INTEGRATED SOIL FERTILITY MANAGEMENT

DEO-GRATIAS HOUGNI

INTEGRATED SOIL FERTILITY MANAGEMENT: A PATH TO SUSTAINABLE INTENSIFICATION OF COCOA PRODUCTION IN WEST AFRICA?

DEO-GRATIAS HOUGNI

INVITATION

You are cordially invited

to attend the public defense of
the PhD thesis entitled:

Integrated soil fertility management: a path to sustainable intensification of cocoa production in West Africa?

by
Deo-Gratias HOUGNI

on Wednesday, 21 June 2023
at 01:30 PM

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Propositions

1. Fertilizer is great for agronomists, but not for old stands of cocoa trees in smallholder Nigerian farms.
   (this thesis)

2. Mother nature covers up nutrient mismanangement in cocoa fields.
   (this thesis)

3. Engineering nitrogen-fixing maize cultivars for African farmers goes against at least three Sustainable Development Goals.

4. Achieving circularity at global scale is a pipe dream.

5. A reduction in the global supply of luxury food ingredients would benefit both smallholder farmers and consumers.

6. Our society is zealous in fighting the negative impacts of climate change, but puts blinkers on to address its major causes.

Propositions belonging to the thesis, entitled

Integrated soil fertility management: a path to sustainable intensification of cocoa production in West Africa?

Deo-Gratias Hougni
Wageningen, 21-06-2023

Integrated soil fertility management: a path to sustainable intensification of cocoa production in West Africa?

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Integrated soil fertility management: a path to sustainable intensification of cocoa production in West Africa?

Deo-Gratias J. M. Hougni

Thesis

Submitted in fulfilment of the requirements for the degree of doctor

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A tous ceux qui n’y croient plus.

Abstract

Cocoa yields in West Africa have stagnated at about 300-400 kg ha^{-1} mainly because the crop is produced in low-input systems. Integrated soil fertility management (ISFM) is proposed to sustainably increase current yields, but its implementation options are poorly defined in tree crop systems. This thesis aimed to explore the potential of ISFM to increase cocoa yields and to deepen the understanding of nutrient cycling in smallholder cocoa farms. A literature review was combined with laboratory experiments, farm surveys and on-farm trials.

The use of improved germplasm, an adequate combination of mineral fertilizers and organic inputs, best crop management, and local adaptation aiming at maximising agronomic use efficiency of the applied nutrients and improve crop productivity form the basis of ISFM. But do these principles apply to tropical tree crops? Based on the large amounts of carbon cycled through leaf litter in mature cocoa crops and the limited availability of on-farm organic resources in smallholder farms, I argue that the core principle of ISFM i.e., combining organic and mineral nutrient inputs, needs to be re-interpreted. Moreover, knowledge gaps on crop nutrition and characteristics of existing cocoa fields impose constraints to effectively implement ISFM. As such, partial application of ISFM in typical West African farms can only result in modest yield increases. How large and how variable are the yield increases associated with fertilizer application? Logically, nutrient supply is the main way to halt nutrient mining and boost productivity in low-input systems. However, an on-farm trial demonstrated that in the short term, none of the three tested fertilizer formulations is the best entry-point for cocoa yield increase in south-western Nigeria. Large between-farm variations in fertilizer yield responses were observed along with inconsistent effects of farmer practices, which further complicates formulation of fertilizer recommendations in the study area.

What ISFM practices can deliver in existing cocoa farms is to improve nutrient cycling, especially regarding the management of organic residues. How much do litterfall and cocoa pod husk management contribute to improved nutrient cycling? Returning commonly abandoned cocoa pod husks to trees can tighten nutrient loops, but the laboratory experiment showed that timing was critical to recover most of

the potassium (K) and reduce on-spot nutrient losses. Besides, the ecological significance of litterfall was confirmed. Litterfall ensures considerable above to below-ground nutrient flows; but nitrogen (N) and phosphorus (P) transfer rates are poorly estimated when the effect of macrofauna is not accounted for as in previous cocoa litterbag studies.

In conclusion, the current knowledge of the cocoa nutrition is limited and insufficient to adequately address the yield gap challenge through ISFM. Testing ISFM practices during establishment or in young mature trees is valuable as it may yield more promising results than in old trees. Since ISFM is not the sole path to sustainable intensification, other approaches must concurrently be explored and possibly integrated.

Table of contents

Chapter 1. General introduction........ 1

Chapter 2. Does the paradigm of integrated soil fertility management apply to perennials? Reviewing the case of cocoa (*Theobroma cacao* L.) 19

Chapter 3. Macrofauna accelerates nutrient cycling through litterfall in cocoa........ 63

Chapter 4. How rich are decaying cocoa pod husks? The kinetics of nutrient leaching........ 87

Chapter 5. Lack of positive short-term responses to fertilizer in existing cocoa crops demands a re-think of entry-points for intensification........ 115

Chapter 6. General discussion........ 145

References........ 169

Summary........ 201

Acknowledgements........ 205

PE&RC Training and Education statement........ 207

About the author........ 209

1

Chapter 1

General Introduction

1.1. Changing views on cocoa and soil fertility

1.1.1. Soil fertility management paradigms in sub-Saharan Africa

“To forget how to dig the earth and to tend the soil is to forget ourselves” said Mahamat Gandhi to acknowledge the often overlooked hard work of farmers. It further reminds us of the link between soil resource management and societal development. This thought is particularly relevant in sub-Saharan Africa (SSA), where agriculture remains the backbone of national economies and the main provider of employment (Shimeles et al. 2018; FAO et al. 2021). For West African countries, the potentially available cropland is estimated at less than 15 million ha under some profitability assumptions (Chamberlin et al. 2014). Under current management, the projected land availability will no longer match the unprecedented population growth (Deen-Swarray et al. 2020); hence, soil fertility decline has become a major concern in achieving food security and eradicating rural poverty in the region (Tully et al. 2015; Vanlauwe et al. 2015b). Cereal yields in SSA have stagnated at about 41% of the world average over the last 20 years (FAO 2022), even though soil fertility research in Africa has been a major focus since colonial times (Mutsaers et al. 2017; Ross 2017). Guidelines evolved to manage African soil fertility better, with noticeable paradigm shifts over time. Vanlauwe et al. (2017) summarized these changes over the last fifty years. At first the primary task of soil fertility researchers in SSA was to map soil resources and identify which crops could grow best where and with what technology. It quickly became essential to propose an alternative to swidden agriculture to improve food self-sufficiency and sustain the extractive economy of cash crops (Nye and Greenland 1960). Given the success of the Green Revolution in other regions, fertilizers were introduced to boost crop productivity. The paradigm of “external inputs” was thus the mainstream in the 1970s but faced practical challenges in implementation, including the lack of investment and adequate markets, high transaction costs, inaccessibility, and low returns due to soil constraints and/or climatic risks (Dawson et al. 2016; Otsuka and Muraoka 2017; Voortman 2013). The “low external input” approach took ground in the 1980s and sought to replace the unavailable fertilizer nutrients with locally available organic resources: mostly cover crops, manure and compost.

Unfortunately the production, collection, and application of the enormous required quantities of organic resources took much work. Besides, organic manures were not as effective as mineral fertilizer in the short term. Interestingly, the combination of organic and mineral resources proved to ensure the highest yields compared to the sole application of either (Miao et al. 2010; Bationo et al. 2012b) by virtue of improved demand-supply synchrony and additional functions performed by organic matter (Vanlauwe 2004). This combination of several approaches was the base of "integrated nutrient management", which has several variants nowadays (Wu and Ma 2015; Kebenei et al. 2021 ; Ayeni 2011; Blesh et al. 2022; Drinkwater and Snapp 2022) of which "Integrated Soil Fertility Management" (ISFM) is the most prominent (Bado and Bationo 2018; Bekunda et al. 2022).

The definition of ISFM provided by Vanlauwe et al. (2010) will be used throughout this thesis. The paradigm of ISFM has become a cornerstone of the soil fertility management literature (Figure 1.1). Implementing ISFM practices aligns with climate-smart agriculture (Gram et al. 2020; Gebreyohannes and Reda 2019) and falls under broader themes such as Integrated Natural Resources Management and Sustainable Intensification (Kihara et al. 2022; Öborn et al. 2017; Vanlauwe et al. 2014). The success of implementing ISFM is undisputed (Bationo et al. 2007; Tittonell et al. 2008; Kihara et al. 2022), and it is appealing to extend its domain to new contexts. Maize-based cropping systems were the origin of the ISFM concept (Vanlauwe et al. 2005), but other cereals (Kebenei et al. 2021; Adamou et al. 2012; Oikeh et al. 2008) and grain legumes followed (Njira et al. 2020; Goswami et al. 2022). Next, ISFM was applied in cropping systems based on roots and tubers (Pypers et al. 2011), and even fruit crops are nowadays included (Srivastava et al. 2021). Tropical tree crops received less attention from soil fertility researchers than most of the staple crops, which appeared to be more important for food self-sufficiency in SSA. Since the global chocolate industry aims at sustainable cocoa production intensification, ISFM has become the ideal means promoted to improve current yields.

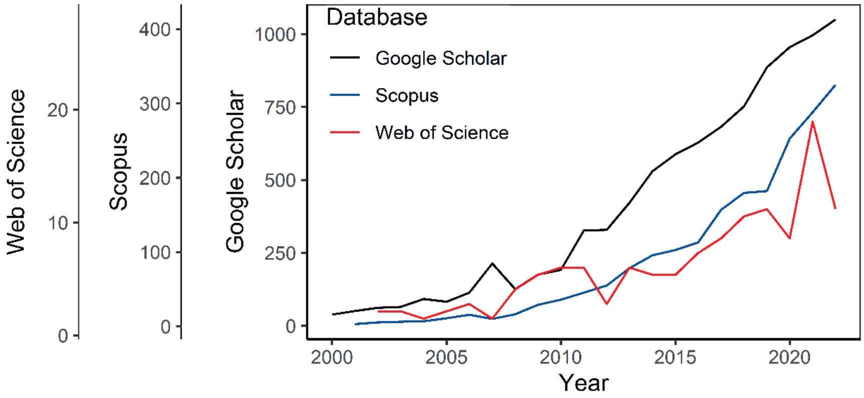

Figure 1.1: Number of “Integrated soil fertility management” citations per year in three major search engines.

1.1.2. Global challenges in cocoa production

According to the legend, when Ferdinand Colombus first saw cocoa beans in 1502, he recorded them as “almonds” (Coe and Coe 2013). At that time, cocoa was only an edible forest product in Mesoamerica, and crop yields were certainly not the major concern of the privileged Maya and Aztec peoples who savoured its beverage. Even though cocoa beans already served as a regional currency (Vail 2009), locating forest patches hosting large numbers of cocoa trees was probably the best one could aim for. Ferdinand and his father, Christopher, probably did not imagine that the indigenous “almonds” would lead to an economy worth hundred billion dollars five centuries later.

Nowadays, five million tons of cocoa beans are traded annually (ICCO 2021), and the demand is projected to increase steadily, thanks to an emerging market formed by a growing middle class in developing countries. The current demand is met by producers all located between latitudes 20º South and 20º North. Smallholder farmers are responsible for 90% of the global production, and four African countries (Côte d’Ivoire, Ghana, Nigeria, Cameroon) provide 70% of it. However, the challenge is that smallholder farming in SSA is confronted with several constraints, of which low yields are only one facet. The main challenges of the global cocoa industry are intricately embedded in one another and may be described as wicked problems (van Bueren et al. 2014). Poor farming practices, ageing of tree stocks, land degradation, pests and diseases, yield decline, instability of cocoa prices, poverty of cocoa farmers, child labour, deforestation and loss of biodiversity, and vulnerability to climate change are the most cited (Clough et al. 2009; Matissek et al. 2012; Macek et al. 2018; Fold and Neilson 2016; Bunn et al. 2017).

Until now, cocoa production was able to meet the global demand through crop expansion, causing deforestation in areas with high biodiversity value. The forest land conversion rate to cocoa in West Africa was estimated at 83,000 and 132,000 ha^{-1} $year^{-1}$ during the 1986-2000 and 2000-2013 periods respectively (Ordway et al. 2017). Even recently, considerable forest loss was mainly attributed to cocoa cultivation in Ghana and Côte d'Ivoire (Brobbey et al. 2020; Ashiagbor et al. 2022; Renier et al. 2022). Cocoa-driven deforestation has become a political issue (Sassen et al. 2022), with tensions between development objectives and conservation efforts. Chocolate consumers in developed countries have gained awareness of the sustainability challenges in the cocoa sector and stimulated stronger commitment by industry and policymakers. More stringent regulations are progressively set to eliminate deforestation directly linked to cocoa expansion (e.g., Fermeglia 2022). However, different cocoa production systems coexist, which are not all responsible for deforestation, at least not to the same extent. For instance, the so called "full-sun cocoa" (monoculture) established on forest land requires a complete replacement of the native vegetation with cocoa trees only (in the mature phase) whereas cocoa agroforestry often involves keeping some native trees and/or planting other tree species (Maney et al. 2022). Cocoa can also be established on degraded pasture or farmland, which could be seen as an afforestation process (Jagoret et al. 2012; Nijmeijer et al. 2019b). Monitoring cocoa-driven deforestation can be difficult in many instances. A better knowledge of cocoa production systems is therefore required.

1.2. Cocoa production systems in West Africa

1.2.1. Overview of farming practices

The ecology and agronomy of cocoa are described in great detail in textbooks (e.g., Hebbar et al. ; Nair 2009; Dand 2011; Guastella et al. 2017; Diby et al. 2017). I only present how cocoa is grown in this section, referencing smallholder farming in West Africa. Practices that are related to soil fertility management are presented in section 2.2. Data presented hereafter are mainly drawn from the Royal Tropical Institute's (KIT) survey in Côte d'Ivoire and Ghana (Bymolt et al. 2018b) and the CocoaSoils programme[1] baseline study conducted in Côte d'Ivoire, Ghana, Cameroon and Nigeria. The CocoaSoils baseline survey (2019) ran with 3170 smallholder cocoa farmers, essentially to update current status of cocoa farming in West Africa. Sampling was led by a research team in collaboration with private partners (companies) involved the program. The results presented in this chapter are based on a preliminary data analysis; figures may vary slightly when the final report is published. Daymond et al. (2022) identified a diversity of cocoa production systems and proposed simple criteria for smallholder cocoa farm typology, including the planting materials, the intensity of management (crop husbandry), the structure of the tree population in the mature phase, land tenure, and the income portfolio of the growers.

Cocoa is often established on arable farmland and degraded pastures, or, as often observed in African countries, in old fallows and forests. Fallows and forestlands were the previous land-uses for 73, 68, 73 and 76% of cocoa fields in Cameroon, Ghana, and Nigeria, respectively (CocoaSoils baseline survey 2019). In the latter case, the forest trees can be completely cleared. However, usually, smallholder farmers proceed by progressive thinning, which provides the necessary shade needed in the early development stages of cocoa plantlets (Fowler 2009). As cocoa trees grow, the shade requirements decrease, but the final shade level is system-dependent. There is a continuum from full-sun (with only cocoa trees in monoculture) to heavily shaded agroforestry systems (characterized by large diversity and abundance of tree species with usually a low density of cocoa trees). Full-sun cocoa is usually more

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[1] A description of the programme is available at https:://cocoasoils.org/

intensively managed than agroforestry systems. Shade trees are not only large forest remnants that cannot be cut, but farmers can plant fruit trees, timber trees, and/or leguminous species such as *Gliricidia sepium* Jacq. to improve soil fertility. Farmers also actively manage natural regrowth so that the tree composition is dynamic, as shown by Jagoret et al. (2018). The tree configuration greatly influences light interception and its distribution through the canopy, which determines the potential of carbon assimilation per stratum and affects the micro-climate (relative humidity, temperature). Long-term management of cocoa agroforestry systems is associated with rehabilitation and/or renovation of the initial cocoa tree stocks. Ageing of cocoa trees is often cited as a major cause of yield decline (Voora et al. 2019; Vekua 2013), especially in the oldest settlements also known as “pioneer fronts” (Cilas and Bastide 2020). However, current farmers do not maintain the fields they have inherited only, and the acuteness of the ageing problem is country-specific (Figure 1.2). Therefore, claims about ageing of cocoa fields must be relativized.

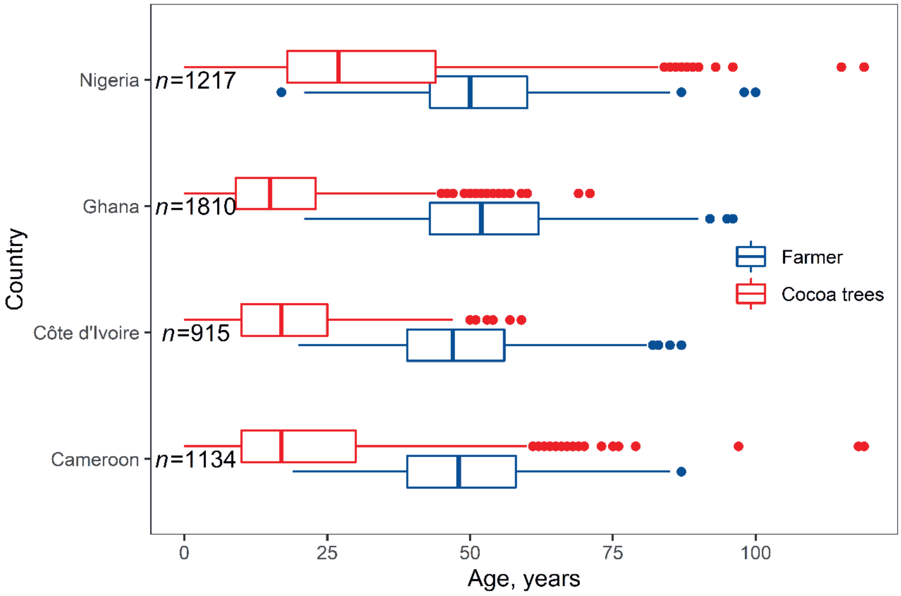


Figure 1.2: Age of cocoa farmers (blue) and of cocoa trees (red) on smallholder farms as reported by interviewees. *n* is the number of surveyed cocoa fields.

In Africa, cocoa fields are mainly planted with seedlings: the use of clonal material is still uncommon, unlike in Latin America. Seeds are planted directly in outfields (planting at stake) or raised in a nursery first and later transplanted. Improved varieties (mostly hybrids) are claimed to be used by more than 50% of farmers in Côte d'Ivoire and Ghana (Bymolt et al. 2018a), but performances of national breeding programs vary from country to country, and formal dissemination channels often prove ineffective. Consequently, the CocoaSoils baseline survey revealed that 54% of farmers in these two countries exclusively acquired planting materials from their own fields or from peers. Since cocoa is an allogamous species, superior traits are poorly maintained during farmer-to-farmer seed exchanges, and genetic heterogeneity characterizes their plantations.

As previously mentioned, cocoa is usually established under the shade of other plants because young plantlets are sensitive to heat and water stress (Balasimha et al. 1991). When previous land use does not provide the required shade, other crops are established during the first years of cocoa seedling growth to provide shade. Preferred crops in West Africa are bananas and plantains, but cassava and cocoyam are also used as temporary shade (Gockowski 2019). During this period, farming practices are mainly determined by the dominant crop. The sensitivity of the young cocoa trees to drought determines the need for replacement, which is not systematic in smallholdings: this often leads to a more or less pronounced heterogeneity in tree age after establishment and irregular spatial gaps within the fields. In this thesis, I generally attribute the modal age of trees in a field to the whole field for simplicity.

From an age of 2-5 years, cocoa trees progressively enter a productive phase and the vegetative growth rate decreases. Once the cocoa canopy reaches its full closure, the trees are considered mature. At maturity, cocoa management generally involves weed, pest, and disease control, pruning, and harvest. Weed pressure decreases with a higher and denser tree canopy. Weeds are controlled with herbicides or manually, done once or twice a year. Pest and diseases are geographically distributed, with black pod disease (mainly caused by *Phytophthora palmivora* and *P. megakarya*) being the major cause of yield loss under moist environments. Mirids (*Sahlbergella singularis* Hagl., *Distantiella theobroma* Distant) are more present in drier areas (Mortimer et al. 2017; Afoakwa 2014). The cocoa swollen shoot virus (CSSV) disease is a serious threat to production, especially in Côte d'Ivoire and Ghana (Amon-Armah et al. 2021). Breeding for resistance in a tree crop is a costly and time-consuming process; therefore, farmers usually employ cultural practices and apply pesticides: mainly insecticides in Côte d'Ivoire and Ghana and fungicides in Cameroon and Nigeria (Table 1.1). A large number of active ingredients are available on a poorly regulated market and are often misused by farmers with low literacy (Aidoo et al. 2019), with foreseeable consequences on the environment and human health (de Silva et al. 2010; Fosu-Mensah et al. 2016; Vaikosen et al. 2019). Pruning is an important management practice that applies to both young and mature phases for cocoa trees and shade trees when possible. Mature cocoa trees are pruned to regulate vegetative growth, reduce pest and disease incidence, and ease other farm activities such as harvest. Shade-tree pruning increases light penetration into the cocoa canopy and accelerates nutrient return to topsoil. On average, West African farmers prune cocoa trees once or twice per year; however, there is a large variability in the quantity and quality of pruning. During flowering, cocoa trees may be hand-pollinated to increase yields. However, despite growing evidence of the benefits of hand-pollination (Groeneveld et al. 2010; Toledo-Hernández et al. 2020), this is not common among smallholder farmers in West Africa (Umeh et al. 2022). A cocoa crop produces pods with beans year-round, with seasonal peaks. Ripe cocoa pods are picked at harvest, gathered in piles, and broken to extract the cocoa beans. In Côte d'Ivoire, Ghana, Cameroon and Nigeria, farmers first ferment and then dry cocoa beans before sale.

Table 1.1: Average use of agrochemicals in *n* surveyed fields in four West African countries on 3170 cocoa farms in total.

Type of inputs	Countries				
	Cameroon (*n*=1193)	Côte d'Ivoire (*n*=953)	Ghana (*n*=1894)	Nigeria (*n*=1256)	4 countries (*n*=5296)
Fertilizer (%)	51	48	38	7	36
Fungicide (%)	85	29	57	90	66
Insecticide (%)	61	68	86	61	70
Herbicide (%)	12	6	25	6	13

1.2.2. Current soil fertility status and management in cocoa

Various indicators are used to describe soil fertility in cocoa, of which pH, cation exchange capacity (CEC), macro-nutrient concentrations (especially P), and soil organic carbon content (SOC) are considered the most relevant (Kongor et al. 2019; Quaye et al. 2021b; Adeniyi et al. 2018; Abdulai et al. 2020). However, there has yet to be a consensus about desirable ranges and thresholds. For smallholder farmers in SSA, the most important descriptors are related to crop growth, yields and selected physical and biological soil properties, including soil colour, workability, water-holding capacity, and macrofauna abundance (Wartenberg et al. 2018; Dawoe et al. 2012).

