils are acidic and have low SOM [82], and the major intervention adopted by farmers to increase soil fertility is the use of mineral fertilisers applied as a single formulation at a nationwide recommended rate. Unfortunately, this approach is suitable for only 6% of the cocoa growing areas. Soil quality of Ghanaian cocoa farms is assessed by measuring physio-chemical properties, based on the assumption that supplying sufficient nutrients to balance the cocoa nutrient requirement alone will increase the quality of the soil. There is currently no consideration of the biological component of soil health in Ghanaian cocoa cropping systems. We recommend development of soil biological indicators that can be used to benchmark interventions that improve soil health and fertility. It is evident that the supply of mineral fertiliser is most effective in soils with high organic matter content [55] and that shade trees on farms increase the supply and mineralisation rate of decomposable organic matter. SOM levels of at least 3% are optimal for cocoa growth [90,91]. The adoption of cocoa agroforestry systems which incorporates an appropriate species mixture and density has the potential to increase the sustainability of cocoa production [17,27,86] and, in farms that are rarely fertilised, the potential of litter fall in these systems to supply nutrients to the cocoa crop should be exploited [8]. However, it is acknowledged that complexities associated with identifying the optimal shade tree species and density, as well as issues associated with shade tree tenure [68], mean that other means to raise SOM levels, increase soil health, and encourage nutrient cycling are required. Site-specific fertiliser recommendations should be implemented that are appropriate to regional soil types and, if possible, integrated with organic amendments that recycle the nutrients in the CPH back into the soil. It is clear that CPH are an important and underutilised resource that have a potential to improve soil health. CPH composting should be encouraged to return nutrients to the soil and decrease the impact of nutrient mining in Ghanaian cocoa production systems.

Funding information

This work was funded by a COCOBOD PhD Scholarship awarded to Dr Betty Amponsah-Doku.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The co-authors acknowledge the kind permission of Betty Amponsah-Doku's husband, Fred Amponsah-Doku, to approve the publication of Betty's PhD literature review posthumously and dedicate this article to her memory.

References

[1] I. Abdulai, et al., Characterization of cocoa production, income diversification and shade tree management along a climate gradient in Ghana, PLoS One 13 (4) (2018) e0195777.
[2] Y. Abou Rajab, et al., Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses, PLoS One 11 (2) (2016) e0149949.
[3] E. Acheampong, et al., Moving forward with REDD+ in Ghana: Shade systems, crown cover, carbon stocks and socio-economic dynamics of smallholder cocoa agroforestry systems, REDD± Energy and Agriculture Programme, Accra, 2014.
[4] K. Acheampong, et al., The influence of shade and organic fertilizer treatments on the physiology and establishment of Theobroma cacao clones, Am. J. Exp. Agric. 6 (6) (2015) 347–360.
[5] S.A. Adeniyi, et al., Development of a composite soil degradation assessment index for cocoa agroecosystems in southwestern Nigeria, Solid Earth 8 (4) (2017) 827–843.
[6] F. Adiyah, et al., Cocoa farmers perceptions of soil organic carbon effects on fertility, management and climate change in the Ashanti region of Ghana, Afr. J. Agric. Res. 17 (5) (2021) 714–725.
[7] S. Agele, A. Agbona, Effects of cocoa pod husk amendment on soil and leaf chemical composition and growth of cashew (Anacardium occidentale L.) seedlings in the Nursery, Am.-Eurasian J. Sustain. Agric. 2 (3) (2008) 219–224.
[8] S. Aleixo, et al., P transformations in cacao agroforests soils in the Atlantic forest region of Bahia, Brazil, Agrofor. Syst. 91 (3) (2017) 423–437.
[9] P. Alvarenga, et al., Recycling organic wastes to agricultural land as a way to improve its quality: A field study to evaluate benefits and risks, Waste Manage. (Oxford) 61 (2017) 582–592.
[10] F. Aneani, K. Ofori-Frimpong, An analysis of yield gap and some factors of cocoa (Theobroma cacao) yields in Ghana, Sustain. Agric. Res. 2 (4) (2013).
[11] L.C. Anglaaere, et al., The effect of land use systems on tree diversity: farmer preference and species composition of cocoa-based agroecosystems in Ghana, Agrofor. Syst. 81 (3) (2011) 249–265.
[12] D.C. Anthonio, E. Aikins, Reforming Ghana ś cocoa sector-an evaluation of private participation in marketing, Masters Thesis, Lulea University of Technology, Sweden, 2009.