Understanding of soil fertility management practices by smallholder cocoa farmers in West Africa requires a more consistent methodology across studies to allow fair comparisons (e.g., Adiyah et al. 2021; Nunoo et al. 2014). Nonetheless, some patterns can be recognized: farmers value the abundance of litter and mainly pruning residues, which are left to decompose *in situ* (Kenfack Essougong et al. 2020). Full-sun cocoa is less preferred than agroforestry systems (Figure 1.3). Management of cocoa pod husks is heterogeneous among farmers (Figure 1.4) not only because of the labour requirement but also because it may be an important secondary source of black pod disease spread (Ndoumbe Nkeng et al. 2016; Ndoungue Djeumekop et al. 2021). Alternatives such as composting are proposed (Kaba et al. 2021; Ogunlade et al. 2012; Ogunlade et al. 2019b; Ogunlade and Orisajo 2020) but have yet to be implemented at scale. Farmers' perceptions and measured effects of mineral fertilizers on cocoa yields and soil quality are also disputed (Lokin 2020; Asare et al. 2017). In addition, limited access to mineral fertilizers and the unavailability of organic amendments hamper widespread adoption among farmers. Traditional cocoa cultivation does not involve nutrient supply (Fowler 2009). However, intensification programs run in Côte d'Ivoire and Ghana have progressively led to changes in farming practices (Ali et al. 2018). Approximately 36% of farmers apply fertilizers (Table 1.1), but actual rates, frequency, and application periods are not well described in large-scale surveys. Nevertheless, a recent trend is that farmers prefer foliar fertilizers whose contents could not be ascertained during the survey.

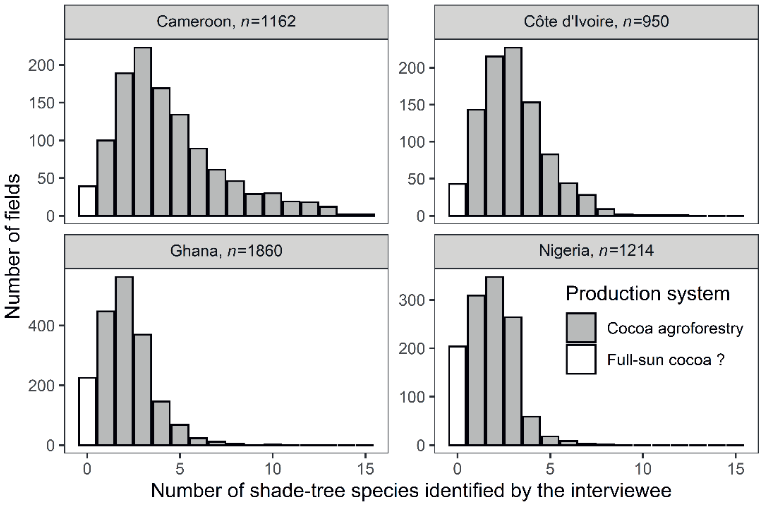


Figure 1.3: Diversity of tree species in West African cocoa fields. *n* is the number of surveyed cocoa fields.

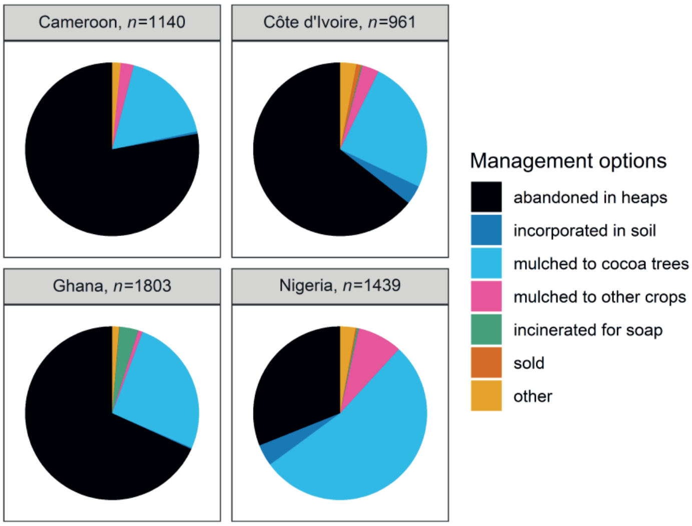


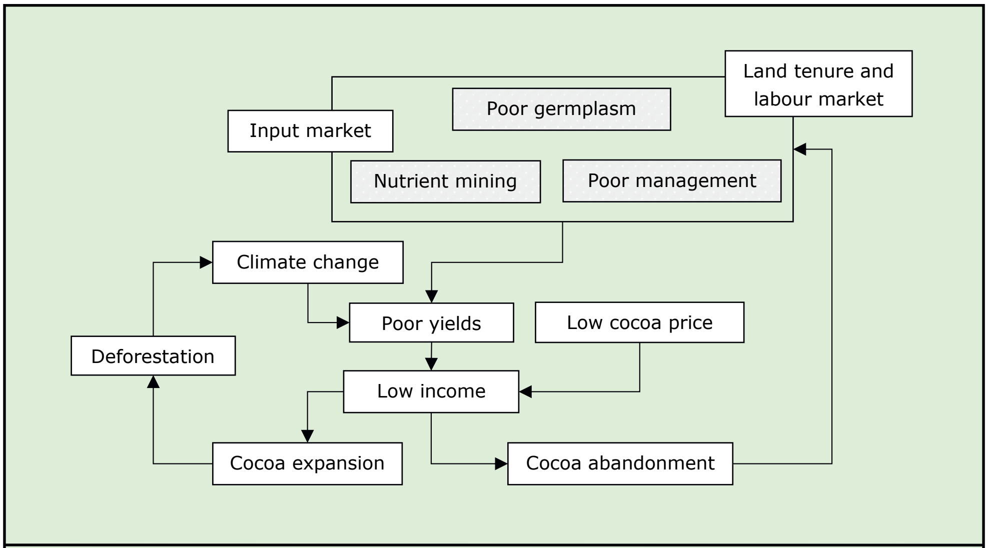
Figure 1.4: Relative importance of different cocoa pod husk management options undertaken by farmers in West Africa. *n* is the number of surveyed cocoa fields.

1.3. Sketching ISFM in cocoa

1.3.1. ISFM as a path to sustainable cocoa intensification

Large cocoa yield gaps are prevalent in West African cocoa production systems and are caused by several intricately linked factors (Wessel and Quist-Wessel 2015; Asante et al. 2022; Daymond et al. 2020). The absent or limited nutrient supply to compensate for continuous offtakes has been identified as the primary cause of low productivity (Baah et al. 2011). Therefore, an adequate nutrient supply is a logical first entry point to maintain and improve cocoa yields. However, fertilizer application rates should not cause adverse environmental effects. Hence, ISFM is an appropriate paradigm to increase cocoa yields sustainably.

Increasing yields and maximising nutrient use efficiency of applied nutrients are the goals of ISFM in cocoa. The expected yield increase leads to better incomes and livelihoods for smallholder cocoa farmers. The causal chain further suggests that improved livelihoods will reduce pressure on remnant forest areas and contribute to reverting the current trend of forest loss and land degradation due to cocoa cultivation. This hypothetical scenario falls under the "land-sparing" approach to sustainable intensification and forms the rationale of the CocoaSoils programme (Box 1.1).



Sustainable intensification of cocoa framed around ISFM

"*The overall objective of CocoaSoils is a sustainable cocoa supply sector with increased productivity of cocoa farms, efficient use of agricultural inputs and improved rural livelihoods while reducing the risk of cocoa-driven deforestation. The main focus of the project includes development of relevant ISFM products...*

The CocoaSoils Initiative is therefore built around the lack of appropriate knowledge on fertiliser recommendations (commonly considered as part of ISFM), other agronomic components and practices, and also includes the use of improved disease-tolerant germplasm and the use of other amendments....

The CocoaSoils Theory of Change is therefore constructed around the demand for R4D products required to intensify cocoa production which in turn will increase productivity of cocoa on existing cultivated land, increase incomes of smallholder cocoa farmers and help reduce pressure on forests."

CocoaSoils monitoring, evaluation and learning plan (internal document)

Box 1.1: Causal diagram of the low cocoa productivity in West African smallholder cocoa farms (top) and the theory of change in the CocoaSoils programme's framework (bottom).

1.3.2. Missing links in cocoa ISFM

Some studies provide recommendations on soil fertility management in cocoa, insisting on the use of organic amendments, mineral fertilizers, or both (e.g., Dogbatse et al. 2021; Amponsah-Doku et al. 2022). However, disagreements on the current methods to assess cocoa nutrient requirements revealed a serious knowledge gap (van Vliet and Giller 2017) and questioned the existing blanket fertilizer recommendations. Appropriate knowledge of soil fertility to inform about proper fertilizer recommendations is a logical entry point of ISFM in cocoa (Box 1.1).

The central principle of ISFM is to combine organic and mineral nutrient inputs, but such a requirement is taken for granted and has yet to be evaluated in tree crops. For instance, litter production is abundant in mature cocoa, roughly estimated at 5 Mg DM ha^{-1} year^{-1} (Hartemink 2005). The large amount of litter questions the relevance of further supply of organic inputs, especially when availability is limited. Likewise, there are conflicting opinions regarding the optimal management of cocoa pod husks. However, the implications of current farmer practices (including husk abandonment in piles) on temporal nutrient immobilisation are largely unknown. Overall, the array of ISFM recommendations may only be suitable for some cocoa production systems, and selecting the most relevant to a context is not straightforward. Therefore, it is fundamental to evaluate the principles of ISFM and how to implement them coherently in existing smallholder cocoa production systems.

1.4. Objectives and outline of the thesis

As part of the CocoaSoils programme, this thesis aims to better understand nutrient cycling in existing smallholder cocoa farms and explore the biophysical potential of ISFM to enhance current yields and nutrient use efficiency. Both the theory and practice of ISFM are examined. Three research questions were addressed:

- Do the principles stated in ISFM apply to existing smallholder cocoa production systems in West Africa (Chapter 2)?
- How much N, P, and K is recycled through selected organic residues generated in cocoa farms (Chapters 3 and 4)?

- Under current farmer management, what is the expected yield response to fertilizer application in mature cocoa fields (Chapter 5)?

In Chapter 2, a comprehensive description of carbon and nutrient stocks and flows in cocoa is proposed to identify knowledge gaps in empirical studies and to evaluate how ISFM principles are aligned with the generic characteristics of tree crop systems. The application of each ISFM principle in cocoa is further discussed, considering the current knowledge and resource availability in smallholder farms. An outcome of the review is the importance of the above to below-ground transfers. Therefore, factors influencing nutrient mobility in litter and in decaying cocoa pod husks during decomposition are assessed in the subsequent chapters.

Chapter 3 focuses on litterfall over which farmers have little control, whereas Chapter 4 is concerned with cocoa pod husks which can be manipulated to some extent. Two hypotheses are tested: (a) macrofauna modifies dynamics of nutrient losses from the litter layer, and (b) rainfall regime determines nutrient losses from abandoned piles of cocoa pod husks. The significance of these losses for cocoa nutrition is discussed.

There is a panoply of ISFM practices of which fertilizer application represents the fastest way to offset negative nutrient balances and potentially increase system productivity. The yield increase in response to the application of fertilizer N, P and K is evaluated in Chapter 5 using an ongoing on-farm experiment. Finally, the general discussion (Chapter 6) integrates the various findings, which are placed in the wider perspective of alternative paths to the sustainable intensification of cocoa.

2

Chapter 2

Does the paradigm of integrated soil fertility management (ISFM) apply to tropical tree crops? Reviewing the case of cocoa (*Theobroma cacao* L.)[1]

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[1] Submitted to the International Journal of Agricultural Sustainability as:
Hougni DGJM; Woittiez LS; Rusinamhodzi L, Schut AGT, Vanlauwe B, Giller KE. Does the paradigm of integrated soil fertility management (ISFM) apply to tropical tree crops? Reviewing the case of cocoa (*Theobroma cacao* L.)

Abstract

Integrated Soil Fertility Management (ISFM), focused on making efficient use of mineral fertilizers and organic resources to enhance crop productivity is a widely-accepted approach in arable cropping systems in Africa. The core principles of ISFM are: (a) the use of improved germplasm; (b) management according to sound agronomic principles; (c) alleviating local site and soil constraints; (d) efficient use of mineral fertilizer; and (e) the use of organic resources. Here, we explore to what extent the principles of ISFM are relevant in cocoa production. Our analysis highlights the large amounts of carbon and plant nutrients that circulate within a mature cocoa plantation, with positive effects on maintenance of soil organic matter and other soil properties and consequences for nutrient availability. The lack of flexibility in renewing germplasm in mature plantations – unless for replanting – prevents smallholder cocoa farmers from reaping the full benefits of implementing the other components of ISFM. Attention to pruning and crop sanitation is key to ensuring healthy and nutrient-responsive cocoa trees. The very nature of tree crop systems complicates accurate assessment of nutrient needs. A simple model is introduced to calculate additions of nutrients needed for balanced nutrition of cocoa based on nutrient removal. Recycling of cocoa pods is important to reduce nutrient removal. Beyond this, few organic resources such as compost or feedstock for biochar are available for use on cocoa in smallholder production systems. Insufficient knowledge of the tree physiology and poor understanding of the impacts of combinations of practices are major barriers to derive generic guidelines for nutrient management in cocoa.

Keywords: perennial crops; agroforestry; carbon stocks; nutrient recycling; soil fertility; biochar; compost.

2.1. Introduction

Yields of cocoa (*Theobroma cacao* L.) in West Africa, the heartland where more than 70% of the world's cocoa is produced, have stagnated around 400-500 kg ha^{-1} (Wessel and Quist-Wessel 2015), a tenth of what is possible (Asante et al. 2022). Declining soil fertility has been highlighted as a major constraint to cocoa production (Hartemink 2005). Substantial nutrient inputs are needed to replace nutrient offtakes and maintain productivity (van Vliet and Giller 2017). Concurrently, there are calls for more 'regenerative' approaches in cocoa production, to reduce the C footprint by enhancing C storage and reducing greenhouse gas (GHG) emissions and to safeguard soil health and to protect and enhance biodiversity. Maintaining and enhancing 'soil health' and soil fertility in cocoa production systems is an important challenge (Amponsah-Doku et al. 2022).

With regard to annual cropping systems, a consensus has emerged around the approach of integrated soil fertility management (ISFM) which is a "set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm, combined with the knowledge of how to adapt these practices to local conditions" for improved nutrient use efficiency and productivity (Vanlauwe et al. 2010). The goal of ISFM is to maximize nutrient use efficiency of applied nutrients, and thereby to ensure adequate nutrient supply for crop growth, maintain soil fertility, and prevent nutrient losses to the environment. The approach focuses on five components: (a) the use of improved germplasm; (b) management according to sound agronomic principles; (c) alleviating local site and soil constraints; (d) efficient use of mineral fertilizer; and (e) the use of organic resources. Together these five principles aim to maximize the agronomic use efficiency of the applied nutrients and improve crop productivity. There is now an established body of ISFM research in arable crops (Bationo et al. 2007; Matusso et al. 2014; Mugwe et al. 2019; Vanlauwe et al. 2017; Vanlauwe et al. 2015a), but ISFM is yet to be evaluated for perennials.

In cocoa production systems in West Africa, farmers use limited amounts of fertilizer, or none at all. Cocoa farmers often rely on the so-called 'forest rent' (Ruf et al. 2015) which is the native fertility of soil after forest clearance; but this is not a sustainable practice, as nutrients are removed from the system without being replaced (Appiah et al. 1997; Smaling et al. 1997). Improving soil fertility in cocoa through ISFM could contribute to sustainable intensification (Pretty 2008) and increased carbon storage in cocoa plantations when shade trees are maintained. But to the best of our knowledge, no study has adapted and tailored the principles and practices of ISFM for perennial cropping systems and in particular to cocoa production systems. Adapting ISFM for perennials is challenging because trees differ from annual crops in several important ways. These include, among others, a larger biomass accumulation, the presence of a thick litter layer, a large internal nutrient storage capacity and physiological mechanisms that result in delayed responses, and a long period between replanting cycles. It is likely that these differences will affect how ISFM principles and practices translate to tree crop systems.

The few studies of ISFM in tree crop systems have focused on coffee (Chemura 2014), coconut (Margate et al. nd), and various fruit tree species (Srivastava 2020). All highlighted the benefits of combining soil amendments, organic inputs, and mineral fertilizers. In cocoa, the term ISFM has been used to emphasize the use of organic residues, including the pod husks, and their combination with synthetic fertilizers to increase productivity (Fungenzi et al. 2021; Ogunlade and Orisajo 2020; Quaye et al. 2021a). While these studies have examined responses of tree crops to organic and mineral fertilizers, the theoretical basis of ISFM in perennial crops remains unexplored.

The aim of this review is to explore how the concept of ISFM matches with systemic characteristics of perennial crops, and how it can further be operationalized (Figure 2.1). Given the above, central questions are: (a) What components of ISFM are relevant to perennial cropping systems?; (b) How does nutrient and carbon cycling operate in such systems?; and (c) What nutrient and organic matter management interventions are needed in the short and long-term? We explore these questions by providing a mechanistic insight of carbon and nutrient cycles in tree crops with a focus on existing smallholder cocoa production systems in West Africa whose characteristics are described elsewhere (Bymolt et al. 2018a; Daymond et al. 2022). This paper is organized in three broad sections. First, we evaluate differences between annual crops and perennial cocoa that require a reinterpretation of the ISFM concept. Second, we assess the key components of the nutrient (N, P, K) and carbon cycles in cocoa. Third, we discuss how these insights might shape the application and practice of ISFM in perennial cocoa systems in future.

Figure 2.1: Two aspects of ISFM in cocoa: (a) Pruning residues and uninterrupted litterfall in mature cocoa plantations ensure continuous carbon and nutrient flows to soil, questioning the relevance of further organic input application as stated in ISFM principles. Cocoa pod husks (b) abandoned in piles at a fringe of a plantation highlight trade-offs between nutrient recycling, spread of pod-borne diseases, and labour requirements.

2.2. Principles of ISFM in perennial cropping systems

There are multiple ways in which perennials differ from annuals, and some of these strongly affect the principles and practices of ISFM. Key ISFM-related characteristics of perennials include: (a) the production cycle and the associated biomass accumulation; (b) the deep and extensive root system with access to a large volume of soil; (c) the modified micro-climate and the subsequent soil protection; (d, e) the large recycling of leaf litter, its impacts on soil organic matter (SOM) accumulation and associated soil biological activity; and (f) the uninterrupted carbon and nutrient cycling. In addition, (g) agroforestry is a common practice among cocoa smallholder farmers which further implies tree-tree interactions. These characteristics are discussed in detail below, while Section 3 is exclusively dedicated to carbon and nutrient cycling in the cocoa agroecosystems. The connection with ISFM practices is explored in Section 4. We anticipate that the implementation and the outcomes of ISFM are age-dependent in tree crops, but hereafter, unless explicitly specified, we mainly focus on mature cocoa.

2.2.1. Production cycle and biomass accumulation in cocoa

The lifespan of individual plants and of the production cycles are probably the most striking differences between annual crops and tree crops. This has implications for above- and below-ground biomass (carbon) accumulation and for the long-term perspective of crop management, which are both key aspects of ISFM. Similar to other perennial crops such as oil palm (Woittiez et al. 2017), the life cycle of cocoa trees is characterized by three main phases: establishment, the mature phase, and ageing/ production decline (Niemenak et al. 2010). In the early stages, the relative growth rate increases rapidly as vegetative organs are formed. Leaves appear in successive flushes on the main stem and later on fan branches following jorquette[3] formation, while apical growth is ensured by staggered chupon[4] development. The establishment phase lasts about 3-5 years (Asante et al. 2017; Quaye et al. 2021a) during which water stress can lead to high mortality rate under rainfed conditions (Acheampong et al. 2019; Padi et al. 2013). High planting densities and replacement are often adopted by smallholder

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[3] The "point at which the vertical stem changes to fan growth on the cocoa tree" (Wikipedia)

[4] A basal shoot sprouting from the main stem, usually undesirable

farmers to mitigate establishment stress, which has implications on tree growth and tree density at later stages in the life of the plantation. Management practices, especially formation and structural pruning operations strongly regulate tree height, canopy shape and volume, vegetative growth, and carbon and nutrient cycling within the system. Whether grown in full-sun or in agroforestry systems, cocoa requires shade during establishment which is provided either by companion crops such as banana or plantain, planted trees (often leguminous species such as *Erythrina* spp. or *Gliricidia sepium* (Jacq.)), or remnant forest trees that are selectively thinned. Hence during establishment, the net primary productivity (NPP) of cocoa is marginal and the standing biomass depends more on the existing vegetation or the planted temporary shade.

After establishment, cocoa biomass increases steadily during the immature phase and asymptotically levels off to plateau around 8-20 years after planting (Figure 2.2a). During the mature phase, biomass remains relatively stable, in part due to pruning. In Ghana, Dawoe et al. (2010) found a significant increase of stem diameter, leaf litterfall, and litter stock from 3 to 15 years, but differences between 15 and 30 year old plantations were insignificant. Depending on the germplasm, cocoa pod production starts 2-6 years after planting, and follows successive phases of increase, plateau and decline (Obiri et al. 2007). These generic growth patterns are highly modulated by environmental resources (mainly water and nutrients), and management, especially pruning. In mature plantations, the cocoa canopy is closed which maximizes the amount of radiation intercepted. There is no evidence that photosynthesis rate per unit leaf area declines with tree age (de Almeida et al. 2018). However, reducing factors such as pests and diseases become more prevalent (Juhrbandt et al. 2010) which potentially constrain NPP (Santoso and Zakariyya 2019). In mature cocoa, NPP stabilizes at variable rates and stocks, as a result of long-term management. Since tree root biomass is often predicted from above-ground biomass (Waring and Powers 2017), the root biomass of tree crops is also expected to increase until tree maturity, and stabilize thereafter.

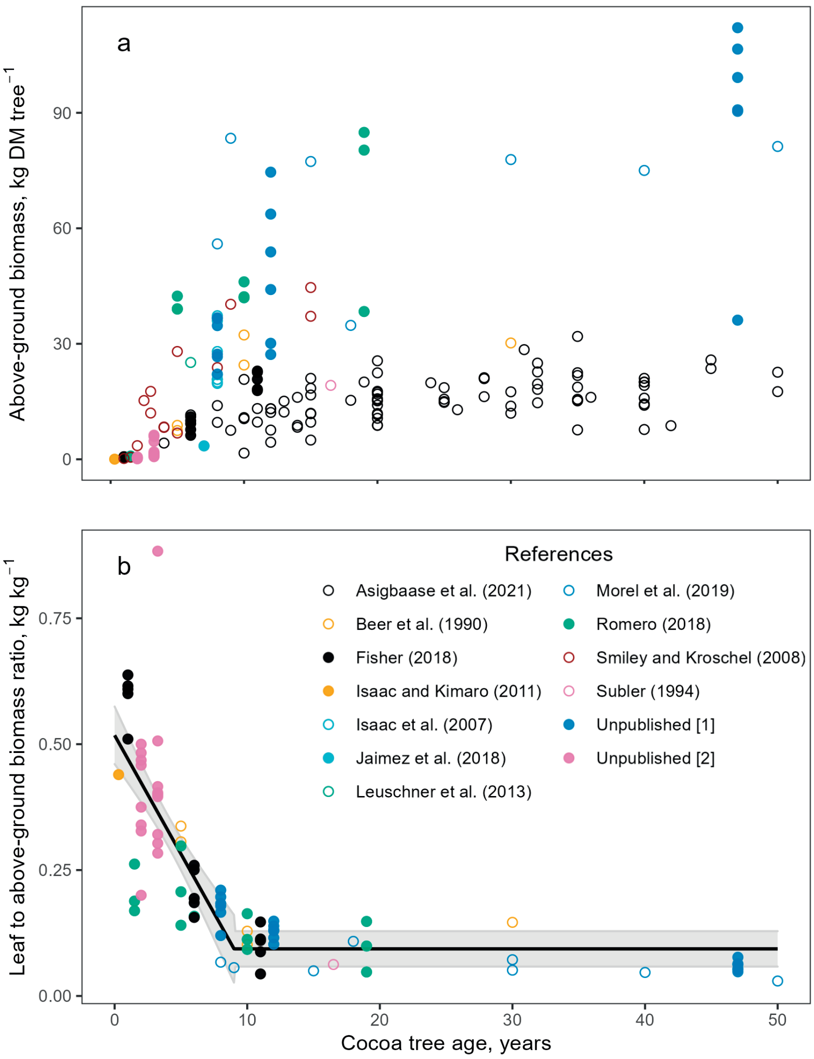

Figure 2.2: Above-ground biomass in cocoa trees and its partition between leaves and wood. (a) Age-dependence of above-ground biomass of individual cocoa trees grown under various conditions; a single value above 200 kg DM tree^{-1} (Morel et al. 2019) was omitted. (b) The relationship between leaf to above-ground biomass ratio and age of individual cocoa trees. In both panels, each colour represents a distinct dataset. Estimation methods were both destructive (solid symbols) and non-destructive (open symbols). A fitted piece-wise linear-plateau regression (estimate ± 95% confidence interval) shows that leaf to above-ground biomass ratio decreases from 0.50 in seedlings to about 0.10 at 08-10 years, and stabilizes thereafter. The data were obtained from eleven publications (Asigbaase et al. 2021a; Beer et al. 1990; Fisher 2018; Isaac and Kimaro 2011; Isaac et al. 2007b; Jaimez et al. 2018; Leuschner et al. 2013; Morel et al. 2019; Calvo Romero 2018; Smiley and Kroschel 2008; Subler 1994) and two unpublished studies that used destructive sampling methods in Côte d'Ivoire and Nigeria (courtesy Ambra Tosto and Olusade A. Ajibona).

2.2.2. Root system: size and distribution

Most annual crops are known for their shallow roots, unlike deep-rooted trees. For instance, the effective rooting depth of maize is often less than 80 cm (Kayser et al. 2012), and much less in presence of soil physical or chemical constraints. By contrast, tree root systems tend to be deeper to ensure physical anchoring, acquire water from deeper layers, and take up more nutrients for some species (Callesen et al. 2016). At seedling stage, a ring of lateral rootlets emerges from the nascent tap root of cocoa tree, and grow superficially (maximum 1 m depth), spreading up to 4-6 m from the stem within 4-6 years. In mature cocoa trees, tap roots are massive, representing up to 84% of the total root system biomass (Carr and Lockwood 2011). Tap roots are usually 1-1.5 m deep (Dand 2011; van Vliet and Giller 2017), but can reach 2.5 m in well drained soils (Mommer 1999). They usually play a marginal role in nutrient and water uptake (Hartemink 2005), but can absorb water from deep soil horizons under dry conditions (Dand 2011). Cocoa trees are characterized by a shallow root activity (Lehmann 2003) with more than 50% of the fine roots located in the surface 0-30 cm of the soil (Abou Rajab et al. 2018; Borden et al. 2019).

Despite their shallow root activity, cocoa trees efficiently explore horizontal space. Average diameter, root biomass density, and specific root length of fine roots measured at three distances from the cocoa stem (below, at the dripline, and beyond the tree canopy) showed no significant difference in various cocoa production systems (Niether et al. 2019). The average root system length was 2.9 ± 1.42 m from the tree base in a 3 m × 3 m spaced cocoa plantation (Nygren et al. 2013), with a complete overlap with roots of adjacent trees. Fine root (< 2 mm) biomass of cocoa trees ranges from less than 1 to 3.55 Mg DM ha^{-1}, across studies (Muñoz and Beer 2001; Nygren et al. 2013). Unless tree density is critically low, cocoa fine roots are thus well distributed horizontally to intercept and capture nutrients and water. The permanent presence of tree root systems further minimizes nutrient losses through leaching from the topsoil. However, pruning may decrease root uptake activity as observed in other species (Peter and Lehmann 2000), although this has not been evaluated in cocoa.

An extensive and dense root system increases plant uptake capacity and soil water holding capacity, and thereby reduces risks of excessive drainage and leaching. Therefore, nutrient losses are thought to be minimal in tree crop systems, with N losses through leaching estimated to be 30-50 times less in perennials than in annuals (Zhang et al. 2011). In the light of the relative superficial rooting depth of cocoa, variations in cocoa production systems, management practices, and nutrient mobility, studies to assess nutrient losses through leaching and erosion in cocoa are required.

2.2.3. Permanent soil cover

The closed canopy of cocoa plantations significantly modifies and buffers the micro-climate, especially air temperature and relative humidity (RH), more so in the increasing complexity of cocoa agroforestry systems. In cocoa, annual litter inputs range from 2 to 20 Mg ha^{-1} (Hartemink 2005; van Vliet and Giller 2017) which further protect the soil against high temperatures and desiccation (Sari et al. 2022). Mean daily air temperature under canopy of different cocoa production systems was found approximately 3°C less than in open space in Ghana (Asare et al. 2017). In addition, relative air humidity and temperature at ground level were relatively stable in Cameroon, with daily records in the range of 29.5-33ºC and 68-78% for the most fluctuating system (Saj et al. 2021). The potential benefits of the litter layer with respect to improved water infiltration into the soil, reducing surface run-off and soil erosion, and its overall effect on water balance remain poorly evaluated in cocoa. Nevertheless, Niether et al. (2017) noted high seasonal variations (about 41% at 0-10 cm depth) of the volumetric water content in the topsoil under cocoa, which was also influenced by amount of shade cover and plantation management. Soil under mature cocoa benefits from a protected environment, and is less exposed to moisture and temperature fluctuations, which favours biological activity.

2.2.4. Soil biodiversity

Soil biodiversity under tree crop systems and agroforestry is strongly determined by the specific habitat created by the trees (Marsden et al. 2020), especially the tree phenology (e.g. deciduous nature, root turnover rate). As a consequence of the protection offered by the litter layer and minimal physical disturbance of the soil (e.g. tillage, compaction) and high C inputs, the abundance and richness of soil fauna were similar in cocoa agroforestry systems and in natural forest in Brazil (da Silva Moço et al. 2009). Microbial biomass is also positively impacted by continuous C inputs through litterfall. In cocoa agroforestry systems in Brazil, the microbial biomass carbon (MBC) averaged 265 mg kg^{-1} soil (Zaia et al. 2012). More abundant MBC was recorded in Bolivia (in the range of 300 to 800 mg kg^{-1}) especially in complex cocoa agroforestry systems (Alfaro-Flores et al. 2015). However MBC is not correlated with microbial activity (Zuber and Villamil 2016).

An advantage of low soil disturbance is an increased diversity of the fungal community and the consolidation of its structure (Mbuthia et al. 2015; Cho et al. 2017). As compared with forest soil, increased abundance and diversity of arbuscular mycorrhizal fungi (AMF) has been observed under cocoa (Edy et al. 2019) which presumably facilitates P uptake. Positive effects of AMF colonization have been demonstrated on cocoa seedlings (Aggangan et al. 2019a; Aggangan et al. 2019b), and we assume that the same may apply to mature plantations. Fungicide application is common in cocoa, which may be detrimental to soil fungi, particularly if persistent chemicals such as blue or red copper are used (Afolabi and Muoghalu 2018). The suggested adverse effects of fungicide application on soil lack empirical evidence (Kähkölä et al. 2012; Norgrove 2007).

Another consequence of low disturbance is the stratification of the soil organic layer (Barreto et al. 2011), which is counterbalanced by the activity of invertebrates contributing to bioturbation of the soil surface horizons. Soil physical characteristics including increased aeration and hydraulic properties due to greater porosity are advantages of macrofauna activity. Soil bulk density is significantly less in complex agroforestry systems than in cocoa monoculture (Niether et al. 2020), more so when comparing cocoa to arable lands. Besides effects on soil physical properties, soil biological activity influences the formation of soil organic matter.

2.2.5. SOM under cocoa

Soil organic matter (SOM) contents are the result of their initial value (dictated by previous land-use), the subsequent flow of C inputs (mainly related to management), and the decomposition rate which is modulated by soil texture (Six et al. 2002), aeration, temperature, pH, moisture regime, and decomposer communities. SOM contents usually do not exceed saturation thresholds (Stewart et al. 2007) which are strongly influenced by the soil texture (Feller and Beare 1997) but are difficult to predict. During establishment of cocoa production systems, SOM decreases are recorded upon forest opening, but thereafter usually increase, up to or close to the contents found in adjacent secondary forests (Dawoe et al. 2014; Norgrove and Hauser 2013; Saputra et al. 2020). As with litterfall, cocoa has a large fine root biomass production (approximately 2.9-3.3 Mg ha^{-1} year^{-1} in 10 year old plantations) with high turnover rates (Mean Residence Time, MRT of 6-9 months) (Hertel et al. 2009). During the establishment phase, this abundant input of annual carbon contributes to progressive SOM build-up until the maturity phase. A recent meta-analysis on a global scale found soil organic carbon (SOC) contents in the top soil at 1.7 ± 0.5% in various cocoa production systems (Niether et al. 2020). Forest conversion to plantation and arable crop generally implies a SOC decrease by less than 20% and more than 40% respectively (Guo and Gifford 2002). Arable crop productivity is often associated with nutrient mineralization from SOM, especially in SSA where SOC contents are less than 1.1% in general (Lorenz et al. 2019) and rates of fertilizer use are limited. There is no data available on SOM changes associated with land-use conversion from arable to cocoa, which we suspect to lead to progressive SOM increase. Given the above mentioned characteristics, we may conclude that generally speaking, soil under tree crops contains more SOC than under annual crops (Schroth et al. 2001). The soil degradation sometimes attributed to cocoa cultivation presumably occurs where cocoa is established on previously forested land (Ruf et al. 2015).

2.2.6. Continuous carbon and nutrient recycling

Perennial systems like cocoa are characterized by continuous internal cycling of carbon and nutrients. In most annual cropping systems of the tropics, dry seasons mark cyclic interruptions of plant growth both above- and below-ground. By contrast, cocoa trees only partially shed their leaves during the drier parts of the year. The superficial lateral root system may undergo a relative quiescence, but does not dry out, while the tap root is more important for water uptake from deep soil horizons. These features structurally reduce opportunity for nutrient leaching. Likewise, during drought, soil biota benefit from water recharge from deeper horizons, as evidenced by soil and litter CO_2 efflux measured in cocoa agroforestry systems (van Straaten et al. 2010). This hydraulic lift (Alagele et al. 2021) is potentially improved if shade trees associated with cocoa have deeper root systems.

2.2.7. Agroforestry

Agroforestry is a common practice in cocoa, and a necessity during the immature phase as the seedlings cannot tolerate full sun. With mature plantations, the continuum of cocoa production systems ranges from monocrop to complex agroforestry systems. In its simplest form, agroforestry is cocoa intercropped with a single or limited fruit/service tree species, with regular planting patterns. Leguminous species add the advantage of fixing atmospheric nitrogen. More complex cocoa production systems comprise various tree species, including forest remnants, and planted (indigenous and/or exotic) species, in general with low cocoa tree densities.

Agroforestry may have multiple benefits and trade-offs related to the utilization of key resources: light (Agele et al. 2016), water (Moser et al. 2010), and nutrients (Isaac et al. 2007b). It also affects other aspects of production such as incidence of pest and diseases, biodiversity conservation, and soil characteristics (Niether et al. 2020). In cocoa agroforestry systems, C accumulation in the associated trees occurs at the expense of cocoa trees. In general, photosynthesis rate and leaf area of cocoa trees are limited at increasing shade levels. Plasticity in these characteristics has been observed, modulated by genotypic traits (Acheampong et al. 2013). Water and nutrient use are complementary when shade-trees develop deeper root systems which reduces the effect of competition with cocoa roots in topsoil (Niether et al. 2017).

One key benefit of agroforestry is the opportunity to include N_2-fixing leguminous tree species in the system. Biological nitrogen fixation (BNF) adds highly variable amounts of N (tens to hundreds kg N ha^{-1} $year^{-1}$) to agroforestry systems, depending on the density of N_2-fixing trees, the pedoclimatic conditions, management, and tree physiology (Isaac and Borden 2019). Although the amounts of N_2 fixed may be substantial, the contribution to cocoa N nutrition is likely to be modest: only 0 to 24% of the legume N coming from nitrogen fixation was transferred to cocoa trees, as measured in rare studies reviewed by Munroe and Isaac (2014). In addition, experimental trials tend to adopt high densities of leguminous trees (69-428 trees ha^{-1}) (Abou Rajab et al. 2016; Bai et al. 2017; Leuschner et al. 2013). By contrast, cocoa agroforestry systems managed by smallholders across continents tend to be more complex, with fewer legume trees and more utilitarian species (Cerda et al. 2014; Sari et al. 2020; Sonwa et al. 2019). Therefore, to evaluate the contribution of leguminous species to cocoa agroforestry, studies need to be scaled-up at field level, and N-transfer rates should be adjusted for actual tree densities and pruning practices as implemented in farmer-managed cocoa plantings.

2.3. Carbon and nutrient cycling in cocoa

In order to maximize nutrient use efficiency, which is a central goal of ISFM, a thorough understanding of nutrient cycles in the agroecosystem and the identification of potential bottlenecks towards improved crop nutrition are required. Here, we highlight the ecological mechanisms that are critical to cocoa nutrition and potentially guide crop management. First, we describe carbon (C) and selected nutrient (N, P, K) cycles for generic mature cocoa trees and their immediate surrounding, regardless of the presence of weeds or associated trees (other crops and shade trees). To do this, we build on an earlier schematic representation of nutrient cycling in cocoa (Hartemink 2005). Secondly, we review specific flows of C and nutrients in relation to crop nutrition. Since C and N cycles are tightly coupled in many respects, the C cycle is considered first. The P and K cycles are only discussed to highlight unique characteristics. When possible, we infer values for unmeasured components of the cycles to compensate for data scarcity.

In Figure 2.3, generic stocks or pools (boxes) and flows or fluxes (arrows) in soils (adapted from Hartemink 2006, p. 184) are extended to cover the above-ground part of the agroecosystem. Three types of flows are distinguished: the above-ground flows, the below-ground flows, and internal flows within the cocoa. The first two flows are external to the trees. The main entry-points are atmospheric CO_2, soil minerals and fertilizers for nutrients. Carbon enters the system through photosynthesis in the leaves and is lost through respiration in the plant, removal of plant materials, and by decomposition of organic matter and minor losses via erosion and leaching. Wet and dry deposition add small amounts of N to the system, and further P and K are gained through weathering of soil minerals. These inputs can be substantially complemented through organic and/or mineral fertilizer application. Nutrient exports occur by means of harvesting (beans and sometimes whole pods) and losses. Losses such as burning of organic materials and removal of other tree parts (e.g. branches for firewood) are infrequent or marginal, and are not included in the scheme.

2.3.1. Internal and external C and nutrient cycles

In the next paragraphs we discuss the internal cycles (within the cocoa tree) and two external cycles: above-ground and below-ground. Wherever possible, we have quantified the magnitude of the stocks and flows in the cocoa system (Table 2.1).

Table 2.1: Average estimates ± standard deviation of major C, N, P, and K stocks and flows in cocoa production systems.

A: Stocks (kg ha^{-1})

Component	Fraction	C	N	P	K	References[5]
Vegetation	Cocoa tree below-ground biomass	4124 ± 2679	81.8 ± 59.3	8.5 ± 8.5	110.1 ± 87	3; 5; 6; 9; 10; 26-29; 31
	Cocoa tree above-ground biomass	14500 ± 10500	316.5 ± 187.1	30.6 ± 21.1	386 ± 238.1	29-31
	Shade tree below-ground biomass	6562 ± 7156				3 ; 26 ; 27
	Shade tree above-ground biomass	27800 ± 32900				3-6; 23; 25-27; 32-34; 37
	All trees below-ground biomass	6437 ± 6367	72.9 ± 66.1	8.5 ± 9.3	102 ± 92.4	3-6 ; 26-29 ; 31-35 ; 37
	All trees above-ground biomass	35200 ± 31600	293.5 ± 218.1	33.4 ± 30.5	374.3 ± 309	3-6; 23; 25-29; 34; 37
Litter	Cocoa leaf litter	989 ± 447	3.9			10 ; 11 ; 13 ; 14
	Cocoa litter	4650				28
	Shade tree leaf litter	642 ± 470	22.5			10 ; 11 ; 13
	All leaf litter	2043 ± 397	73.5 ± 39.4	4.7 ± 1.8	36.9 ± 24.5	13 ; 14 ; 18 ; 20 ; 21
	All litter	3330 ± 1782	50 ± 14.7	4.9 ± 1.8	18.7 ± 11.8	1; 4; 5; 10; 11; 13; 20-21; 26; 28; 32-35; 37
Soil	From 0-10 cm to 0-300 cm	54000 ± 36500	1819 ± 1043	13.6 ± 8.5	294 ± 155	3; 4; 5; 9; 16; 23; 26; 30; 33; 34; 36
	From 0-20 cm to 0-40 cm	48700 ± 23900	1271 ± 56	21.5 ± 1.4	135 ± 29	4; 5; 9; 26; 30; 33; 34

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[5] References are listed in Appendix.

B: Flows (kg ha^{-1} $year^{-1}$)

Component	Fraction	C	N	P	K	References[6]
Atmospheric deposition (*Additions*)			7.4 ± 2.3	0.7 ± 0.4	12 ± 2.2	1; 2
Harvest (*Removals*)	Beans	520 ± 343				3-8
	Whole pods	4276 ± 2103				3; 9
Rain-wash (*Transfers*)			-0.1 ± 2.6	0.8 ± 0.3	37.1 ± 9.7	1; 2
Litterfall (*Transfers*)	Cocoa leaves	1441 ± 1060	50 ± 54.5	2.9 ± 2.1	14.6 ± 15.6	5; 7; 10; 11; 12-14
	All cocoa aerial organs	2581 ± 1656	91.1 ± 21.3	6.3 ± 1.4	56 ± 41.1	3; 4; 15; 16
	Shade tree leaves	1682 ± 1124	65.3 ± 43.6	3.4 ± 1.7	8.7 ± 4.2	3; 4; 17
	All shade tree aerial organs	2139 ± 1155	61 ± 1.4	5.5 ± 3.5	23 ± 14.1	4; 5; 7; 10-14; 18; 19
	All leaves	3179 ± 1295	186.9 ± 115.2	9.9 ± 3.8	40.8 ± 11.3	7; 14; 18; 20
	All twigs	333 ± 161	12.9 ± 14.3	0.8 ± 0.6	2.2 ± 1.8	10-13; 20
	All reproductive organs	693 ± 396				11; 20
	All aerial organs	3328 ± 1642	104.8 ± 67.2	7 ± 3.8	32.1 ± 24	3; 4; 10-13; 16; 17; 20-22; 36; 37

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[6] References are listed in Appendix.

B (continued): Flows (kg ha^{-1} year^{-1})

Component	Fraction	C	N	P	K	References[7]
Pruning (*Transfers*)	Cocoa leaves	1187 ± 501				4; 5
	Cocoa twigs	868 ± 18				4
	All cocoa aerial organs	2171 ± 653	80 ± 24.5			4; 25; 37
	Shade tree leaves	940 ± 1329				4
	Shade tree twigs	1503 ± 2125				4
	All shade tree aerial organs	2351 ± 2015	55 ± 7.1			4; 37
	All leaves	1845 ± 1492				4
	All twigs	2370 ± 2143				4
	All aerial organs	3194 ± 1793	91.2 ± 38	3	35	4; 24; 25; 37

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[7] References are listed in Appendix.

2.3.1.1. The cocoa tree internal cycle

We mainly consider nutrient uptake via fine roots, although some foliar absorption of nutrients also occurs in cocoa (de Souza Júnior et al. 2019). Nutrients are channelled from the roots through the vascular system to aerial organs for maintenance, growth, and various metabolic functions. Carbon and nutrients from leaves and fine roots are recycled within the system (Figure 2.3). Growth of other organs (either vegetative or reproductive) is a permanent sink of C and nutrients, as accumulation results in substantial immobilization. Since metabolites are synthesized, translocated and utilized or stored in various organs, C and nutrients that are not part of structural materials are potentially redistributed within the tree (Figure 2.4). An important feature of trees is that considerable amounts of carbohydrates and other metabolites are purposively stored to buffer future stresses including limitation of the photosynthetic capacity, bud burst, defoliation after drought event, etc. To capture this complexity, we create a virtual pool (i.e. the cocoa reserve pool) in Figure 2.3 that represents these non-structural and available products.

This reserve pool is physically split among bark and sapwood of stems, branches, tap and lateral coarse roots, but also in twigs and leaves (or shoots). Non-structural carbohydrates, proteins, free amino-acids, polyphosphates, and phospholipids are common forms of storage (Chapin et al. 1990). Both short-term and long-term storage co-exist, which can either be active or passive (Dietze et al. 2014). A well-documented mechanism of nutrient reallocation in tree species is resorption from leaves during senescence (Brant and Chen 2015), adding nutrients to the reserve pool. Resorption efficiency is often measured in foliage only, and thus there are no estimates from cocoa fine roots despite their presumably rapid turnover.