[13] Q. Araujo, et al., Soil quality index for cacao cropping systems, Arch. Agron. Soil Sci. 64 (13) (2018) 1892–1909.
[14] R. Asara, The relationships between on-farm shade trees and cocoa yields in Ghana, PhD Thesis, Department of Geoscience and Natural Resource Management, University of Copenhagen, Frederiksberg, 2015.
[15] R. Asare, A review on cocoa agroforestry as a means for biodiversity conservation, World Cocoa Foundation Partnership Conference, Brussels, Citeseer, 2006.
[16] R. Asare, et al., Influences of shading and fertilization on on-farm yields of cocoa in Ghana, Exp. Agric. 53 (3) (2017) 416–431.
[17] R. Asare, et al., On-farm cocoa yields increase with canopy cover of shade trees in two agro-ecological zones in Ghana, Clim. Dev. 11 (5) (2019) 435–445.
[18] R. Asiamah, et al., Soil resources in Ghana, in: B.A. Bationo, R. Tabo, B.S. Waswa, et al. (Eds.), Synthesis of Soil, Water and Nutrient Management Research in the Volta Basin, Ecomedia Ltd, Nairobi, 2008, pp. 25–41. Nairobi, Kenya, Ecomedia Ltd:.
[19] M. Asigbaase, et al., Biomass and carbon stocks of organic and conventional cocoa agroforests, Ghana, Agric., Ecosyst. Environ. 306 (2021) 107192.
[20] M. Asigbaase, et al., Tree diversity and its ecological importance value in organic and conventional cocoa agroforests in Ghana, PLoS One 14 (1) (2019) e0210557.
[21] A.R. Atangana, et al., Rebuilding Tree Cover in Deforested Cocoa Landscapes in Côte d'Ivoire: Factors Affecting the Choice of Species Planted, Forests 12 (2) (2021) 198.
[22] V.C. Baligar, N.K. Fageria, Soil aluminum effects on growth and nutrition of cacao, Soil Sci. Plant Nutr. 51 (5) (2005) 709–713.
[23] B. Basso, et al., Review of crop yield forecasting methods and early warning systems, in: Proceedings of the first meeting of the scientific advisory committee of the global strategy to improve agricultural and rural statistics, FAO Headquarters, Rome, Italy, 2013.
[24] A. Bationo, et al., in: Assessment of soil fertility status and integrated soil fertility management in Ghana. Improving the Profitability, Sustainability and Efficiency of Nutrients through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems, Springer, 2018, pp. 93–138.
[25] M.P. Bernal, et al., Current approaches and future trends in compost quality criteria for agronomic, environmental, and human health benefits. Advances in agronomy, Elsevier 144 (2017) 143–233.
[26] D. Bisseleua, et al., Biodiversity conservation, ecosystem functioning, and economic incentives under cocoa agroforestry intensification, Conserv. Biol. 23 (5) (2009) 1176–1184.
[27] W.J. Blaser, et al., Shade trees have limited benefits for soil fertility in cocoa agroforests, Agric., Ecosyst. Environ. 243 (2017) 83–91.
[28] D.O. Boateng, et al., Impact of illegal small scale mining (Galamsey) on cocoa production in Atiwa district of Ghana, Int. J. Adv. Agric. Res. 2 (2014) 89–99.
[29] D. Bossio, et al., Soil microbial community response to land use change in an agricultural landscape of western Kenya, Microb. Ecol. 49 (1) (2005) 50–62.
[30] C. Breisinger, et al., The role of cocoa in Ghana's future development. Ghana Strategy Support Program (GSSP) Background Paper No. GSSP 0011, International Food Policy Research Institute (IFPRI), 2008.

[31] R.M. Cezar, et al., Soil biological properties in multistrata successional agroforestry systems and in natural regeneration, Agrofor. Syst. 89 (6) (2015) 1035–1047.
[32] D.C. Coleman, et al., Fundamentals of soil ecology, Academic press, 2017.
[33] M. da Silva Moço, et al., Soil and litter fauna of cacao agroforestry systems in Bahia, Brazil, Agrofor. Syst. 76 (1) (2009) 127–138.
[34] E. Dawoe, Conversion of natural forest to cocoa agroforest in lowland humid Ghana: impact on plant biomass production, organic carbon and nutrient dynamics, PhD Thesis, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, 2009.
[35] E.K. Dawoe, et al., Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana, Plant Soil 330 (1) (2010) 55–64.