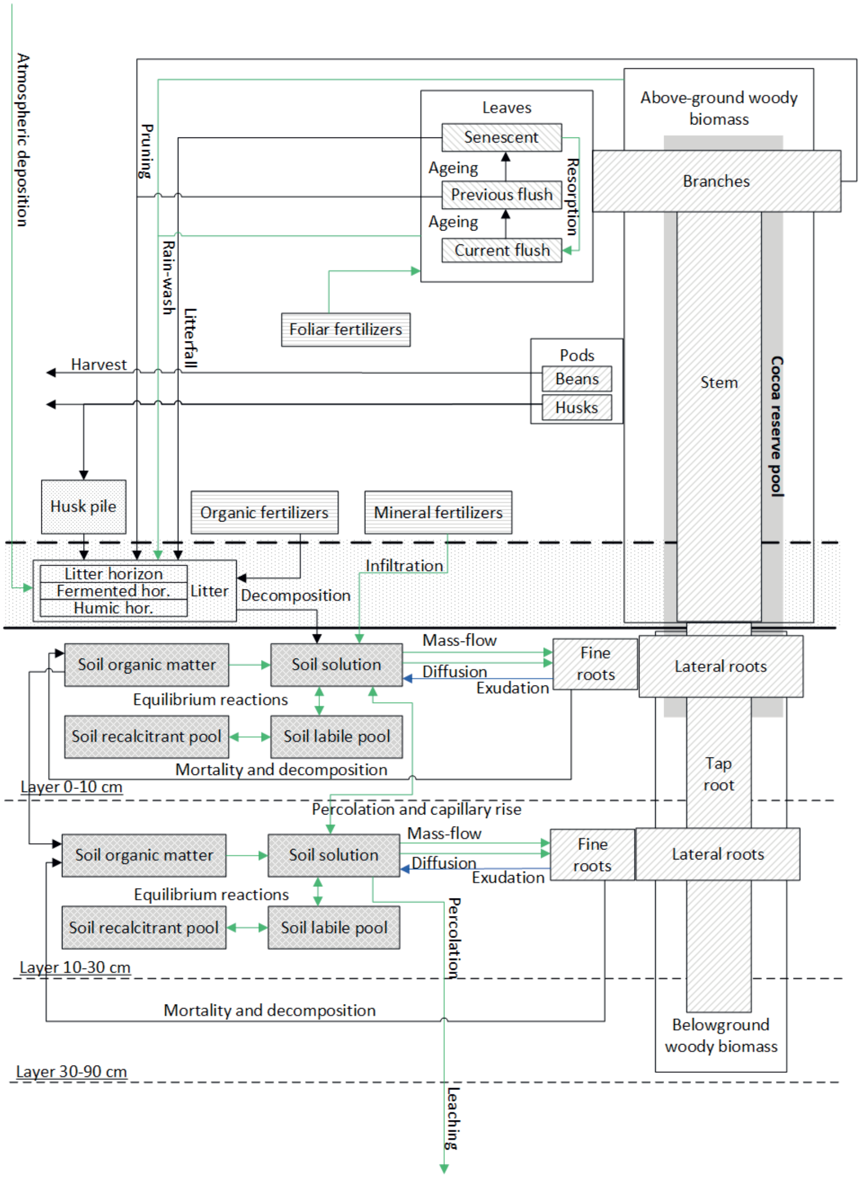

Figure 2.3: Carbon and nutrient cycling in a mature cocoa plantation. Flows of mainly organic carbon (blue), nutrients (green), and both (C and nutrients) are shown in relation to the cocoa tree only. Internal flows linking the various tree organs to the conceptual reserve pool are not represented here, but further detailed in Figure 2.4.

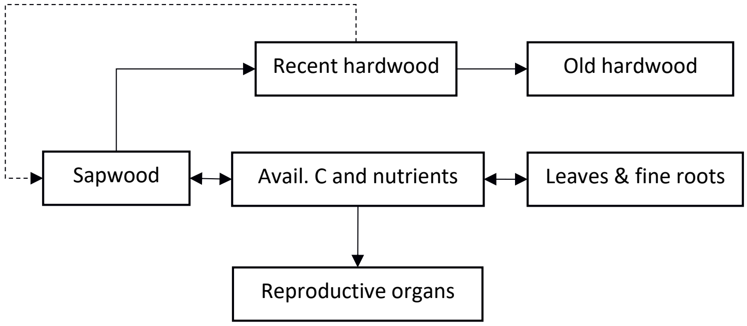

Figure 2.4: Simplified representation of flows of C and nutrients within the cocoa tree. Available assimilates and nutrients (newly formed/absorbed or products of resorption) originate from leaves and roots (resource acquisition), and are distributed to all organs for maintenance, vegetative growth (fine roots, leaves and wood), reproductive growth, and/or storage in vegetative organs. The stored products can sooner or later be remobilized for the same metabolic purposes if supply is less than demand (e.g. soil nutrient deficiency, reduced photosynthesis under low radiation, after defoliation, or water stress). A hypothetic mechanism for tree resilience involves remobilizing resources from heartwood in case of extreme events (dash line). Vegetative growth, especially wood growth increases storage capacity while leaf flushing and fine root growth increase assimilation capacity. Stored products are irreversibly immobilized in hard wood, which is also considered as part of wood growth. Regulatory mechanisms (sink competition and source-sink relationships) are not represented here.

2.3.1.2. The external above-ground cycle

The external nutrient cycling includes C and nutrient transfer from plant to soil through litterfall, pruning, rain-wash, and cocoa pods and husks that drop from the tree or are returned to the soil after harvest. The passage of nutrients through the litter layer represents a main transitory step with nutrient MRT varying with the mobility of each element. Thus, N and P experience much longer MRT than K since the latter is mostly present in the vacuole and is released much sooner, when cell wall breakdown is initiated or during rain-wash (Hougni et al. 2021). The MRT of P in the litter layer is thought to be longer than that of N due to strong immobilization of P in tropical soils (Bai et al. 2022); however findings are inconsistent (Fontes et al. 2014), possibly due to differences in methodology.

Carbon lignification and abundance of polyphenols in residues control the breakdown of organic material and the release of most macronutrients. Initial litter quality is modulated by intensity of pruning, nutrient resorption efficiency for fallen vegetative organs, and management of reproductive organs (pod husks and mummified pods). Specifically, management of cocoa pod husks can either increase nutrient losses (if removed from the field), amplify spatial heterogeneity (if abandoned in piles after beans extraction), or promote nutrient transfer to the soil (if incorporated after beans extraction). If applied, organic fertilizers further enlarge the size of the nutrient pools in the litter layer. The extent to which mineral fertilizers can alter the decomposition rate of litter is still unclear and hard to predict (Camenzind et al. 2018; Knorr et al. 2005), but it is probably negligible when nutrients are applied in a ring around the stem, as recommended.

2.3.1.3. The external below-ground cycle

Carbon and nutrient cycles are poorly studied below-ground, mainly due to methodological limitations. Nutrients mainly flow from various sources (above-ground litter and SOM decomposition, adsorption-desorption from soil particles, rain-wash and percolation, mineral weathering, fertilizer application) to the soil solution and to roots. Conversely, carbon flows from roots to soil (exudation, root litter decomposition), and from litter to soil to fuel biological activities. Fast nutrient transfer to the soil solution originates mainly from mineral fertilizers when applied, but also from products of rain-wash and atmospheric deposition that have been enriched when passing through the litter layer. Slow and steady nutrient supply to the soluble soil pool is ensured by the exchange with the cation and anion exchange complex and organic matter decomposition, complemented by weathering of soil minerals, and long-term release from organic inputs. Microbial mediation in the soil-root interactions is omitted in Figure 2.3, for simplicity. Vertical nutrient transfers between soil layers include percolation and capillary rise of soil solution, and activity of soil biota (e.g. termites). Nutrient losses in the soil are due to run-off, soil erosion, leaching, denitrification and volatilization, with occasional gaseous losses when fires occur. For simplicity, only leaching is included in Figure 2.3, as this is the most studied process. Soil hosts the most complex processes linked to C and nutrient cycling; but simplification has often led to focus on above-ground litter and SOM decomposition, overlooking the bidirectional root-soil interactions, including root nutrient absorption.

2.3.2. Quantification of key stocks and flows

The overview of the cycles prompts to two main questions: (a) what are the largest stocks and flows, and (b) which are the most conducive to increase cocoa NPP in general, and crop yield in particular? Table 2.1 summarizes major C and nutrient stocks and flows in cocoa agroecosystems. On average, the largest quantified pools of C and nutrients are soil (with 30 Mg C ha^{-1} in 0-30 cm depth), cocoa tree above-ground biomass (15 Mg C ha^{-1}), and cocoa litter (5 Mg C ha^{-1}). Most intense C and nutrient flows include cocoa litterfall (2.6 Mg C ha^{-1} year^{-1}), pruning (2.2 Mg C ha^{-1} year^{-1}), and harvest (0.74 Mg C ha^{-1} year^{-1}). Rain-wash and atmospheric deposition are less studied, probably because they are modest (Table 2.1) and strongly depend on location. By contrast, pruning, which potentially induces as large a nutrient transfer as litterfall (Schneidewind et al. 2018), deserves more comprehensive evaluation.

Detailed data on C and nutrient partitioning among tree organs are less available as they often require destructive sampling, with large tree to tree variability. Roots, stem and branches, and leaves respectively accounted for 22-25%, 65-69%, and 9-10% of total biomass of 10-20 year old trees measured in Ecuador and Côte d'Ivoire (Fisher 2018; Calvo Romero 2018). Mechanistic growth models such as SUCROS-Cocoa (Zuidema et al. 2005) rely on empirical allometric relations to allocate assimilates among tree organs, which can be updated as more data become available (e.g. Figure 2.2b). For example, in a semi-quantitative diagram, Dand (2011, p. 44) allocated 2-3 times more carbohydrates to vegetative growth (especially stem growth) than reproduction in a 15-year old cocoa tree. However, a comparison across studies reveals some plasticity in NPP partitioning (Figure 2.5). In most systems, 40-60% of NPP is allocated to pod formation while total NPP was found to be in the range of 3-15 Mg ha^{-1} year^{-1} in the compiled dataset. Large variations in NPP and its partitioning make it challenging to identify generic and accurate allometric relations among tree organs that help to quantify reallocation of assimilates.

Estimating nutrient uptake by cocoa trees is not easy. Even if nutrient stocks in soils can be estimated, these may not help predicting bioavailability or actual uptake by trees. The actual nutrient uptake has never been measured except in the seedling stage (Oberthür et al. 2018; Ruseani et al. 2022). In doing so, the effect of fertilizer application on seedling growth has been demonstrated. In mature trees, measurement of either nutrient absorption rate (at root level) or uptake (at leaf or even tree level) are more challenging due to tree size, the time-scale, and inadequate sampling techniques. Accurate assessment of resource capture and partition within the tree are a bottleneck to advance our understanding of ISFM in cocoa. But simple measurements in the external cycle such as pruning are possible yet mostly undocumented.

Changes in N:P:K stoichiometry from vegetation to litter and to soil indicate two main features. First, N:K ratio increases from approximately 1 in trees to 3 in litter, and 6 in soil, indicating K impoverishment in the external cycle (inferred from Table 2.1). This is likely due to progressive removal by rain-wash (above-ground) and deep percolation (below-ground). We conclude that either K undergoes a shorter cycle or K losses through run-off and leaching are probably much higher than reported in previous studies: 1.2-1.5 kg K ha^{-1} year^{-1} in absence of fertilizer application (Hartemink 2005). Indeed, since soil structure is modified during lysimeter installation, and suction cups are too small in size, these studies can only account for matrix flow, but not for preferential flows. Besides, there are currently no available data on the surface and subsurface lateral flows, especially at the peak of the rainy season. These limitations may have masked K losses in previous studies. The second feature is an increase in N:P ratio from 14 in vegetation to 134 in soil (inferred from Table 2.1) which also suggests strong P limitations in soil. Since it was available P that was reported, we believe that strong P adsorption in tropical soils, modulated by soil pH, strongly competes with plant uptake. If these hypotheses are validated, P and K applications should be carefully monitored to reduce system inefficiencies.

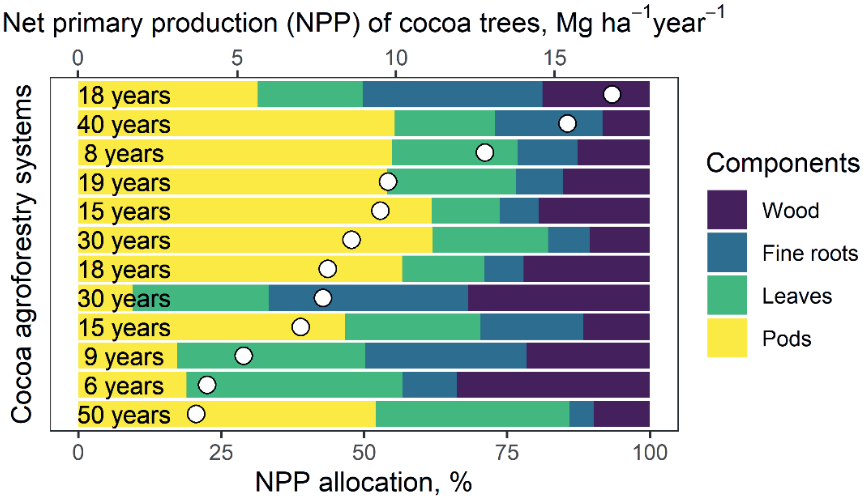

Figure 2.5: Net primary production (NPP, white circular dots) and its relative allocation between organs (coloured bars) of cocoa trees (6-50 years old, on the y-axis) in various agroforestry systems, estimated from literature (Abou Rajab et al. 2016; Leuschner et al. 2013; Morel et al. 2019; Moser et al. 2010). Main assumptions are as follow: leaves represent 80% of litterfall (unpublished data); pod index is set at 25 (dos Santos et al. 2018); and cocoa beans represent 50% of whole pod mass (Daymond et al. 2002). Increased C assimilation is required, but is not sufficient to improve cocoa yields in assessed production systems. Large NPP allocation to wood is unproductive, and could reflect unexploited potential to increase yields. Therefore, knowledge to increase NPP allocation to reproductive organs is as important as knowledge to increase NPP. A modest allocation to leaf biomass characterize the most productive systems, suggesting high photosynthesis rates at leaf level. Soil nutrient deficiency (which can be materialized by excessive C investment in fine roots) can limit NPP.

The diversity of tree species in cocoa agroforestry systems implies that the stocks and flows of C and nutrients are affected by the presence of associated trees. Agroforestry trees contribute substantially to carbon accumulation and to carbon and nutrient cycling in cocoa agroforestry systems (Table 2.1). Overall, across cocoa agroforestry systems (from less than 20 shade trees ha^{-1} to more than 200 trees ha^{-1}), the above-ground C pool of associated trees (28 ± 33 Mg C ha^{-1}) is twice as large as that of cocoa trees (15 ± 11 Mg C ha^{-1}). Leaf litterfall from associated trees (1.7 ± 1.1 Mg C ha^{-1} year^{-1}, 65 ± 44 kg N ha^{-1} year^{-}

^{1}) is similar to that of cocoa trees (1.4 ± 1.1 Mg C ha^{-1} year^{-1}, 50 ± 55 kg N ha^{-1} year^{-1}). Nevertheless, since fallen cocoa leaves decompose less quickly, the standing litter C is richer in cocoa leaves (1 ± 0.4 Mg C ha^{-1}) than in other tree leaves (0.6 ± 0.5 Mg C ha^{-1}). Woody materials in the standing litter could be substantial, so that the total litter amounts to 3.3 ± 1.8 Mg ha^{-1}.

2.4. Implementation of ISFM in cocoa

In this section, we discuss implementation of the five key components of ISFM in cocoa systems: the use of improved germplasm and implementation of good agricultural practices; alleviating local site and soil constraints; mineral nutrition of cocoa (particularly the estimation of correct quantities and application according to the 4R principles); and the use of organic fertilizer sources from within and from outside of the plantation.

2.4.1. Improved germplasm and crop management as components of ISFM

Integrated soil fertility management requires the implementation of sound agronomic practices and the use of improved germplasm that will efficiently make use of organic and mineral nutrient inputs. The use of suitable cultivars is therefore the first prerequisite for the success of upgraded nutrient management. Major cocoa producing countries host breeding programs to advance genetic gains (Bekele and Phillips-Mora 2019; Monteiro et al. 2009), but achievements towards yield improvement are poorly documented (Adebayo et al. 2021; Adewale and Nduka 2020; Edwin and Masters 2005). An important aspect of plant vigour is the potential benefit of orthotropic over plagiotropic architecture for vegetative propagation, which is still a disputed question lacking strong evidence (Tovar et al. 2022; Miller and Guiltinan 2003; Sodré and Gomes 2019). Besides, adoption of improved cocoa planting materials remains marginal among smallholders (Adebayo et al. 2021). Improved cocoa cultivar dissemination programs have been implemented in major cocoa producing countries (Edwin and Masters 2005; Umaharan 2018). However, smallholders mainly obtain seeds through informal channels. As observed in a baseline survey of the

CocoaSoils program in 2019 over the four major African producing countries, 57% of the 5200 surveyed cocoa fields managed by smallholders were exclusively planted with seeds obtained from own farms and/or from neighbours. As a consequence, top-down efforts towards disseminating improved cultivars are often not effective. Since cocoa plantations are maintained over decades, the majority of current smallholder farms may not reap the full benefits of ISFM. Applying other best-management practices in such a context is a clear compromise between ISFM principles and the quest for urgent increase in productivity.

For new and future cocoa plantations, not only planting material, but also good field establishment is required. Even when nurseries can produce vigorous seedlings as compared to direct seed sowing method, water and possibly heat stresses are unavoidable during field establishment in rainfed conditions. Drought stress is prominent in most cocoa production environments, causing 20-55% plantlet mortality (Acheampong et al. 2019; Ofori et al. 2014). Proper shading of seedlings reduces the severity of drought, but cannot completely alleviate water stress. This often results in replanting schemes, failure to maintain intended tree density, and age variation within the plantation. The stress imposed on a seedling during the establishment phase can later impair growth of the tree (Zweifel and Sterck 2018). For other species, extreme drought legacy last for more than three years in temperate forests (Wu et al. 2018). Nonetheless, it has been argued that the initial stress events are necessary for tree acclimation and adaptation, as these help to overcome more severe subsequent episodes (Kozlowski and Pallardy 2002). Environmental stress including water deficit and heat can be exacerbated by poor crop management.

Pruning is a key aspect of cocoa management (Tosto et al. 2022). Not only can pruning influence nutrient flows from plant to soil, but it also is the most practical way to regulate the balance between vegetative and reproductive growth within the tree (Iqbal et al. 2012). Pruning alters light interception through the canopy and can lead to increased photosynthetic rate of the remaining leaves (Susanti et al. 2017) so that the immediate reduction of leaf area can be compensated (Anten and Ackerly 2001). Pruning also induces new leaf flushing (van Vliet and Giller 2017), allowing the tree to recover from defoliation within a season; this results in rejuvenation of the canopy leaves. In turn, massive leaf flushing is said to precede flowering (Nair

2010) although the underlying mechanism remains unclear. It is also unknown how the replenishment of internal reserves utilized for new leaf flushing triggers further nutrient uptake. Beside nutrient cycling, pruning increases aeration in the canopy which lowers relative humidity with consequences for insect and disease management. In addition to sanitation, pruning is meant to ease general management of the plantation, especially harvesting. These embedded effects of pruning make it a central farming practice in cocoa for which recommendations are provided (Vos and Ritchie 2003). However, technical specifications for pruning intensity are often poorly supported by experimental evidence.

In previous studies, various combinations of farming practices showed variable effects on yield and/or profit in mature cocoa plantations (Akrofi-Atitianti et al. 2018; Aneani and Ofori-Frimpong 2013; Olujide and Adeogun 2006; Toledo-Hernández et al. 2020). Pest and disease control, nutrient supply, hand-pollination, and pruning often ranked among the most critical practices (Danso-Abbeam and Baiyegunhi 2019; Daymond et al. 2020; Kongor et al. 2017; Umeh et al. 2022). However, inconsistency among studies suggests that no universal hierarchy can be established; rather, a context-specific prioritization of practices may be valid. In addition, most studies did not clearly delineate the effect of biophysical and socioeconomic determinants of cocoa yields. Besides, for each practice or set of practices, the required intensity or frequency of application need to be determined considering returns to production factors such as capital and labour (Scudder et al. 2022). Similar to environmental stress (Asante et al. 2021), we believe that management practices exert a legacy effect on cocoa growth and productivity, which has yet to be quantified. At any stage of development and for any production system, cocoa trees require attentive management to optimize nutrient use efficiency under the constraints imposed by both germplasm, environment, and market.

2.4.2. Alleviating soil constraints to ISFM

The most commonly reported soil related constraint in cocoa production is soil acidity (Amponsah-Doku et al. 2022; Olasoji et al. 2022; Shamshuddin et al. 2011). Soil acidity is said to be a major challenge in some cocoa growing areas of Ghana (Doe et al. 2022), but the full extent of soil acidity problems across West Africa is unclear. Soil pH values as low as 3.5 have been reported in Ghana (Quaye et al. 2021b). However, it is unclear what degree of acidity can be tolerated by cocoa, given that it originates from tropical forests. Aluminium toxicity - and rarely manganese toxicity - have also been mentioned in cocoa (Anda et al. 2013; Baligar and Fageria 2005; Ribeiro et al. 2013). Other problems commonly associated with soil acidity in tropical soils include poor availability of phosphorus due to strong P-fixation, and calcium and magnesium deficiencies. Soil acidity may also affect the choice of N fertilizer to be used, for example calcium ammonium nitrate may be useful to provide calcium and limit any increase in aluminium saturation in acid soils that could be caused by long-term use of ammonium-based fertilizer. Disentangling the various soil acidity problems is complex and although amendments such as lime may be effective, there is a danger of over-application.

Soil erosion is of greater concern during establishment of the cocoa trees than in mature plantations due to the lack of soil cover. Claims of low SOC content as a production constraint (Adeniyi et al. 2018) are often made in the context of low-input systems, and remain inconclusive. Cocoa trees are susceptible to waterlogging, so poor drainage can be a local production constraint. Water scarcity may also limit cocoa growth, either due to growing cocoa under less favourable agroecological environments or the recurrence of extreme climatic events. Prevalence and incidence of soil physical and biological constraints (limited rooting depth, hard pan formation, soil-borne pests and diseases) on cocoa production are yet to be documented, at the exception of the black pod disease mainly caused by *Phytophthora palmivora* and *P. megakarya* (Afoakwa 2014). The primary source of inoculum is the soil, and initial dispersion occurs through rain splash (Raju et al. 2021), while abundant litter significantly reduces contamination of low-hanging pods (Surujdeo-Maharaj et al. 2016). However, soil fumigation did not reduce disease incidence on pods (Ndoungue et al. 2018), probably because of the larger importance of secondary sources of inoculum including aerial organs and debris and the multitude of vectors (aerosols, insects, rodents). When cocoa trees are severely attacked by pests and/or diseases, the tree nutrition can be affected either through a reduced nutrient uptake, or productive resources are mainly diverted for defence metabolism.

2.4.3. Mineral nutrition

Nutrition of cocoa has been extensively discussed, and it is clear that there are many approaches to determine crop nutrient requirements (van Vliet and Giller 2017). Few long-term experimental studies on nutrient responses in cocoa have been conducted since the 1960s and there is little agreement on fertilizer recommendations. On the other hand, mechanistic cocoa growth modelling is still in an early development stage (Asante et al. 2022; Schroth et al. 2016; Zuidema et al. 2005), and there is insufficient empirical knowledge to model nutrient limitations in cocoa dynamically. Here, we briefly describe the basics for developing a nutrient balance model in cocoa, which can be used to estimate nutrient requirements. We then discuss methods of organic and mineral fertilizer application, and how these can match crop demands.