[36] E.K. Dawoe, et al., Effect of land-use conversion from forest to cocoa agroforest on soil characteristics and quality of a Ferric Lixisol in lowland humid Ghana, Agrofor. Syst. 88 (1) (2014) 87–99.
[37] A. Daymond, et al., Mapping cocoa productivity in Ghana, Indonesia and Côte d'Ivoire. International Symposium on Cocoa Research (ISCR), Lima, Peru, 13-17 November 2017, International Cocoa Organization (ICCO), 2018.
[38] M.D.G. de Luna, et al., Removal of sodium diclofenac from aqueous solution by adsorbents derived from cocoa pod husks, J. Environ. Chem. Eng. 5 (2) (2017) 1465–1474.
[39] E. Dossa, et al., in: An assessment of inherent chemical properties of soils for balanced fertilizer recommendations for cocoa in Ghana. Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems, Springer, 2018, pp. 325–336.
[40] E. Dossa, et al., in: Improving fertilizer recommendations for cocoa in Ghana based on inherent soil fertility characteristics. Improving the profitability, sustainability and efficiency of nutrients through site specific fertilizer recommendations in West Africa agro-ecosystems, Springer, 2018, pp. 287–299.
[41] O. Doungous, et al., Potentials of cocoa pod husk-based compost on Phytophthora pod rot disease suppression, soil fertility, and Theobroma cacao L. growth, Environ. Sci. Pollution Res. 25 (25) (2018) 25327–25335.
[42] B. Duguma, et al., Smallholder cacao (Theobroma cacao Linn.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities, Agrofor. Syst. 51 (3) (2001) 177–188.
[43] T.K. Elisée, T. Emile, Valorisation of Cocoa Pod's Shells Production in the Area of South-Central Cameroon by Composting with Addition of Tithonia Diversifolia, Int. J. Res. Pharmacy Biosci. 4 (4) (2017) 32–42.
[44] G.O. Essegbey, E. Ofori-Gyamfi, Ghana cocoa industry—an analysis from the innovation system perspective, Technol. Investment 3 (4) (2012) 24853.
[45] FAOSTAT (2020). License: CC BY-NC-SA 3.0 IGO. Extracted from: www.fao.org/faostat/. Data of Access: 08-04-2021.
[46] C. Fidelis, B.R. Rao, Enriched cocoa pod composts and their fertilizing effects on hybrid cocoa seedlings, Int. J. Recycl. Organic Waste Agric. 6 (2) (2017) 99–106.
[47] N. Fierer, et al., How microbes can, and cannot, be used to assess soil health, Soil Biol. Biochem. 153 (2021) 108111.
[48] A. Fontes, et al., Nutrient stocks in litterfall and litter in cocoa agroforests in Brazil, Plant Soil 383 (1) (2014) 313–335.
[49] J. Gockowski, D. Sonwa, Biodiversity and smallholder cocoa production systems in West Africa, Sustain. Tree Crops Program (STCP) Working Paper Ser. (2008) 6.
[50] J. Goma-Tchimbakala, et al., Comparison of some soil chemical properties in four Terminalia superba plantations and a natural tropical forest in Mayombe, Congo, J. Appl. Sci. 8 (22) (2008) 4152–4158.
[51] P. González-García, Activated carbon from lignocellulosics precursors: a review of the synthesis methods, characterization techniques and applications, Renew. Sustain. Energy Rev. 82 (2018) 1393–1414.
[52] D.-G. Hougni, et al., How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching, Plant Soil 463 (1) (2021) 155–170.
[53] M.E. Isaac, et al., Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of Theobroma cacao by vector analysis, Nutr. Cycling Agroecosyst. 78 (2) (2007) 155–165.
[54] P. Jadin, J. Snoeck, La methode du diagnostic sol pour calculer les besoins en engrais des cacaoyers, Café Cacao Thé (1985).
[55] T. Jayne, et al., Towards a sustainable soil fertility strategy in Ghana. Food Security Policy Research Papers, Department of Agricultural, Food, and Resource Economics, Michigan State University, East Lansing, Michigan, USA, 2015.
[56] C. Kayode, et al., Nutrient Release Pattern of Cocoa Pod Husk Based Composts in an Incubation Study, Int. J. Plant Soil Sci. 4 (2015) 513–520.
[57] S. Kolavalli, M. Vigneri, The cocoa coast: The board-managed cocoa sector in Ghana, International Food Policy Research Institute, Washington DC, 2018.
[58] J.E. Kongor, et al., Assessment of soil fertility and quality for improved cocoa production in six cocoa growing regions in Ghana, Agrofor. Syst. 93 (4) (2019) 1455–1467.
[59] A. Kroeger, et al., Forest-and Climate-Smart Cocoa in Côte d'Ivoire and Ghana: Aligning Stakeholders to Support Smallholders in Deforestation-Free Cocoa, World Bank, 2017.
[60] M. Lawal, et al., Bio-Remedial Potentials of Cocoa and Kolanut Pod Residues for Root-Knot Nematodes (Meloidogyne spp.) Management and Soybean Productivity, J. Organic Agric. Environ. 5 (1) (2017).
[61] F. Lu, et al., Valorisation strategies for cocoa pod husk and its fractions, Curr. Opin. Green Sustain. Chem. 14 (2018) 80–88.
[62] A. Mohammed, et al., Nutrient Stocks and Distribution in Ghanaian Cocoa Ecosystems, Int. J. Agronomy 2020 (2020) 8856314.
[63] A.M. Mohammed, et al., Carbon storage in Ghanaian cocoa ecosystems, Carbon Balance Manage. 11 (1) (2016) 1–8.
[64] R. Mortimer, et al., Supporting and regulating ecosystem services in cacao agroforestry systems, Agrofor. Syst. 92 (6) (2018) 1639–1657.
[65] E.I. Moyin-Jesu, Use of plant residues for improving soil fertility, pod nutrients, root growth and pod weight of okra (Abelmoschus esculentum L), Bioresour. Technol. 98 (11) (2007) 2057–2064.
[66] M.E. Munongo, et al., Production and characterization of compost manure and biochar from cocoa pod husks, Int. J. Adv. Sci. Res. 2 (2) (2017) 26–31.
[67] K.J.-C. N'guessan, et al., Mapping cacao fertiliser requirements in Côte d'Ivoire, Imperial J. Interdiscip. Res. 3 (6) (2017) 2454 -1362.
[68] F. Nasser, et al., Climate-Smart Cocoa in Ghana: How Ecological Modernisation Discourse Risks Side-Lining Cocoa Smallholders, Front. Sustain. Food Syst. 4 (2020) 73.
[69] A. Nigussie, et al., Agricultural waste utilisation strategies and demand for urban waste compost: evidence from smallholder farmers in Ethiopia, Waste Manage. (Oxford) 44 (2015) 82–93.
[70] S. Obalum, et al., Soil organic matter as sole indicator of soil degradation, Environ. Monit. Assess. 189 (4) (2017) 176.
[71] B.D. Obiri, et al., Financial analysis of shaded cocoa in Ghana, Agrofor. Syst. 71 (2) (2007) 139–149.
[72] D. Oduro-Mensah, et al., Nutritional value and safety of animal feed supplemented with Talaromyces verruculosus-treated cocoa pod husks, Sci. Rep. 10 (1) (2020) 1–16.
[73] C. Ofori-Boateng, K.T. Lee, The potential of using cocoa pod husks as green solid base catalysts for the transesterification of soybean oil into biodiesel: Effects of biodiesel on engine performance, Chem. Eng. J. 220 (2013) 395–401.
[74] K. Ofori-Frimpong, et al., Relative efficacy of cocoa pod husk-based compost on growth and nutrient uptake of cocoa seedlings in the nursery, Ghana J. Agric. Sci. 43 (1) (2010) 55–59.
[75] K. Ofori-Frimpong, et al., Shaded versus unshaded cocoa: implications on litter fall, decomposition, soil fertility and cocoa pod development. symposium on multistrata agroforestry systems with perennial crops, CATIE Turrialba, Costa Rica, 2007.
[76] B. Olu-Owolabi, et al., Biosorption of Cd2+ and Pb2+ ions onto mango stone and cocoa pod waste: Kinetic and equilibrium studies, Sci. Res. Essays 7 (15) (2012) 1614–1629.
[77] K. Opoku-Ameyaw, et al., Cocoa manual—a source book for sustainable cocoa production, Cocoa Research Institute of Ghana, Tafo, 2010.
[78] E. Owusu-Bennoah, C. Visker, Organic wastes hijacked, ILEIA Newsletter 10 (3) (1994) 12–13.
[79] S.D. Parra-González, J. Rodriguez-Valenzuela, Determination of the soil quality index by principal component analysis in Cocoa Agroforestry System in the Orinoco Region, Colombia, J. Agric. Ecol. Res. Int. (2017) 1–8.

[80] J. Pérez-Flores, et al., Leaf litter and its nutrient contribution in the cacao agroforestry system, Agrofor. Syst. 92 (2) (2018) 365–374.