2.4.3.1. Modelled nutrient demand of cocoa

A nutrient balance model is based on the premise that nutrients which leave the system or are immobilized in woody biomass need to be replaced (van Vliet and Giller 2017). Such a model is useful for several reasons: (a) it allows for estimating nutrient requirements as a basis for experimentation; (b) it allows to derive site-specific recommendations, taking into account factors such as the age of the trees, soil characteristics (including native soil fertility), and potential of germplasm; and (c) if sufficient data are available to make realistic offtake estimates then a model may achieve better nutrient balancing, and increase nutrient use efficiency. But there are also several pitfalls (van Vliet and Giller 2017) including over-estimation of nutrient requirements (because soil pools are not taken into account sufficiently), and nutrient concentrations in pod husks and vegetative biomass are highly variable, which strongly affect the model predictions.

When developing a cocoa nutrient balance model, the following data is required. First, nutrient concentrations in different organs must be known; usually estimates are based on destructive measurements (Fisher 2018; Calvo Romero 2018). Second, general tree growth patterns must be known or estimated; this is necessary to account for immobilization in wood, investment into leaves and root turn-over, nutrient removal in pods, etc. (e.g. Figure 2.2b). It is important to note that cocoa, like other perennials, does not have a stable harvest index, so the allocation of biomass to pods needs to be estimated unlike in annual crops. Third, information must be available regarding on-site biomass and nutrient management, particularly the management of cocoa pod husks, pruning residues, and leaf litter, to determine if nutrients are removed from the system or recycled. Fourth, short- and long-term nutrient recovery needs to be estimated. This is critical because it directly relates to nutrient input requirements. However, recovery is difficult to estimate precisely because it is affected by crop demand, soil water and sorption capacity and availability of other nutrients.

A cocoa nutrient balance model has been developed and is being tested (Vasquez-Zambrano et al. in preparation). For an elaborate and very detailed example of a nutrient balance model in a perennial crop (oil palm), see Goh and Po (2004).

2.4.3.2. Nutrient supply through mineral fertilizers

Mineral fertilizers provide nutrients in a readily available form and can ensure synchrony between nutrient availability in soil and crop demand, resulting in expected high uptake and use efficiency and minimization of losses. However, most current fertilizer recommendations lack a strong empirical grounding. The 4Rs of nutrient stewardship (Johnston and Bruulsema 2014) provide an important framework and guidelines on the types of fertilizers to be used, amounts, timing, and methods (where) to apply the fertilizer. In addition, site-specific factors affecting efficiency of fertilizer use must be considered. Depending on the location, the fertilizer market offers multiple formulations which potentially increases flexibility for site-specific application, but also complicates a farmer’s choice; so far, decision-support tools lack to fill this gap.

The amount or right rate of fertilizer in cocoa is tree age-dependent, and affected by the cropping system used, with mono-cropped cocoa having higher yield potentials and hence higher nutrient needs (Arthur et al. 2022). In light of the physiological role of each nutrient (van Vliet and Giller 2017) and plausible nutrient interactions (Rietra et al. 2017), the main strategy is to ensure vigorous early growth, high yields, and to maintain those high yields for the long term. In terms of balance among the nutrients, K is needed in larger quantities than N, and P is required in considerably smaller quantities (Snoeck et al. 2016; Thong and Ng 1980). Thus, unlike in most annual crops where the N:P:K fertilizer notation often depicts the order of importance of the nutrients, in cocoa, a different balance may be expected, which could also be site-specific.

The most common fertilizer application methods are the ‘ring method’ (Asare and David 2011), and broadcasting to a lesser extent (Cudjoe et al. 2016). The ring method consists in clearing a band 0.1-0.5 m wide, in a radius of 0.7-1 m from the cocoa tree trunk, by pushing aside the mulch, applying the fertilizer and covering with mulch (Nlend-Nkott and Asare 2021). The specific ring dimensions and distance from the tree are essential to target areas of active roots to ensure high capture and uptake efficiency, especially in younger plantations. The thick mulch layer in cocoa plantations may prevent substantial losses of nitrogenous fertilizers such as urea through volatilization. However, immobilization of N may occur because of the wide C:N ratio of the leaf litter (Table 2.1) resulting in short term unavailability of N.

Foliar fertilizer are often applied in small quantities to supplement regular fertilizers (Kasran et al. 1991), although their efficacy in cocoa remains unproven. A recent survey indicated variable use of foliar fertilizers among West African smallholder cocoa farmers: more in Cameroon and Ghana than in Côte d'Ivoire and Nigeria (Table 2.2). The target nutrients in foliar fertilizers are often K, Mg, Zn and B, and some commercial products include N and P even though foliar P absorption is marginal (Boroughs et al. 1963). Foliar fertilizers are mainly applied when there is need for quick correction of a deficient nutrient, which may be effective in case of confirmed micronutrient deficiency. Correction of macronutrient deficiencies (primary or secondary) through foliar fertilizers is unlikely given the vanishingly small application rates that are recommended (about 6 L ha^{-1} $year^{-1}$). Several foliar fertilizer products are on the market, but there is general lack of scientific data to prove their efficacy in terms of adsorption on plant organs, absorption and translocation.

Table 2.2: Average use of mineral fertilizers in *n* surveyed fields in four West African countries on in total 3170 cocoa farms. Data were retrieved from a preliminary analysis of the CocoaSoils baseline survey (2019). More than one type of fertilizers was used in several fields. Differences between countries probably resulted from technical preferences made by extension agencies and the recent developments in agrochemical markets.

Indicators	Countries				
	Cameroon (*n*=1193)	Côte d'Ivoire (*n*=953)	Ghana (*n*=1894)	Nigeria (*n*=1256)	4 countries (*n*=5296)
Proportion of cocoa fields in which fertilizers were applied (%)	51	48	38	07	36
Proportion of cocoa fields in which foliar fertilizers were sprayed (%)	50	05	27	04	23
Proportion of cocoa fields in which broadcasting method was used (%)	00	00	12	00	04
Proportion of cocoa fields in which ring method was used (%)	01	44	01	03	09

2.4.4. Organic resource management

The recent discourse on regenerative agriculture places organic matter inputs at the centre of soil health (Schreefel et al. 2020). There are two broad groups of organic inputs i.e. produced *in-situ* (pod husks, pruned residues, litter) and *ex-situ* (animal manure, compost, biochar) whose management may require similar approaches.

2.4.4.1. Readily available resources in the plantation

Considering the large amounts of litter found in cocoa plantations, its role in nutrient supply is important (about 50 kg N ha^{-1} $year^{-1}$, 3 kg P ha^{-1} $year^{-1}$, 15 kg K ha^{-1} $year^{-1}$) but restricted by the low nutrient concentrations. Since the flow of nutrients from litter to soil may not meet the entire crop requirements, balanced nutrition of cocoa requires additional inputs. The role of litter as a mulch is important to encourage infiltration of rainfall and prevent soil erosion. During establishment, litter provided by temporary vegetation is critical, and requires careful management. In mature cocoa, there is no obvious incentive to actively manage litter. As compared to litter, pruned residues have not been studied, although leaves of pruning residues contain more nutrients than senescent fallen leaves (Calvo Romero 2018) and are likely to decompose faster. Spreading pruned residues of shade trees, especially from leguminous species, can improve cocoa nutrition; although only the closest cocoa trees are likely to benefit. Probably of greater concern is the management of woody materials (stem, branches, and stumps) at the end of a production cycle, because these represent large nutrient stocks. Unlike oil palm trunks that are more fibrous and are sometimes shredded and returned to soil (Uke et al. 2021), shredding cocoa wood may be less practical, enhance CO_2 emissions, and spread disease. A residue which deserves a special management in cocoa is the pod husk.

Cocoa pod husks are richer in nutrients (about 2% N, 0.15% P, 3% K) than cocoa litter but are not always returned to the plantation. There are several options to recycle pod husks: they are often simply abandoned in heaps, but can be spread as mulch, and/or incorporated in soil. In most favourable decomposition conditions, pod husks undergo 95% mass loss within a year or two. However, when cocoa pod husks are exposed as usually observed, rainfall abundance and frequency further determine nutrient release patterns (Hougni et al. 2021). Husks can also be composted or used to make biochar (see below). The heat generated by composting or biochar production potentially reduces *Phytophthora* spp. inoculum abundance by 70-100% (Doungous et al. 2018). However uncontrolled conditions of compost preparation (poor aeration and temperature control, open storage) can lead to substantial nutrient losses (e.g. 8-60% N, 14-39% P, 1-38% K) as observed with other substrates (Michel et al. 2004; Bernal et al. 2009). Insufficient heat will also cause persistence of disease inoculum, so that the composted pod husks can become an important source of disease spread. Similarly, untreated pod husks present the same unevaluated risk when reused as mulch in cocoa. Indeed, propagules can survive up to 18 months (Bailey and Meinhardt 2016) and can spread over 7-9 m (Ndoumbe Nkeng et al. 2016). Safer cocoa pod husk treatment modes are complete incineration (ash production), charring, or removal from fields with expected trade-offs about carbon and nutrient cycles.

2.4.4.2. Resources from outside the plantation and organic matter processing techniques

The cost of mineral fertilizer and in particular recent price spikes, has led to suggestions that organic manures should be promoted to supply nutrients for cocoa and to maintain soil fertility. Crop-livestock integration is a key component of ISFM with arable crops to recycle nutrients within the farm system. This has a number of benefits, not least in that some of the nutrients fed to livestock in crop residues are returned to the fields. There has been relatively little attention to use of animal manures in cocoa. Indeed, livestock are not a major component of the smallholder cocoa farm systems. The recent CocoaSoils baseline survey of cocoa farmers in West Africa indicated that very few households (1% or less) own cattle, and only 15% rear 3-6 sheep or goats (Table 2.3). As a rule of thumb, the excreta of one Tropical Livestock Unit (TLU) kept under zero-grazing conditions can produce roughly 780 kg DM manure in a year (Rufino et al. 2007).

For those rearing sheep or goats, this would result in approximately 350 kg DM year^{-1} of manure, or a supply of about 6 kg N year^{-1}. Poultry is the most common livestock kept by half of cocoa farmers, with a median number of less than 20 chickens per farm (Table 2.3) which would deliver about 150 kg DM manure year^{-1}. Poultry manure is not normally a resource collected on farm as most poultry is free range, but even if all their manure was collected and assuming 5% N in the manure (Kirchmann and Witter 1992), that would amount to only 3-6 kg N year^{-1} for a typical cocoa farm that raise chicken. However, as the N is present as uric acid, which is readily hydrolysed to ammonium, much of the N is lost by volatilization during aerobic decomposition (Kirchmann and Witter 1989). For plantations close to large poultry farms, poultry manure can be an important resource, although the economics of its use in terms of purchase and transport have not been investigated. Given that rates of application of animal manures required are in the range of 5 Mg ha^{-1} or more, it is clear that only a small fraction of the cocoa growing area could be fertilized with manure produced on farm. If manures are available, it is likely they will be targeted to production of e.g. vegetable crops within the farm system.

Table 2.3: Potential of on-farm manure to improve mineral nutrition of cocoa in West African smallholder cocoa farms. See details in Table 2.2; here *n* indicates the number of farmers that answered the questions about livestock.

Indicators	Countries				
	Cameroon (*n*=688)	Côte d'Ivoire (*n*=828)	Ghana (*n*=827)	Nigeria (*n*=799)	4 countries (*n*=3142)
Proportion of households reporting raising livestock in the household					
All species (%)	45	60	67	35	52
Cattle (%)	00	01	00	00	00
Sheep (%)	02	19	19	02	11
Goats (%)	22	15	23	06	16
Pigs (%)	17	05	03	00	06
Rabbits (%)	00	00	01	00	00
Chicken (%)	30	46	52	32	40
Median size of the herd owned by households engaged in cocoa farming					
Cattle	00	05	13	03	05
Sheep	04	05	06	04	05
Goats	03	04	06	04	05
Pigs	03	04	06	04	04
Rabbits	16	00	07	28	07
Chicken	10	15	18	10	13
Expected amounts of manure and N potentially produced in a typical smallholder cocoa farm[1]					
Manure from cattle (kg DM year^{-1})	00	3418	8544	2020	3418
Manure from sheep (kg DM year^{-1})	273	342	410	239	342
Manure from goats (kg DM year^{-1})	205	273	410	273	342
Manure from pigs (kg DM year^{-1})	410	547	820	547	547
Manure from rabbits (kg DM year^{-1})	106	00	48	192	178
Manure from chicken (kg DM year^{-1})	68	103	123	68	89
N from cattle (kg N year^{-1})	00	79	197	47	79
N from sheep (kg N year^{-1})	06	08	09	06	08
N from goats (kg N year^{-1})	05	06	09	06	08
N from pigs (kg N year^{-1})	13	17	25	17	17
N from rabbits (kg N year^{-1})	02	00	01	04	01
N from chicken (kg N year^{-1})	03	05	06	03	05

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[1] Calculations were based on the estimation of living animal mass for different species (Benoit and Veysset 2021), the potential production of manure (Rufino et al. 2007), and the N content of manure (Kirchmann and Witter 1992).

Other organic resources that can be used are compost and biochar, which could be produced on-farm or imported from outside the farm. The quality of compost depends on the blend of organic materials used. Nutrient concentrations are relatively small, but much larger than applying crop residues directly to soil, because a considerable proportion of C is lost during composting. Effective composting requires compost heaps to be at least 1 m^3, so that thermophilic microorganisms take over and temperatures are raised to ensure proper sanitation of crop residues. Guidance on making good compost suggests that heaps are turned regularly to re-aerate the heaps, ensure mixing and to stimulate more complete and rapid decomposition (Rynk 2022), but this is labour-demanding and rarely done on-farm. If compost heaps are not covered with plastic or a layer of straw, gaseous losses of N during composting can be substantial. Organic mineral fertilizer application has a great potential to increase cocoa seedling growth in nursery (Dogbatse et al. 2021; Fidelis and Rajashekhar Rao 2017; Salifu et al. 2020), especially because nutrient requirements are modest. Combining compost made from pod husks and NPK fertilizer also gave greater yield responses in Nigeria than compost or fertilizer alone, and appeared to reduce crop loss due to black pod (Ogunlade and Orisajo 2020). Fungenzi et al. (2021) also found that compost applied at a rate of 10 Mg ha^{-1} $year^{-1}$ together with NPK fertilizer for seven years gave greater yield responses in cocoa than fertilizer alone. Although the major benefit of compost is generally considered to be its role in maintaining SOM, these authors could detect no significant change in SOM despite the large amounts of compost added.

Considerable research has focused on the production of biochar which is a more stable form of organic matter than compost with a larger surface area and cation exchange capacity. Biochar (often referred to as black carbon) is a solid, recalcitrant and high carbon material produced by pyrolysis of biomass under controlled conditions. Biochar has been shown to have numerous benefits in soil (Hossain et al. 2020). For instance, Pouangam Ngalani et al. (2022) concluded that biochar made from cocoa pod husks can increase pH and the availability of phosphorus in soil. Given that the rates of biochar applied equate to 52 t ha^{-1} for the smallest and 208 t ha^{-1} for the largest rate applied[2] in this study, this is hardly surprising. Thomazini et al. (2015) demonstrated that biochar can reduce greenhouse gas emissions from soil in incubation studies, although at rates added equivalent to 260 t ha^{-1}. Biochar also has potential to reduce cadmium uptake in cocoa (Ramtahal et al. 2022). As with compost, the critical question is what feedstock can be used to produce biochar. Substantial attention has been paid to production of small furnaces that can be deployed in rural areas (Quansah 2021). Conversion rates of biochar from pod husks are about 32-38% (Quansah 2021); but in general, biochar yield ranges between 14 and 94%, with other feedstocks (Kalus et al. 2019). Several studies have examined use of cocoa pod husks to produce biochar, although perhaps making biochar from cocoa pruning residues deserves more attention. Hossain et al. (2020) highlighted the need for long-term field studies to understand the impacts of biochar in soil, in relation to the biochar feedstock and application rates. These recommendations are highly pertinent for cocoa.

If organic residues originate from within the farm, whether as animal manures or to make compost or biochar, this is potentially a good way of ensuring effective recycling. However, it does not represent a net contribution of nutrients or sequestration of carbon and is essentially a case of “robbing Peter to pay Paul” when considered in the broader farm context.

2.4.4.3. Scope of using organic resources in cocoa

The above discussion clearly demonstrates that organic resources can be useful to provide nutrients and to maintain SOM and soil fertility. Organic resources such as compost or biochar can be useful in seedling production (Quansah 2021) and establishment of cocoa plants in the field. In mature cocoa, a thorough analysis is needed at the farm and farming system level to fully understand the potential of managing organic resources from both within and between farm systems in the same locality. This needs a fuller understanding of the labour, equipment (in the case of biochar), and skills required for production and use

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[2] Assuming a bulk density of 1.3 kg dm^{3}, one hectare of soil to a depth of 20 cm weighs 2.6 × 10^{6} kg, a rate of application of 20 g kg^{-1} equates to 52 Mg ha^{-1} and a rate of 80 g kg^{-1} to 208 Mg ha^{-1}.

of organic amendments, including a full cost-benefit analysis. Greater attention to recycling of organic resources within the cocoa plantation, and in particular cocoa pod husks, is clearly warranted.

2.5. Concluding remarks

Improving or maintaining soil fertility, ensuring adequate crop mineral nutrition, and effective nutrient recycling are the core objectives of ISFM. While the basic principles are just as pertinent for perennial crops as for arable crops, there are important differences related to the capacity to alter soil properties, carbon accumulation, and nutrient cycling within the agroecosystem. In annual cropping systems, ISFM is focused on crop rotations and crop-livestock integration, with crop residue management and organic inputs as key entry-points. By contrast, nutrient cycling, essentially at plot level, is central to ISFM in cocoa. In particular, nutrient immobilization in and remobilization from tree biomass must not be overlooked. Our analysis highlighted challenges to estimate and match crop nutrient demand and supply, and shows that currently, there is little scope for smallholder farmers to integrate livestock, composting or biochar production into cocoa production.

Agronomic preconditions for increased nutrient uptake are numerous, starting from choice of planting materials and establishment phase. Ensuring good establishment of cocoa with strong root systems has long-term effects on growth and yield of the plantation throughout the production cycle – which means that implementation of ISFM in current smallholder cocoa farms will *de facto* not achieve desired results. This highlights the need for re-establishment to regenerate cocoa plantations, which would also allow the use of improved cocoa germplasm. More insight in how pruning can be used to manipulate the balance between leaf biomass and pod production, while maintaining optimal conditions to limit pest attacks, is required to adjust farming practices as a first step to increase productivity. There are differences in flow rates and losses of N, P, and K in the cocoa system which determine their availability when recycled. A better understanding of flows, losses and limitations to crop growth are essential for balanced nutrient management.

Although we focus our discussion on enhancing nutrient use efficiency and cocoa yield, sustainable production of tree crops also requires consideration of pooled resource availability, use efficiency and profitability at farm level. This implies valuation of other economic products and ecosystem services, especially in agroforestry systems. Another challenge to soil fertility management in intensified tree crop systems which we do not address here is to guarantee successive production cycles on the same site.

Appendix

List of references in table 2.1.

No	Citation	No	Citation
1.	Dawoe et al. (2017)	20.	Muoghalu and Odiwe (2011)
2.	Gutzler et al. (2010)	21.	Nijmeijer et al. (2019a)
3.	Abou Rajab et al. (2016)	22.	Hertel et al. (2009)
4.	Beer et al. (1990)	23.	Isaac et al. (2005)
5.	Leuschner et al. (2013)	24.	Picchioni et al. (2020)
6.	Moser et al. (2010)	25.	Vervuurt et al. (2022)
7.	Ofori-Frimpong et al. (2007)	26.	Asigbaase et al. (2021a)
8.	Puentes-Páramo et al. (2016)	27.	Borden et al. (2019)
9.	Morel et al. (2019)	28.	N'Gbala et al. (2017)
10.	Aranguren et al. (1982)	29.	Calvo Romero (2018)
11.	Fontes et al. (2014)	30.	Isaac et al. (2007a)
12.	Perez-Flores et al. (2018)	31.	Fisher (2018)
13.	Saj et al. (2021)	32.	Madountsap Tagnang et al. (2018)
14.	Yao et al. (2021)	33.	Norgrove and Hauser (2013)
15.	Owusu-Sekyere et al. (2006)	34.	Somarriba et al. (2013)
16.	Sreekala et al. (2001)	35.	Sari et al. (2020)
17.	Beer (1988)	36.	Dawoe et al. (2010)
18.	Sauvadet et al. (2020)	37.	Schneidewind et al. (2018)
19.	Schwendenmann et al. (2010)		

3

Chapter 3

Macrofauna accelerates nutrient cycling through litterfall in cocoa[1]

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[1] Submitted to the Biology and Fertility of Soils journal as:
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Abstract

The internal flows of nitrogen (N), phosphorus (P), and potassium (K) through cocoa systems are poorly quantified, yet this is needed for effective nutrient management. The aim of this study was to better understand N, P, and K cycling through litterfall in smallholder cocoa fields. Annual litter production, relative mass loss and nutrient loss rates from cocoa leaf litter were assessed in three farms in South-Western Nigeria.

Litterfall was measured fortnightly close to the base of the cocoa tree and at the edge of the tree canopies, from January 2020 to December 2021. Leaf litter decomposition rates were determined over 388 days in 2 mm mesh litterbags to exclude macrofauna and in open frames on the ground with macrofauna access. Concentrations of C, N, P, and K were measured in the remaining litter at 180, 244, 314, and 388 days after incubation.

Annual estimates of litterfall (10 tons DM ha^{-1}) did not differ between the traps close to and away from the cocoa trunk ($P > 0.05$). The annual nutrient removal from litter was roughly estimated at 101 kg N, 5 kg P and 89 kg K ha^{-1} $year^{-1}$. Relative litter decomposition rates (k) were 2.33×10^{-3} and 1.70×10^{-3} day^{-1} in frames and litterbags respectively ($P < 0.05$). Macrofauna access significantly reduced C:N ratio in the remaining litter, and increased N and P loss by 28 and 69% respectively.

In conclusion, nutrient flows through litterfall are considerable, and N and P transfer rates to soil are likely to be under-estimated in standard litterbag experiments that exclude macrofauna.

Key-words: soil macrofauna; fractionation effect; litter disappearance; spatial heterogeneity; nutrient release.

3.1. Introduction

Cocoa in West Africa is mainly produced in low-input systems (Wainaina et al. 2021; Daymond et al. 2022); therefore farmers rely largely on natural biogeochemical processes to maintain or improve the inherent soil fertility (Appiah et al. 1997; Duguma et al. 2001; Kenfack Essougong et al. 2020). In production systems where nutrients are to be provided, balanced nutrition of the cocoa trees must account for the soil nutrient supply. Henceforth, a deeper understanding of the recycled flows of nutrients in litter is needed to improve fertilization strategies and to better supplement naturally-available nutrients. This poses questions on how to best measure litterfall, litter decomposition rates and nutrient cycling through the litter.

Natural sources of nutrient inputs in low-input systems are atmospheric deposition, nitrogen fixation and soil mineral weathering, all of which may be negligible in tropical environments (Hartemink 2005; Ossohou et al. 2020). Substantial amounts of nutrients are recycled and returned to the soil in litterfall. The accumulated litter progressively decomposes and releases nutrients which can later be available for microbial and plant uptake. Therefore, the flow of nutrients through litterfall and litter decomposition plays a major role in maintaining soil fertility and productivity of smallholder cocoa fields. The variability in cocoa litterfall and litter turnover rates have not been studied in detail. Hence, the contribution of litter decomposition to nutrient mineralization and soil nutrient availability is poorly understood in cocoa.

Only a few authors studied cocoa litterfall in West Africa, and these have not addressed spatial and temporal variations in detail. We found only two peer-reviewed papers from Ghana (Asigbaase et al. 2021b; Dawoe et al. 2010) and Nigeria (Muoghalu and Odiwe 2011; Ogunlade and Iloyanomon 2009), and a single one each for Côte d'Ivoire (Yao et al. 2021) and Cameroon (Saj et al. 2021). In these studies, annual litterfall was quantified, but without a clear and consistent link to the amounts of transferred nutrients.

Assessing spatiotemporal variation of litter stocks and the related nutrient flows in forests and tree crop systems is inherently challenging due to methodological limitations. Protocols for litterfall experiments vary strongly between studies: litter trap size, number and spatial distribution of litter traps, and duration of the experiment are not standardized, which affects the conclusions. In cocoa agroecosystems, the optimal position of litter traps relative to cocoa trees is often not clear. When specified, litter traps are set either randomly (e.g. Fontes et al. 2014) or at a fixed distance to the cocoa trees in systems where cocoa is planted at regular spacing (e.g. 0.5 m, Schneidewind et al. 2018). Regular shifting of litter traps may increase spatial representativity (Dawoe et al. 2010; Schroth and Sinclair 2003). Cocoa trees are typically pruned into a "cup shape" (Tosto et al. 2022) which should reduce branch interlocking between adjacent trees. This shape likely results in a gradient in litterfall from the stem of the cocoa trees to the edge of the canopy. In practice, it is unclear how heterogeneous the litter is under cocoa trees, meaning that positioning of the litter trap may have a large effect on amounts of litter trapped. The extent to which the position of the litter trap influences the accuracy of litterfall estimation is unknown, especially in traditional cocoa agroecosystems characterized by irregular planting patterns.

Litter decomposition is affected by various soil organisms, which are broadly classified according to their size: macro- (larger than 2 mm), meso- (from 100 µm to 2 mm), and micro-fauna (less than 100 µm) (Centenaro et al. 2018). Macrofauna is diverse and abundant in soils under natural ecosystems and in no-till agricultural systems (Maria de Aquino et al. 2008; Smith et al. 2008); this is also expected under cocoa. Macrofauna greatly contributes to litter fragmentation, ingestion, and mixing with soil particles, but they also control microbial communities and activities (Lavelle et al. 2006), thus affecting litter decomposition and nutrient mineralization rates. However, to our knowledge, their relative contribution to litter transformations and nutrient release in cocoa has not been quantified yet.

The choice of litterbag mesh size determines which organisms can access the substrate. Standard incubation trials partially or totally exclude macrofauna. Usually, the size of litterbag mesh varies from 0.5 to 2 mm, which excludes macrofauna (e.g. beetles, earthworms, ants, and termites) normally present in cocoa litter (da Silva Moço et al. 2009). Mesh sizes reaching 10 mm are used in other systems (Lecerf 2017), but those are not included in cocoa litter studies. Therefore, most cocoa litter decomposition studies have not accounted for macrofauna activity and its role in cocoa litter decomposition is largely unknown.

The aim of this study was to better understand nutrient cycling through litterfall in smallholder cocoa fields. The first objective was to evaluate differences in annual amounts of litterfall close to- and away from- the stem of cocoa trees. The second objective was to quantify the effect of macrofauna on the rate of cocoa leaf disappearance from the litter layer, and on changes in N, P, and K concentrations of the remaining litter. We hypothesized that (1) litter fell more abundantly close to the stem than at the edge of the canopy, and (2) macrofauna increased the litter mass loss rate (disappearance) as well as N and P loss from the cocoa leaf litter (nutrient removal rates). An experiment was conducted in southwestern Nigeria that involved litterfall measurements over two consecutive years, and an incubation trial of cocoa leaf litter with and without access of macrofauna over one year.

3.2. Materials and Methods

3.2.1. Study area and site description

The study area falls in the sub-humid agroecological zone characterized by average monthly temperatures in the range of 23.5°C (September) to 27.7°C (January) and 45.5 to 97.6% relative humidity (RH). The annual rainfall is unimodal with a long rainy season with a total between 1377 mm and 1965 mm while the dry season runs from December to March. Occasionally, a dry-spell occurs in August, as it happened during the first year of data collection.

The experiment ran from January 2020 to December 2021 in South-Western Nigeria, in three farmer-owned cocoa fields of about 1.5 ha each (hereafter named “Ago-Owu”, “Akowonjo-Akoko”, and “Ijebu-Itele”) that were 100-300 km apart. The major soil types in all selected fields were predicted to be lixisols (Hengl et al. 2021). The texture was sandy loam to sandy clayey loam (Table 3.1). Cocoa was established on forest lands. The fields are representative of low-shade cocoa agroforestry systems managed by smallholders in the region. Oil palms (*Elaeis guineensis* Jacq.), cola trees (*Cola nitida* Schott & Endl.) and few forest-remnants form the upper canopy while cocoa and *Citrus* spp. share the lower canopy. Other field characteristics are shown in Table 3.1.

3.2.2. Data and observations.

In each field, all observations were made in two plots (21 m × 21 m) established 30-50 m apart (Figure 3.1). Interpolated monthly rainfall and daily air temperature for the three sites were obtained from the National Aeronautics and Space Administration (NASA) agroclimatology predictor (https://power.larc.nasa.gov/data-access-viewer/).

The cocoa tree aboveground biomass was estimated using a cocoa-specific allometric equation (Eq. 3.1) developed for nearby cocoa plantations of similar production systems in Oyo state (Ajibona O., Unpublished MSc thesis).

$$AGB = 0.055\ D^{2.267} \qquad \text{(Eq. 3.1)}$$

where AGB (kg) is the aboveground biomass of the cocoa tree, and D (cm) the stem diameter measured at about 30 cm above the ground surface.

The gap fraction, the percentage of incident radiation intercepted by the whole canopy, was estimated based on hemispherical photographs taken in November 2020 at 1 m aboveground, under the canopy of five randomly sampled cocoa trees. The images were processed using default settings of the Gap Light Analyzer (GLA) software (Frazer et al. 1999).

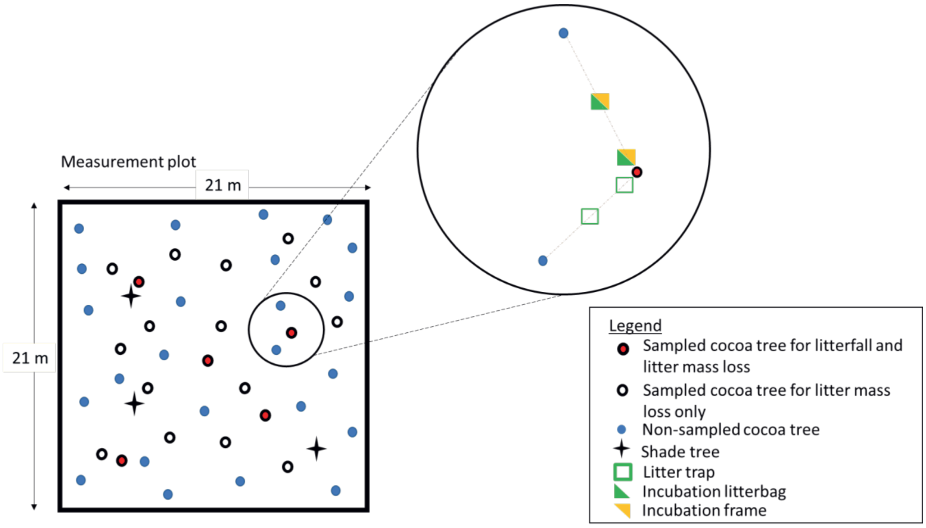

Figure 3.1: Layout of an experimental plot in a farmer's field.

3.2.2.1. Litterfall

Litterfall was estimated based on the standard litter trap method (Anderson and Ingram 1993). Within each plot, five cocoa trees were randomly selected, and paired litter traps (0.8 m × 0.5 m) were placed: one at a distance of 20 cm from the cocoa tree (hereafter "close"), and the other half-way between the tree and an adjacent cocoa tree, at an average distance of 1.38 ± 0.5 m from the stem (hereafter "away"). The away litter traps fell within the area under interlocking branches of two adjacent cocoa trees. All litter traps were set regardless of the position of shade-trees. However, litter trap positions never fell directly under the canopy of a shade tree. Litterfall was collected fortnightly, from January 2020 to December 2021. Due to travel restrictions at the onset of the Covid-19 pandemic and at times of civil unrest, we were unable to collect litter from April 2020 to June 2020 and from February 2021 to March 2021 in any field. At Akowonjo-Akoko, the 2021 civil conflicts were more intense, and the farm was not accessible from February 2021 to May 2021. At the end of these periods, the entire litterfall was quantified.

All litter samples extracted from the litter traps were oven-dried at 65ºC to constant mass and sorted into cocoa leaves, shade-tree leaves, and other fragments (mostly twigs). Each component of the litterfall, i.e. cocoa leaf litter, shade-tree leaf litter, and other fragments, was aggregated per year for analysis.

3.2.2.2. Soil and litter analyses

Ten soil samples from 0 to 30 cm depth were randomly collected in each plot using a soil auger. These samples were pooled for each field, air-dried, mixed thoroughly, and sub-sampled for physical and chemical analysis. Soil texture was determined by the hydrometer method (Dane et al. 2002). Soil pH was determined in 1:2.5 (w/v) soil to water suspension (McLean 1983). Exchangeable cations, Ca^{2+}, Mg^{2+} and K^+ were extracted by the Mehlich-3 procedure. Cation concentrations were determined by atomic absorption spectrophotometry (AAS) and phosphate content by the molybdate blue procedure (Bray and Kurtz 1945). Organic carbon content was determined using the Walkey-Black chromic wet oxidation method (Nelson and Sommers 1996). Total nitrogen content was determined by the Kjeldahl digestion method using concentrated sulphuric acid and sodium copper sulphate catalyst mixture and distillation in boric acid. Soil bulk density was determined using two randomly sampled cores per plot (Grossman and Reinsch 2002).

Concentrations of N, P, and K in cocoa leaf litter were determined after pooling samples per field (Table 3.1). Total N, P, and K contents in cocoa leaf residues were respectively analysed with Kjeldahl method, molybdate blue colorimetry, and AAS after digestion. Carbon and nutrient flows through cocoa leaf litterfall were estimated annually by multiplying concentrations estimated in freshly fallen cocoa leaf litter (as collected in December 2019) with the dry mass of cocoa leaf litterfall aggregated per year.

3.2.2.3. Cocoa leaf litter disappearance and nutrient losses

Cocoa leaf litter mass loss and nutrient loss from the litter layer were assessed *in situ* through the incubation method (Anderson and Ingram 1993). Forty grams of freshly fallen cocoa leaves were collected in December 2019 and enclosed either in 40 cm × 30 cm litterbags of 2 mm mesh size or placed directly on the soil surface within a frame of equal size covered by 2 mm mesh to prevent mixing with foreign materials such as subsequent litterfall or disturbance by wind and animals. The initial mass of cocoa leaves (40 g per sample) was set to simulate a total leaf litter mass of 3300 kg ha^{-1}. Before the incubation, the soil surface was cleared from pre-existing residues and the frames and litterbags were gently placed, labelled, and fixed with bamboo pegs to avoid undesired movements. Litterbags and frames were placed side by side. A total of twenty four sets of litterbags and frames were placed per plot, each under a randomly selected cocoa tree. Between January 2020 and January 2021 and starting at 14 days after incubation (DAI), one set of litterbag and frame was randomly retrieved at 14 day intervals during the rainy season and at 21 day intervals during the dry season.

The residues from the litterbags and frames were oven-dried, soil particles brushed-off and their dry weight was determined. Cocoa leaf litter mass loss data was used to estimate the relative decomposition constant rate k for litterbags (k_B) and for frames (k_F), based on a first-order exponential decay model (Eq. 3.2, Olson 1963):

$$m_t = m_i e^{-k\,t} \qquad \text{(Eq. 3.2)}$$

where m_i and m_t are the initial and residual cocoa leaf litter mass at t days after incubation (DAI) respectively, and k is the estimated parameter.

Leaf litter was analysed to determine C, N, P, and K concentrations as in section 2.3. One sample per plot was taken from the residues retrieved from litterbags and frames at 0, 180, 248, 314, and 388 DAI. The amount of C, N, P and K in the litter residues was calculated from the elemental concentrations and the dry mass of the residues. The effect of macrofauna on C and N, P, and K loss was estimated at 180, 248, 314, and 388 DAI, by comparing the amount of nutrients in the residues (relative to the initial amount at start) between litterbags and frames. The effect of macrofauna on the quality of the remaining litter was assessed by evaluating nutrient ratios (namely C:N, C:P, and N:P) in the residues.

3.2.3. Statistical analyses

Annual amounts of cocoa leaf litterfall collected close to- and away from- the cocoa tree stems were analysed using a linear mixed-effect model. Fixed-effect factors were the distance to the stem (close vs away) and year, without interaction. The random-effect factors included in the model were the fields, plots within field, and the sampled trees within each plot. The two other components of the total litterfall, i.e. shade tree leaves and other fragments, were analysed in the same way. Annual amounts of C, N, P, and K that flow through cocoa leaf litterfall were only analysed by means of descriptive statistics.

The relative decomposition rates of cocoa leaf litter (k) were estimated as per equation (Eq. 3.2), i.e. by calculating the slope of the relationship between time (t) and the log-transformed residual mass of litter (m_t/m_i). The values of k_F and k_B were estimated for each plot within each field using linear regression, and compared through an analysis of variance (ANOVA).

The C, N, P, and K concentrations in the residual cocoa leaf litter, the nutrient ratios (C:N, C:P, and N:P), and the relative loss were analysed with linear mixed-effects models, considering the sampling dates (0, 180, 248, 314, and 388 DAI), the elements (C, N, P, or K), the effect of macrofauna, and their interaction as fixed-effect factors. Random-effect factors were the fields and plots within each field.

Differences between litterfall collected close and away, and between k_F and k_B were evaluated with a Wald-type F test. All analyses were performed in R (R Core Team 2013).

Table 3.1: Cocoa farm characteristics, soil physico-chemical and litter chemical properties of the study sites

Parameters	**Location**		
	Ago-Owu	Akowonjo-Akoko	Ijebu-Itele
Coordinate (decimal degrees)	4.2031 °E, 7.1482 °N	5.6203 °E, 7.4383 °N	4.3667 °E, 6.9833 °N
Elevation (m)	272	328	295
	Soil properties		
Sand (g kg^{-1})	680 ± 0.0	730 ± 7.1	750 ± 4.2
Silt (g kg^{-1})	90 ± 1.4	90 ± 1.4	90 ± 1.4
Clay (g kg^{-1})	230 ± 1.4	180 ± 5.7	160 ± 2.8
Bulk density (Mg m^{-3})	1.11 ± 0.2	1.15 ± 0.1	1.12 ± 0.1
pH (H$_2$0)	6.85 ± 0.1	6.20 ± 0.3	6.70 ± 0.7
Organic carbon (g kg^{-1})	11.80 ± 0.7	8.53 ± 0.7	9.60 ± 2.2
Total Nitrogen (g kg^{-1})	1.21 ± 0.0	0.79 ± 0.1	0.86 ± 0.1
Available P (mg kg^{-1})	3.51 ± 1.4	2.80 ± 1.4	0.82 ± 0.4
Potassium (cmol kg^{-1})	0.18 ± 0.04	0.14 ± 0.01	0.15 ± 0.01
Calcium (cmol kg^{-1})	6.47 ± 0.79	5.25 ± 0.49	1.63 ± 0.45
Magnesium (cmol kg^{-1})	0.87 ± 0.01	0.53 ± 0.01	0.40 ± 0.08
	Tree population characteristics		
Age of plantation (years)	18	15	23
Shade tree density (trees ha^{-1})	27	8	56
Cocoa tree density (trees ha^{-1})	985	1087	1162
Cocoa stem diameter (cm)	14.2 ± 2.79	18.1 ± 3.66	13.8 ± 2.81
Cocoa canopy diameter (cm)	221 ± 47.7	337 ± 62	154 ± 61.1
Tree height (cm)	488 ± 79.4	407 ± 70.9	440 ± 64.7
Cocoa tree above-ground biomass (kg ha^{-1})	23407 ± 10486	44801 ± 21076	25982 ± 11864
Cocoa canopy cover (%)	77.70 ± 5.51	76.80 ± 6.15	76.7 ± 3.03
	Initial litter quality		
Carbon (g kg^{-1})	610 ± 1.27	555 ± 64.14	637 ± 1.04
Nitrogen (g kg^{-1})	10.80 ± 0.00	9.25 ± 0.17	11.15 ± 0.87
Phosphorus (g kg^{-1})	0.65 ± 0.06	0.50 ± 0.00	0.50 ± 0.00
Potassium (g kg^{-1})	11.80 ± 0.12	5.80 ± 0.23	11.30 ± 0.00
C:N	56.44 ± 0.12	59.96 ± 5.81	57.34 ± 4.36
C:P	943 ± 81.83	1111 ± 128.29	1273 ± 2.08

3.3. Results

3.3.1. Carbon and nutrient flows through litterfall

On average 10.62 ± 3.57 Mg ha^{-1} dry matter of litterfall was recorded across sites. Approximately 93% of this litterfall was senescent cocoa leaves. Shade tree leaves and other fragments (mostly twigs) contributed very little to the litter under cocoa canopy (Table 3.2). For all fractions (cocoa leaves, shade tree leaves, and other fragments), there was no significant difference in the amounts of litterfall collected close and away from the cocoa trees ($P > 0.05$). Within field and even within-plot variations were much smaller than between-field variation, accounting for 3, 16 and 59% of total variation respectively. Differences between the two years were not significant ($P > 0.05$). Monthly variations were large as litterfall increased when rainfall reduced in the drier period of the year (Figure 3.2).

Table 3.2: Mean (± standard deviation, Mg ha^{-1}) annual mass of litterfall estimated close to- and away from- the cocoa tree stems across years and study sites. Figures in brackets are the relative contribution (%) to the total. No significant difference was observed between fractions collected close and away from the cocoa trees.

Position of the litter trap	Fractions of litterfall			
	Cocoa leaves	Shade tree leaves	Other fragments	Total
Close	10.04 ± 3.47 (92.4)	0.07 ± 0.27 (0.5)	0.75 ± 0.60 (7.2)	10.83 ± 3.57
Away	9.70 ± 3.48 (93.1)	0.07 ± 0.20 (0.6)	0.63 ± 0.53 (6.4)	10.40 ± 3.59

The annual transfer of cocoa leaves to the litter layer corresponded to a flow of 5.87 ± 1.93 Mg C ha^{-1} year^{-1}. The estimated N and K flows through cocoa leaf litterfall were considerable: 101 ± 32 kg N ha^{-1} year^{-1}

and 89 ± 27 kg K ha^{-1} $year^{-1}$. In contrast, the amounts of P transferred through cocoa leaf litterfall was small, with an average of 5 ± 2 kg P ha^{-1} $year^{-1}$ (Figure 3.3).

3.3.2. Cocoa leaf litter disappearance

Macrofauna substantially enhanced cocoa leaf disappearance from the litter layer, as k_F was 1.35 times larger than k_B ($P < 0.05$). The additional cocoa leaf litter mass loss that can be attributed to the presence of macrofauna was about 8% at 388 DAI (Figure 3.4).

3.3.3. Stoichiometry of the decomposing cocoa leaf litter

Macrofauna also affected the quality of the decaying cocoa leaf litter. Carbon concentrations of the remaining cocoa leaf litter slightly decreased from 60% at the beginning of the incubation (0 DAI) to about 55% at 248 DAI, with no significant differences between litterbags and the open frames ($P > 0.05$). At 314 DAI and at 388 DAI, C concentrations were lower in the frames than in the litterbags ($P < 0.01$, Figure 3.5). These results suggested that microbial respiration occurred throughout the duration of the incubation, but was only strengthened by macrofauna activity towards the second half of the experiment.

Access of macrofauna did not affect the observed gradual changes in N, P, and K concentrations of the cocoa leaf litter during incubation ($P > 0.05$). As a result of decline in C concentrations and increase in N and P concentrations, the C:N and C:P ratios decreased over time ($P < 0.001$). The N:P ratios also declined ($P < 0.001$) because C:P ratios declined more drastically than C:N ratios (Table 3.3). However, only C:N ratios were reduced in the frames, as compared to the litterbags ($P < 0.01$). At 388 DAI, the average C:N ratios were estimated at 34.4 with and 38.1 without access of macrofauna respectively.

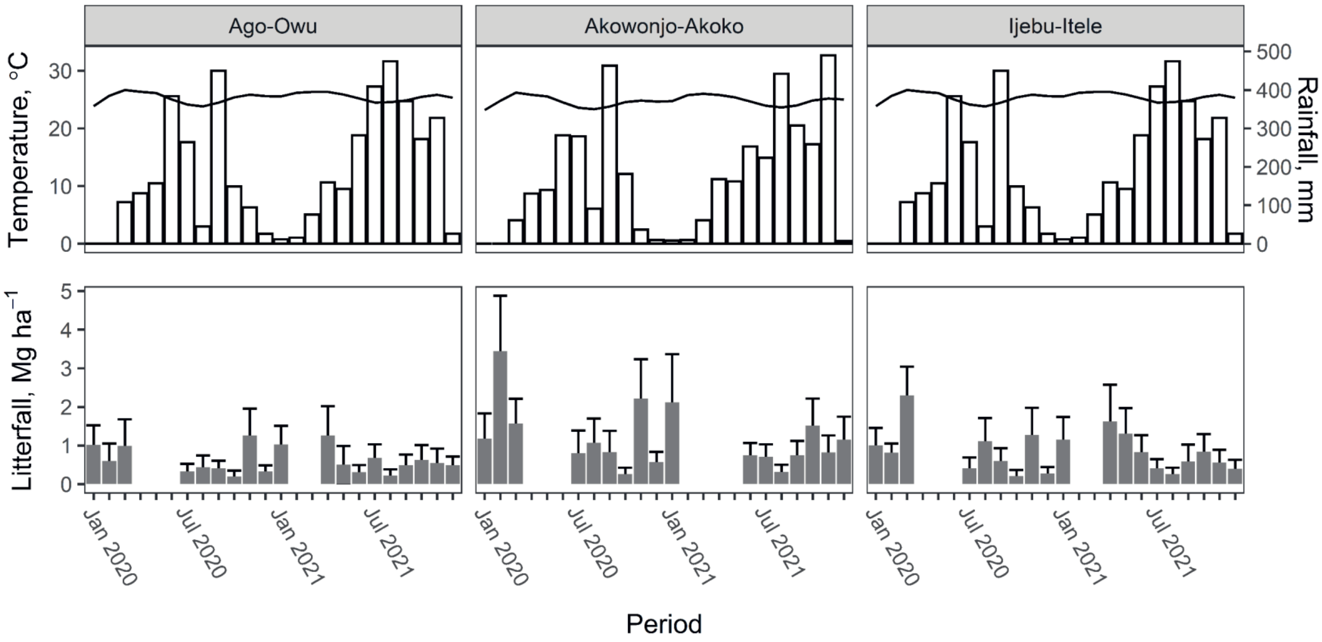

Figure 3.2: (Upper panels) Monthly rainfall (bars) and average temperatures (lines), and (lower panels) amounts of total litterfall (mean ± standard deviation) in three smallholder cocoa farms in South-Western Nigeria. Litterfall collected during March-May 2020 and February-March 2021 are not represented.