[81] A.K. Quaye, et al., Predictors of integrated soil fertility management practice among cocoa farmers in Ghana, J. Agric. Food Res. (2021) 100174.
[82] A.K. Quaye, et al., Geospatial distribution of soil organic carbon and soil pH within the cocoa agroecological zones of Ghana, Geoderma 386 (2021) 114921.
[83] J.E. Raneri, et al., A rapid tree diversity assessment method for cocoa agroforestry systems, Ecol. Indic. 130 (2021) 107993.
[84] F. Ruf, G. Schroth, Chocolate forests and monocultures: a historical review of cocoa growing and its conflicting role in tropical deforestation and forest conservation, in: Agroforestry and biodiversity conservation in tropical landscapes, Island Press, Washington, 2004, pp. 107–134.
[85] F. Saladini, et al., Sustainability assessment of selected biowastes as feedstocks for biofuel and biomaterial production by emergy evaluation in five African countries, Biomass Bioenergy 85 (2016) 100–108.
[86] M. Sauvadet, et al., Cocoa agroforest multifunctionality and soil fertility explained by shade tree litter traits, J. Appl. Ecol. 57 (3) (2020) 476–487.
[87] D. Snoeck, et al., The soil diagnostic method for formulating fertilizer requirements on cocoa in Ghana, 4th International Conference of the African Soil Science Society, Accra, Ghana, 2007.
[88] D. Snoeck, et al., Temporal changes in VAM fungi in the cocoa agroforestry systems of central Cameroon, Agrofor. Syst. 78 (3) (2010) 323–328.
[89] D. Snoeck, et al., Mapping fertilizer recommendations for cocoa production in Ghana using soil diagnostic and GIS tools, West Afr. J. Appl. Ecol. 17 (2010) 97–107.
[90] D. Snoeck, et al., in: Cacao nutrition and fertilization. Sustainable agriculture reviews, Springer, 2016, pp. 155–202.
[91] E. Somarriba, et al., Carbon stocks and cocoa yields in agroforestry systems of Central America, Agric., Ecosyst. Environ. 173 (2013) 46–57.
[92] G. Sosu, Growth of cocoa seedlings as affected by different growth media and different polybag sizes, PhD Thesis, University of Ghana, 2014.
[93] S. Sriharti, S. Dyah, Utilization of cacao waste (Theobroma cacao L) for composting by using various activator materials, in: AIP Conference Proceedings, AIP Publishing LLC, 2018.
[94] M. Syamsiro, et al., A preliminary study on use of cocoa pod husk as a renewable source of energy in Indonesia, Energy Sustain. Dev. 16 (1) (2012) 74–77.
[95] F. Teal, et al., Ghana cocoa farmers survey 2004: report to Ghana Cocoa Board, CSAE-Oxford University, 2006.
[96] D.A. Tetteh, et al., Effect of cocoa farming intensification on biodiversity and ecosystem properties in southern Ghana, J. Ecol. Natl. Environ. 10 (7) (2018) 172–181.
[97] R.P. Udawatta, et al., Agroforestry practices and soil ecosystem services, in: M.M. Al-Kaisi, B. Lowery (Eds.), Soil health and intensification of agroecosytems, Academic Press, London, UK, 2017, pp. 305–333.
[98] P. Vaast, E. Somarriba, Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation, Agrofor. Syst. 88 (6) (2014) 947–956.
[99] J.A. Van Vliet, K. Giller, Mineral nutrition of cocoa: a review, Adv. Agron. 141 (2017) 185–270.
[100] L.C. Vriesmann, C.L. de Oliveira Petkowicz, Cacao pod husks as a source of low-methoxyl, highly acetylated pectins able to gel in acidic media, Int. J. Biol. Macromol. 101 (2017) 146–152.
[101] A.C. Wartenberg, et al., Does shade tree diversity increase soil fertility in cocoa plantations? Agric., Ecosyst. Environ. 248 (2017) 190–199.
[102] M. Wessel, P.F. Quist-Wessel, Cocoa production in West Africa, a review and analysis of recent developments, NJAS-Wageningen J. Life Sci. 74 (2015) 1–7.
[103] World Bank (2013). Ghana : Cocoa Supply Chain Risk Assessment. Washington, DC.
[104] I.W.G. WRB, World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps, Food and Agriculture Organization of the United Nations Rome, 2015.
[105] P.A. Zuidema, et al., A physiological production model for cocoa (Theobroma cacao): model presentation, validation and application, Agric. Syst. 84 (2) (2005) 195–225.