Table 3.3: Change in stoichiometry of decomposing cocoa leaf litter with (+) or without (-) access of macrofauna. Non-significant differences (P > 0.05) are denoted ns, and time is expressed in days after incubation (DAI).

Ratios	Macrofauna	Time (DAI)				P-value for ANOVA F-test		
		180	248	314	388	Time	Macrofauna	Interaction
C:N	+	44.8	38.9	34.2	34.4	P < 0.001	P < 0.01	ns
	-	47.9	41.5	38.8	38.1			
C:P	+	967	568	335	290	P < 0.001	ns	ns
	-	975	623	397	311			
N:P	+	21.5	14.5	9.9	8.52	P < 0.001	ns	ns
	-	20.4	15.2	10.3	8.25			

3.3.4. Nutrient loss from decomposing cocoa leaf litter

Carbon and nutrients were not lost from cocoa leaf litter at similar rates, with large differences in relative amounts at 180, 248, 314 and 388 DAI. Between the start and the end of the incubation period, relative amounts of C, N, and K were reduced by 56%, 33%, and 90% respectively (Figure 3.6). Amounts of P increased by a factor 2 in Akowonjo-Akoko, and remained nearly constant in the two other sites. This increase in Akowonjo-Akoko was unexpected. When data from the three sites were combined, an overall increase in P amounts was found ($P < 0.001$). The increase in P contents in the remaining cocoa leaf litter was less pronounced when macrofauna had access, especially at 314 DAI ($P < 0.05$) and at 388 DAI ($P < 0.001$).

More than 64% of K was lost from the cocoa leaf litter at 180 DAI, irrespective of the access of macrofauna ($P > 0.05$). Nitrogen loss was gradual, and significantly larger losses were observed when macrofauna had access. At 180 DAI, 5% N was lost with no effect of macrofauna ($P > 0.05$). At 248 and 388 DAI, 10 and 19% of N were respectively lost without access, against 27 and 47% when macrofauna had access ($P < 0.05$).

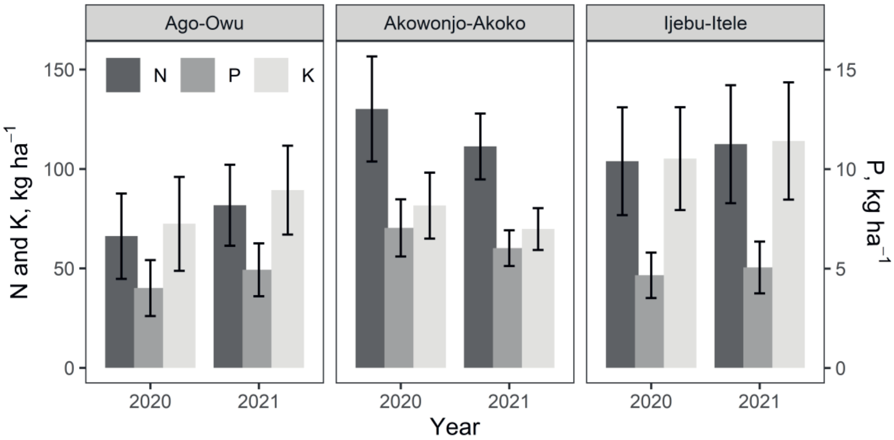

Figure 3.3: Amounts (mean ± standard deviation) of N, P, and K estimated in annual cocoa leaf litterfall in three smallholder cocoa farms in South-Western Nigeria

3.4. Discussion

This study highlighted three main results. (1) There was a large amount (10 Mg ha^{-1}) of dry mass annually recycled through litterfall, and large variations were observed between fields, but also between trees in the same field. (2) Considerable amounts of carbon and nutrients (101 kg N) were present in litterfall in these cocoa fields; however only a small fraction of N and P may become available for uptake by trees within a year. (3) Macrofauna access in frames resulted in 8% additional mass loss of leaf litter per year when compared to incubation in standard litterbags only, and increased N and P loss by 28 and 69%, respectively. Phosphorus was strongly immobilized within the litter layer. Potassium (K) was rapidly lost in both frames and litterbags, whereas N was first immobilized within the litter, and subsequently released and lost during the second half of the year. Greater losses of N and P were observed in frames than in litterbags towards the end of the experiment.

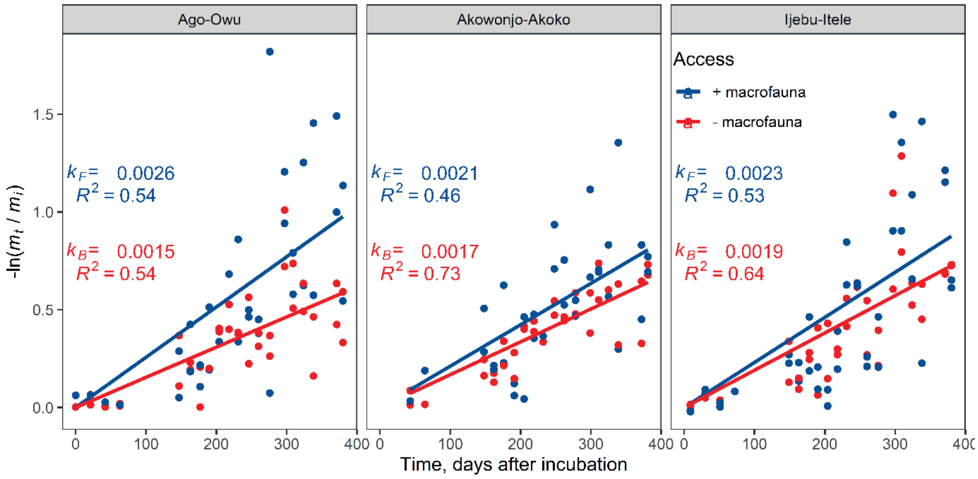

Figure 3.4: Cocoa leaf disappearance rate from the litter layer in three smallholder cocoa farms in South-Western Nigeria. The legend refers to the sampling methods, with frames and litterbags corresponding to + macrofauna and – macrofauna respectively.

Recorded amounts of annual litterfall were close to estimates (5-10 Mg ha^{-1} year^{-1}) for various cocoa production systems in Côte d'Ivoire (Yao et al. 2021), Cameroon (Saj et al. 2021), and Ghana (Dawoe et al. 2010), but larger than estimates for Brazil (Fontes et al. 2014), Mexico (Perez-Flores et al. 2018), and Indonesia (Sari et al. 2022). These differences between studies are likely due to climate, age of cocoa trees and production system, but also management (Andivia et al. 2012). Results from this study suggest that 34-186 kg N ha^{-1} year^{-1}, 37-175 kg K ha^{-1} year^{-1}, and 2-10 kg P ha^{-1} year^{-1} were likely transferred from cocoa trees to soil through litterfall. For N and K, these estimates align with the ranges (84-175 kg N ha^{-1} year^{-1} and 16-124 kg K ha^{-1} year^{-1}) reviewed by van Vliet and Giller (2017). Observed P contents in litterfall and hence flows to soil were smaller than observed in other studies (5.8-17 kg P ha^{-1} year^{-1}), which indicated that the cocoa trees in this study had less P in their senescent leaves. The initial P concentrations in the senescent cocoa leaves (0.55 mg g^{-1}) were significantly smaller than the reported values of 1.2 ± 0.5 mg g^{-1} (Hartemink 2005), perhaps reflecting the very poor P status of the soils (Table 3.1).

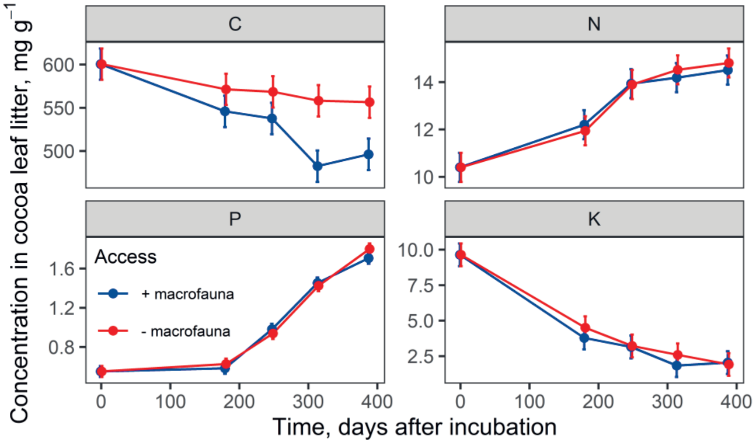

Figure 3.5: Estimates (± standard error) of C, N, P, K concentrations in decomposing cocoa leaf litter enclosed in litterbags (- macrofauna) and frames (+ macrofauna) in three smallholder cocoa farms in South-Western Nigeria. The legend refers to the sampling methods, with frames and litterbags corresponding to + macrofauna and – macrofauna respectively.

Annual flows through cocoa litterfall represented about 34%, 18%, and 26% of nutrient stocks in the cocoa trees, respectively for N, P, and K (Hartemink 2005). The relatively large amounts of N and K that flow through litterfall contrast with fairly limited quantities exported through harvest offtakes. For a yield of 1000 kg dry beans ha^{-1} (approximately three times the average yield in West Africa), nutrient removals in cocoa beans represent approximately 15% of N and K, and 35% of P amounts in litterfall (Hartemink 2005).

Nutrient cycling through litter in cocoa has potential implications on nutrient use efficiency (NUE) and nutrient management strategies as shown by Vonk et al. (2022) in cereals. After tree establishment, these internal flows may be sufficient to cover a large part of the nutrient demand, and the influence of fertilizers is relatively small, yet important to compensate offtakes. In addition, a major knowledge gap in mineral nutrition of cocoa is the effect of fertilizers on the internal nutrient flows including litterfall, pruning, throughfall and root turn-over. In order to quantify the long-term nutrient recovery in cocoa, offtake measurements are needed in combination with evaluations of internal cycles in long-term fertilizer trials (Sylvester-Bradley et al. 2022).

Accurate estimation of nutrient flows through litterfall requires proper measurement of litterfall and of nutrient concentrations in senescent leaves. In this study, the annual nutrient flows through litterfall were estimated from the nutrient concentrations obtained from litterfall collected in December only. This could lead to under- or overestimation of the nutrient flows, as Sreekala et al. (2001) found significant seasonal variations in N, P, and K concentrations and in amounts of monthly cocoa litterfall. Therefore, an accurate estimation of nutrient flows through litterfall should account for temporal variations in both quantity (amounts) and quality (nutrient concentrations) of litterfall.

In this study, litterfall near the stem was not different from litterfall at the edge of the canopy. This suggests that the position of the litter trap does not affect measurements, for fields with cocoa tree densities comparable to this study (approximately 1000 trees ha^{-1}). West African cocoa farmers usually adopt tree densities in the range of 1000-2500 trees ha^{-1} (Sonwa et al. 2019). In contrast, lower cocoa tree densities (about 548 ± 192 trees ha^{-1}) are preferred in Central America (Somarriba et al. 2013). In fields characterized by lower densities and/or large gaps between cocoa trees (e.g. due to severe mortality and insufficient replanting), significantly smaller amounts of litterfall may be found away than close to the stems (Barnes et al. 2011). Accurate estimation of litterfall in these conditions may require to account for area loss (large gaps without cocoa trees) and incomplete canopy closure.

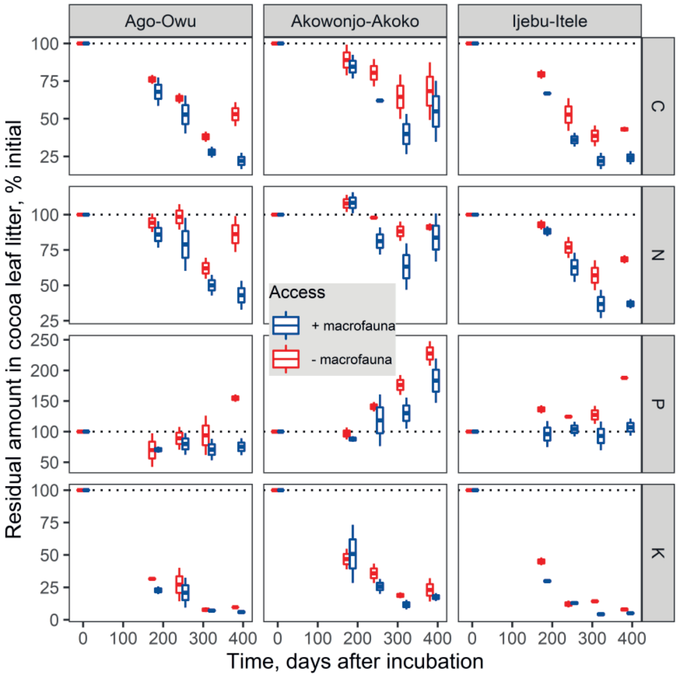

Figure 3.6: Carbon and nutrient loss from decomposing cocoa leaf litter in three smallholder cocoa farms in South-Western Nigeria. The legend refers to the sampling methods, with frames and litterbags corresponding to + macrofauna and – macrofauna respectively.

The amount of litterfall in this study varied strongly, with large differences between fields and between trees within a single plot. Heterogeneity in litterfall causes variability in macronutrient availability in forest soils (Xia et al. 2015). More studies are needed to identify what tree characteristics are best correlated with the annual litterfall; this will allow rapid prediction of litterfall (Geng et al. 2022). Ultimately, increasing the number of litter traps per plot and adhering to rigorous sampling protocols can improve representativity and accuracy of litterfall measurements. The median number of litter traps used in previous studies is three per plot (Yao et al. 2021; Saj et al. 2021; Dawoe et al. 2010; Sari et al. 2022) while in this study, we used five litter traps close to- and five away from- the base of the cocoa trees. For example, increasing this number from three to ten can halve the standard error of the estimated litterfall (data not shown).

Shade tree density and diversity were not accounted for in this study, which was justified by the observed low density of shade trees. In addition, their contribution to soil organic matter (SOM) and cocoa nutrition is presumably marginal and limited to the area covered by their canopy (Barnes et al. 2011). Only the cocoa trees in the vicinity of shade trees will be affected by resource competition (Schmidt et al. 2022). In this study, the litter trap in which the contribution of shade tree leaves was largest, received an amount equivalent to 0.95 Mg DM ha^{-1} year^{-1}.

Litter decomposition rates can be measured in various ways, including the mass balance method (combined measurements of standing litter stock and inputs through litterfall), the mass loss method involving incubation in litterbags, litter-baskets or in tethered litter, or through respiration measurements (Berg and McClaugherty 2014; Schroth and Sinclair 2003; Nadelhoffer and Blair 1999). Each measurement method represents decomposition processes differently (microbial catabolism, physical fragmentation and leaching). Hence, the selection of the appropriate method depends on the objective. In cocoa, the two most used methods are the mass balance and the mass loss methods (Kaba et al. 2021; Mohammed et al. 2019; Yao et al. 2021; Rojas-Molina et al. 2021). It is challenging to compare the estimated decomposition rates because of variations in substrates (cocoa leaves, twigs, shade tree leaves, and various combinations), protocols, analytical procedures, and calculated indices. Nevertheless, the mean residence time (MRT), defined as the “time to replace the equilibrium amount of C by the (annual) supply” (de Willigen et al. 2008), is a common measure of the average time of any particle (e.g. a freshly fallen leaf) in a particular state (the litter layer). Mean residence time (MRT) of C and major macronutrients have been estimated in the cocoa litter layer. For instance, Fontes et al. (2014) found that N, P, and K had similar MRTs (about 1.5, 1.2, and 1.4 years respectively). Asigbaase et al. (2021c) also reported low MRT values and a fast release of N, P, and K from the litter layer (respectively 60, 55, and 70% losses within 6 months). In this study, a much larger MRT was found (> 1 year for N and P) than previously reported. The large differences between these studies are probably related to the diversity of systems and methods used, including the timing of the experiment relative to rainfall patterns (Cusack et al. 2009; Yahdjian and Sala 2008) and environment conditions affecting litter decomposition.

An unexpected result was the increasing P concentrations and P amounts in litter that was observed in Akowonjo-Akoko. This is counter-intuitive because P amounts remain constant over time when completely immobilized in microbial mass, or decline as a result of loss from the litter layer. An increase in P amounts was also observed for leaf litter of cocoa and two shade tree species in a previous study (Bai et al. 2022). The mechanisms driving such an increase in P amounts in litter are still unknown and deserve to be further examined.

3.5. Conclusion

A better understanding of nutrient cycling in tropical tree cropping systems is needed. The amounts and rates at which nutrients are transferred from vegetation to soil are poorly quantified in cocoa but are important for nutrient management strategies. This study found that the position of litter traps under cocoa trees did not affect the estimated amounts of annual litterfall; however, within-field heterogeneity in litterfall can be substantial and expose estimations based on few litter traps to large inaccuracy. The large amount of litterfall (10 Mg ha^{-1} year^{-1}) represented a recycling within the cocoa fields of 101 kg N. The estimated values for the relative litter decomposition rate (k) differed between frames and litterbags ($P < 0.05$). Macrofauna access significantly increased the litter and N and P loss rates from the litter layer to the soil, but not for K. Macrofauna was also associated with a considerable reduction of carbon concentration in the remaining litter, thereby narrowing its C:N ratio. Therefore, litterbag experiments in cocoa probably underestimate rates of N and P loss from the litter layer.

In mature cocoa, relatively large amounts of nutrients are recycled through litterfall and other pathways, when compared to offtakes in smallholder farms. These internal nutrient flows can be large and may overshadow the short-term effects of modest fertilizer applications. Therefore, cocoa yield responses to nutrient supply must be evaluated in the long-term to account for the expected increase in vegetative growth and subsequent changes in nutrient flows. Likewise, crop nutrient management strategies should be adjusted accordingly.

4

Chapter 4

How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching[1]

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[1] A slightly modified version was published as: Hougni DGJM, Schut AGT, Woittiez LS, Vanlauwe B, Giller KE (2021) How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching. Plant and Soil 463 (1-2):155-170. doi:10.1007/s11104-021-04885-1

Abstract

Recycling of cocoa pod husks has potential to contribute to mineral nutrition of cocoa. Yet little is known of the nutrient content and nutrient release patterns from the husks. The potassium (K) rich husks are usually left in heaps in cocoa plantations in Africa. We aimed to understand and quantify release patterns of K and other nutrients from husks under varying rainfall regimes and assessed the effects of partial decomposition and inundation on nutrient leaching rates.

We incubated chunks of cocoa pod husks to assess decomposition rates and we measured nutrient leaching rates from two sets of husk chunks: one set was placed in tubes that were submitted to simulated scheduled rainfall events while the second set was continuously inundated in beakers.

Decomposition of husks followed a second-order exponential curve (k: 0.09 day^{-1} ; ageing constant: 0.43). Nutrient losses recorded within 25 days were larger and more variable for K (33%) than for other macronutrients released in this order: Mg > Ca ≈ P > N (less than 15%). Potassium leaching was mainly driven by rainfall frequency ($P < 0.05$) and reinforced by intense rainfall, especially at lower frequency. Under water-saturated conditions, 11% of K was leached out within 48 h from fresh husks compared with 92% from partially decayed husks.

Some initial decomposition of cocoa pod husks is required to expose K to intense leaching. As decomposition progresses, abundant K losses are to be expected under frequent and/or intense rainfall events.

Keywords: Nutrient cycling . Potassium. Cocoa pod husks . Leaching tubes. Farmer practices

4.1. Introduction

Cocoa (*Theobroma cacao* L.) is a major source of income for about 5 million small-scale farmers (Poelmans and Swinnen 2016). Approximately 74% of the global production originates from four countries in West and Central Africa: Côte d'Ivoire, Ghana, Cameroon and Nigeria (ICCO 2020), where the cocoa plantations are among the least productive in the world (Oomes et al. 2016). A recent survey in the two countries that produce the most cocoa - Côte d'Ivoire and Ghana - set the average cocoa bean yields at 352 and 423 kg ha^{-1} respectively (Bymolt et al. 2018b). This is less than one-tenth of the potential yield of cocoa in West Africa (Zuidema et al. 2005). The most often reported causes of this poor productivity are high incidence of pests and diseases, sub-optimal farming practices such as pruning and shade management, ageing of plantations, and the lack of adequate plant nutrient supply (Wessel and Quist-Wessel 2015). The vast majority of cocoa plantations in West Africa is planted on cleared forest land whose nutrient capital accumulated over a long period (Ruf et al. 2015). The fertility of the forest soil is progressively depleted by continuous nutrient offtakes in the cocoa beans with inadequate recycling or inputs of nutrients.

At cocoa harvest the ripe pods are plucked and taken to a work station located on the plantation or nearby where the pods are split to extract the beans. The husks of the cocoa pods are most often simply left to rot in heaps at the work station. The cocoa pod husks contain substantial amounts of nutrients, especially potassium (van Vliet and Giller 2017). With an amount of nutrients estimated at 10.6–31.4 kg N ha^{-1} and 27.2–77.2 kg K ha^{-1} for 1000 kg of cocoa beans harvested (Hartemink 2005), poor management of the husks can cause fairly large losses from the plantations. The fresh cocoa husks weigh 10 times more than the dry beans they contain (Khanahmadi et al. 2016; Mansur et al. 2014). Based on this ratio and with an estimated 80% moisture content of the husks (Campos-Vega et al. 2018), the West African production of 3.5 million tons of dry beans (ICCO 2020) corresponds to 35 million tons fresh matter (FM) and seven million tons dry matter (DM) of cocoa husk generated in 2019, most of which is not actively managed. Active management of the cocoa pod husks thus provides a great opportunity to improve nutrient cycling in cocoa plantations.

Recommended Good Agricultural Practices (GAP) for cocoa plantations include active husk management (e.g. composting, mulching). When the pods are infected with black pod disease due to Phytophthora spp., they should be incorporated in soil or burnt to avoid inoculant dissemination through aerosols and insects. For healthy pods, it is recommended that farmers should use the husks to mulch the plantation (Asare and David 2011). Yet we lack a thorough understanding of how rapidly nutrients are lost from the husks or how they should best be managed as mulch. The initial high moisture content of the husks and humid climate in which cocoa is grown are conducive to rapid decomposition, and leaching losses from the soil can be further exacerbated by abundant rain.

Knowledge of the nutrient value and nutrient release patterns from cocoa pod husks is lacking, yet essential to improve plantation management. Although previous studies have revealed that rainfall is the main driver of nutrient leaching from various crop residues (Calonego et al. 2005; Rosolem et al. 2005; Salètes et al. 2004), little is known about cocoa pod husks which have a thick and highly differentiated pericarp (Lu et al. 2018). Indeed, most experimental designs did not differentiate the effect of the amount of rainfall from that of its frequency. Besides, when cocoa is grown in lowlands, heaps of cocoa pod husks may be exposed to temporary inundation. The speed and magnitude of nutrient leaching under such conditions remain poorly understood. Our research objective was to describe the kinetics of nutrient leaching from the husks and evaluate the effects of rainfall amounts and frequency, biomass decay, and inundation on nutrient leaching patterns. We hypothesized that leaching rates of K depend on water saturation, rainfall frequency and amounts, but not on biomass decomposition. To test this hypothesis, three laboratory experiments were conducted. The first experiment quantified the decomposition rate of cocoa pod husks at ambient temperature, high relative humidity, and in absence of biotic manipulation; the second experiment assessed the effect of the size of husk chunks and the amount and frequency of rainfall on nutrient loss rates from the chunks inserted in leaching tubes; and the third experiment tested the rate of nutrient leaching from husks in conditions of permanent water saturation that simulated inundation.

4.2. Materials and methods

Thirty freshly-harvested cocoa pods were collected from a smallholder cocoa farm in Cote d'Ivoire. After splitting the pods and removing the beans and pulp, the husks were packed and shipped to the Netherlands where they were stored at 4 °C. All the husks were delivered as half-pod, broken longitudinally. Before using any husk, we discarded 2 cm from both proximal (close to the peduncle) and distal ends, as well as 1 cm from the longitudinal edge to reduce any potential gradient in nutrient partitioning as observed in pears (Saquet et al. 2019) and to avoid bruised areas. We carried out a preliminary analysis of the husk nutrient content and the values were well within indicative ranges (Table 4.1).

Table 4.1: Composition of cocoa pod husks

Component	Measured values (average ± standard deviation, %)	Ranges reported in literature (%)	References
C		40.9–50.23	1, 3, 8
N	1.21±0.38	0.17–2.23	1, 3, 8
P	0.14±0.04	0.15–0.32	2, 3, 4, 8
K	2.89±0.84	2.52–3.8	2, 3, 4, 8
Mg	0.26±0.06	0.11–0.28	2, 3, 4, 8
Ca	0.26±0.10	0.18–0.46	2, 3, 4, 8
S		0.14–0.97	1, 3, 8
Cellulose		12.9–35	2, 4, 5, 6, 7
Hemicellulose		8.7–12.8	2, 4, 7
Lignin		14–38.8	2, 4, 6, 7

(1) Adjin-Tetteh et al. (2018) ; (2) Campos-Vega et al. (2018); (3) Fidelis and Rajashekhar Rao (2017); (4) Lu et al. (2018); (5) Mansur et al. (2014); (6) Thomsen et al. (2014); (7) Titiloye et al. (2013); (8) Tsai and Huang (2018)

4.2.1. Experimental setup

We conducted three laboratory experiments. To analyse the relation between decomposition and leaching kinetics, an incubation experiment (Experiment 1) was established to measure the decomposition rate of husks. We ran two separate leaching experiments which differed in the degree of water saturation and duration of saturated conditions (Experiments 2 and 3).

4.2.1.1. Experiment 1: decomposition of cocoa pod husks

In the first experiment the decomposition rate was analysed. Six replicate husks were sliced into 10 chunks of 25 g, giving a total set of 60 chunks that were used to quantify biomass loss over 63 days. At the onset of the experiment, the weight of each chunk was measured while the initial moisture contents of the husks were assessed from additional pieces. All the 60 chunks were incubated in the dark at 20 °C and a relative humidity (RH) of 100%, in aerobic conditions. To realize these conditions, the chunks were placed in individual aluminium crucibles, floating in a tray filled with water, the whole apparatus being enclosed in a plastic foil, with an ample headspace. At 0, 2, 4, 6, 8, 12, 16, 28, 49 and 63 days, one chunk per replicate was randomly selected and both fresh and dry weight (after 48 h in a 105 °C oven) were recorded.

4.2.1.2. Experiment 2: nutrient leaching from leaching tubes

The treatments applied in this experiment were the size of the chunks, the frequency of the simulated rainfall, and the rainfall amount per rain event. We selected 16 husks of 400–600 g each, which were sliced into chunks of 2 g, 5 g or 25 g (hereafter referred to as small, medium, and large, respectively). Fifty grams fresh matter (FM) of chunks of the same size from each husk were used to fill individual PVC cylinders of 10 cm diameter to a height of 20 cm. Chunks from a given husk served to fill entirely one or more tubes. Two leaching treatments with demineralized water were used to simulate either a heavy (50 mm per event) or a light rain shower (12.5 mm per event). The water was sprinkled over each tube at 2, 4, or 8 day intervals. A treatment was a unique combination of either level of the three above-mentioned factors (e.g. “2 d, 50 mm, small” represented a tube containing small chunks that received every other day the equivalent of 50 mm of water, see Appendix Table 4.3). A blank treatment (leaching tube with no cocoa pod husk) was also included to detect any background nutrient contamination. The experiment ran for 31 days and was arranged in a 3 × 3 × 2 completely randomized design with three replicates. Room temperature was maintained at 20 °C throughout the experiment, while a paper-cup placed on the top of the leaching tube raised the RH inside the tubes to about 100%.

The leaching tubes (Figure 4.1) were blocked at their base with a flat rubber-stopper perforated in the centre to create a small outlet. A filter-paper (20 µm mesh) was inserted in the tube, and mounted on the top of the rubber-stopper. The top of the tube was loosely covered with a perforated paper-cup used as dripper that delivered 1–1.6 mL/min. All leachates were collected until 48 h after water had been sprinkled; the volume was measured for each tube. A leachate sample was taken for each tube and analysed for K content. In addition, selected samples (Appendix Table 4.3) were analysed for other nutrients (N, P, Ca, Mg). At the end of the experiment (day 31), residual DM weight of chunks was determined.

4.2.1.3. Experiment 3: potassium leaching under water saturated conditions

In this experiment two batches of husks were subjected to permanent water-saturation: the first batch had only fresh husks while the second one consisted of husks that already decayed for three-weeks to reflect the initial phase of husk decomposition. Three husks served as replicates, and were sliced into chunks of 25 g. Individual chunks (one per husk) were maintained at 15 cm depth in a beaker containing 2 l of distilled water. Over the first 48 h, a sample of the solution (10 ml) was taken at 20 min, 40 min, 1, 1.5, 2, 3, 4, 6, 10, 20, 36, and 48 h and each sample was analysed for its K content. The same procedure was repeated 3 weeks later with the second batch, using chunks from the same pods that had been kept in the incubator at 20 °C at a relative humidity of 100%.

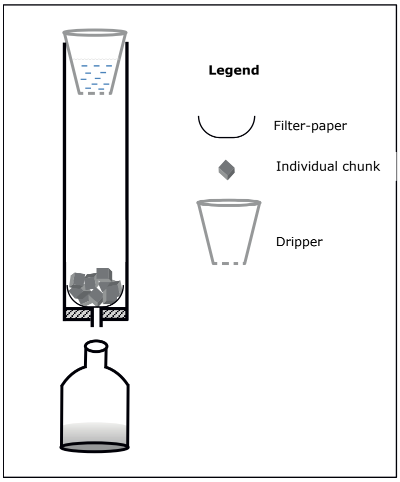

Figure 4.1: Sketch of an individual leaching tube in Experiment 2.

Nutrient contents of leachates and of the initial husks were estimated. Potassium (K), Ca, and Mg were determined using Atomic Absorption Spectroscopy (AAS), whereas N-NO_3^-, N-NH_4^+ and P-HPO_4^{2-} were measured spectrophotometrically with a segmented-flow analyser as described by Houba et al. (2008). Due to the relatively limited presence of ionic forms of N, P and Ca in the cell, we refer to these as “structurally-bound” elements in contrast with K and to a lesser extent Mg.

4.2.2. Data analysis

We expressed the residual amount of nutrients in husks and the residual weight (DM) as percentage of the values at the start of the experiments. The data were analysed for each experiment, with weight losses in experiments 2 and 3 estimated from curves developed using data from experiment 1 (explained below). Model performance was evaluated using the Akaike Information Criterion (AIC), the Schwarz Bayesian Criterion (BIC), the residual mean square error (RMSE), and the likelihood ratio test.

4.2.2.1. Experiment 1

To describe the decomposition of the chunks, we used a second-order exponential model (Eq. 4.1, Yang and Janssen 2000). It expressed the percentage residual dry weight (*C*) as a function of time *t* (days), and was characterized by a constant decomposition rate *k* (day^{-1}) and a rate-modifier termed the 'ageing coefficient' (*a*) which basically allows for decrease of parameter k over time.

$$C_i = e^{-kt^a} \qquad \text{for the } i\text{th husk; } i \in [1, 6] \qquad \text{(Eq. 4.1)}$$

A decomposition curve was fitted to observations with a non-linear mixed-effects model with pod as the random factor to account for non-linearity of most biological processes and the expected pod-to-pod variability in initial nutrient concentration. In doing so, we determined the model's parameters and estimated the loss in weight of husks over time.

4.2.2.2. Experiment 2

We first compared losses of the different nutrients, by plotting the average residual amounts observed in the husks. We found that K losses followed curvilinear patterns for most leaching tubes, whereas trends were unclear for the other nutrients. Since we did not observe losses larger than 20% for the structurally-bound elements (N, P, Ca, Mg), we only compared their respective losses on day 25. For these elements we ran an analysis of variance (ANOVA) based on a linear mixed-effect model, considering only four contrasted treatments: "2 d, 12 mm, large", "2 d, 50 mm, small", "8 d, 12 mm, large", and "8 d, 50 mm, small" (see Appendix Table 4.3 for detail of treatments).

Potassium (K) was lost in larger and more variable amounts than the other nutrients. All the treatments were thus taken into account in the following analyses. We used a non-linear mixed-effect regression to describe K loss kinetics over a period of 50 days and to analyse the variations among treatments. This model (see details below) described residual K as a logistic function of time, but it also involved a multiple linear regression of the estimated parameters on the predictors (rainfall amount, frequency, size of chunks). Because the effect of chunk size was minimal in the full model that explained variation of one of the parameters, it was excluded from the set of explanatory variables for that parameter.

We compared the residual amount of the structurally-bound nutrients on the 25th day of experiment 2, based on a linear model (Eq. 4.2). The explanatory variables were the type of nutrient (X_1) and the treatment (X_2).

$$Y_{k,i|j} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 \qquad \text{(Eq. 4.2)}$$

where $Y_{k,i|j}$ was the residual amount of the kth nutrient, measured on the *j*th tube on which the *i*th treatment was imposed, with $j \in [1, 12]$, $k \in [1, 4]$, and $i \in [1, 4]$;

X_1 was the macronutrient analysed;

X_2 was the treatment imposed on the chunks in the *j*th tube;

β_0 was the global intercept of the model;

β_1, β_2, and β_3 were the estimated coefficients associated to the individual effects of the macronutrient, the treatment and their interaction, respectively.

In order to describe patterns and evaluate variance of K loss through leaching, a non-linear regression (including a logistic function) was fitted to data from experiment 2. The logistic function (Eq. 4.3) was required to fit the general model which included two imbricated sub-models (Eq. 4.4 and Eq. 4.5) that were multiple linear regressions. The parameters *Xmid* (time to 50% K loss, days) and RL (leaching rate, day^{-1}) were regressed on rainfall, rain frequency, and size, while the parameter *Asym* (unitless) was kept constant throughout with a unique estimated value of 1.16 ± 0.02 ($P < 10^{-4}$).

$$Y_{abc|j} = \frac{Asym}{1+e^{RL_{ab|j}(X - Xmid_{abc|j})}} \qquad \text{(Eq. 4.3)}$$

with $Xmid_{abc|j} = \beta_0 + \beta_1 X_a + \beta_2 X_b + \beta_3 X_c + \beta_4 X_a X_b + \beta_5 X_b X_c + \beta_6 X_a X_c + \beta_7 X_a X_b X_c$ (Eq. 4.4)

and $RL_{ab|j} = \beta_8 + \beta_9 X_a + \beta_{10} X_b + \beta_{11} X_a X_b$ (Eq. 4.5) as sub-models, where Y was the percentage residual K measured on the jth tube at X days, $j \in [1, 54]$;

Asym was the coefficient describing the asymptotic value of initial K content (unitless);

Xmid was the coefficient describing the inflexion point or time at 50% K loss (days);

RL was the coefficient describing the leaching rate (day^{-1});

X_a was the frequency at which rainfall events were scheduled, with $a \in [1, 2]$;

X_b was the amount for individual rainfall events, with $b \in [1, 2]$;

X_c was the size of the chunks, with $c \in [1, 3]$;

β_0 and β_8 were the global intercepts of the sub-models;

β_1-β_7, and β_9-β_{11} were coefficients associated to the individual and combined effects of either predictor.

4.2.2.3. Experiment 3

In inundated husks, K loss through leaching was expected as result of the strong concentration gradient between the immersed husks and the surrounding water, in line with Fick's first law of solute diffusion. To test if different rates of cocoa pod husk decay resulted in similar trends of K loss, we compared K leaching kinetics from fresh chunks with a set of chunks that was allowed to decompose for a 3-week period in an incubator at 20 °C. Loss of K under water-saturated conditions was described using Eq. 4.1, where C now represented the residual K (%) in the chunk at time t (hours). Similar to decomposition, the second-order decay curve was fitted to the data, using a non-linear mixed effects model. The estimated coefficients were compared using Welch's modified t-test (Welch 1947).

All the models were fitted in R (R Core Team 2013) via restricted maximum likelihood (REML) using the 'nlme' package (Pinheiro et al. 2019) whereas t-tests were run with the 'BSDA' package (Arnholt and Evans 2017). The mixed-effects models included a random-intercept (husks for Experiments 1 and

3, and tubes for Experiment 2) with unconstrained variance-covariance matrices obtained via Log-Cholesky parametrization (Pinheiro and Bates 1996).

4.3. Results

4.3.1. Decomposition of cocoa pod husks

Cocoa pod husk decay was described satisfactorily by a second-order exponential function ($R^2 = 0.77$, Figure 4.2). The fitted second-order exponential model showed a sharp decrease with 24% and 32% DM weight loss after 14 and 30 days respectively, gradually followed by a phase of slower weight loss and reduced decomposition rates. Extrapolating this model to a year suggested that more than 33% of the initial DM weight of the husks would remain in absence of exogenous factors such as human manipulation, macrofauna activity or fluctuating environmental conditions. The second order model was more accurate (RMSE of 0.05%) than the first-order model (RMSE = 0.11%) which had a smaller coefficient of determination ($R^2 = 0.71$, Appendix Table 4.4).

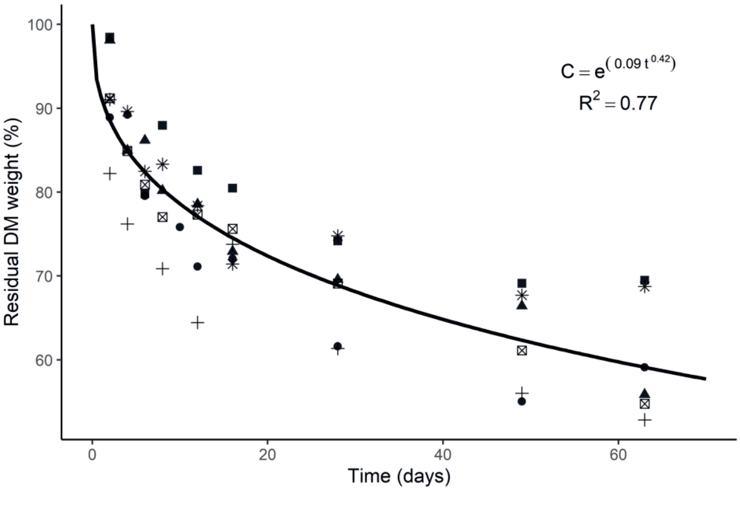

Figure 4.2: Fitted decomposition model to observations from chunks of cocoa pod husks left at 20˚C, 100% RH. Each replicate is represented by a different symbol.

4.3.2. Overview of nutrient leaching under scheduled rain simulations

Of all the nutrients tested, K losses were strongest and most variable across the treatments (e.g. 33 ± 21% on day 25). More structurally-bound nutrients N, P, Ca, Mg recorded average losses of less than 15% at the end of the experiment (day 31, Figure 4.3). Nutrient losses on day 25 significantly differed among the more structurally-bound nutrients ($P < 0.05$), with Mg being the most leachable among these (10 ± 9%). On the contrary, N was hardly released throughout the experiment, with less than 1% lost from any of the treatments, suggesting that the inorganic N content of the husk cells was either very small or that any N released was strongly immobilized. Treatments did not affect nutrient losses ($P > 0.05$, Appendix Table 4.5).

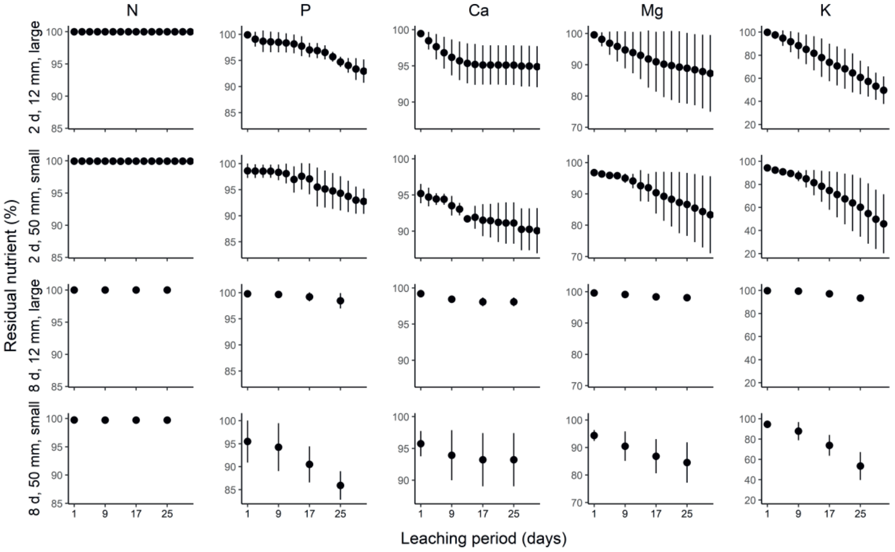

Figure 4.3: Average (± standard deviation) nutrient losses from cocoa pod husks (n=3) for selected treatments in a scheduled leaching experiment (Experiment 2). For each row, the minor y-axis was labelled after the treatment with, in this order: rain frequency (2-day versus 8-day intervals), rainfall amount (12.5 versus 50 mm per event), and size of the chunks (small versus large).

4.3.3. Effects of the size of chunks, amounts and frequency of rainfall on potassium leaching

4.3.3.1. Leaching curves

For most combinations of rainfall amount (12.5 and 50 mm) and frequency (2, 4 or 8 day intervals) the size of the chunks did not consistently influence K leaching patterns over the simulated period (0–50 days, Figure 4.4), with exception of 12.5 mm rainfall at an 8-day interval. For this latter treatment, leaching curves were very dissimilar across chunk sizes, with the smallest chunks losing 33% more K than the largest chunks on day 50 (Figure 4.4c).

The effect of the interaction between frequency of rainfall and rainfall amount on K leaching was significant ($P < 0.05$, Table 4.2). The rainfall frequency did not affect K loss patterns when 50 mm rainfall events were provided. Treatments with 50 mm and 2, 4 and 8-day rainfall frequency intervals did not differ more than 18% in the total amount of K lost on day 50 (Figure 4.4b and c). The estimated effect of rainfall frequency was larger at 12.5 mm rainfall. Treatments with 12.5 mm and 8-day intervals lost 12–45% K on day 50 while the treatments with 12.5 mm and 2 day intervals lost 80–82% K (Figure 4.4a and c).

The amount of rainfall per rainfall event intensified K losses, more so for less frequent rainfall events (Figure 4.4). The differences between the treatments with 12.5 mm and 50 mm per rainfall event at 2, 4 and 8-day intervals were 4–5%, 10–23% and 22–56% respectively.

We also compared rainfall regimes, 12.5 mm every 2 days with 50 mm every 8 days, with the same cumulative amount of rainfall (200 mm at day 31).The total K lost did not differ between rainfall regimes, with largest differences about 13% on day 47 (Figure 4.4). Based on the model, it was expected that these differences would become smaller if the experiment were run for a longer period of time, to less than 5% by day 83 (not shown).

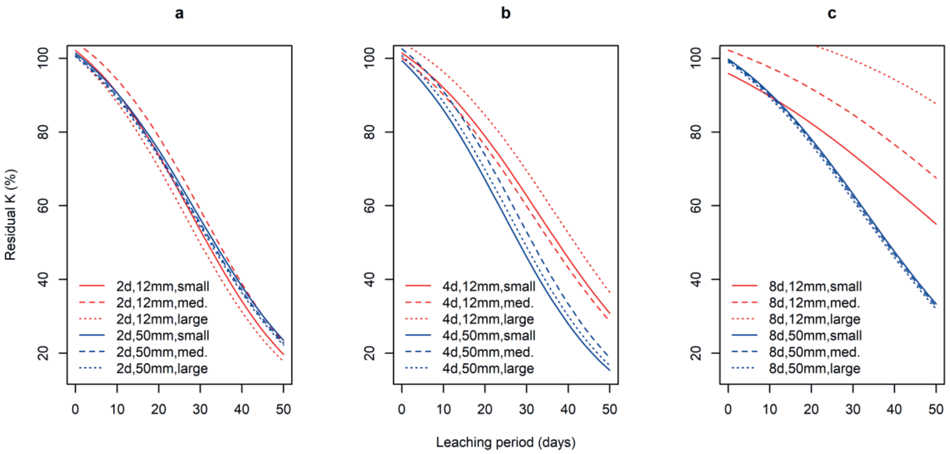

Figure 4.4: Simulated effects of the chunk size of cocoa pod husks (line type) and rainfall (line colour) on K leaching patterns at different scheduled rain frequencies (subplots) over a period of 50 days. Treatments are indicated in the legend in this order: rainfall frequency (day intervals), rainfall amount (mm), and size of the chunks (small, medium or large).

4.3.3.2. Model parameters

The rainfall frequency had the largest effect on the estimated values of time to 50% K loss (*Xmid*) and K leaching rate (*RL*, Figure 4.5). Potassium leaching from cocoa pod husks increased with rainfall frequency. Reducing rainfall frequency from 2 to 8-day intervals, resulted in increased *Xmid* value of 19 days ($P < 0.001$), decreasing leaching rates by 54% ($P < 0.001$). Overall, quadrupling the amount of water did not have a significant effect on the parameters *Xmid* and *RL* (Table 4.2). However, at 8-day rainfall intervals, *Xmid* decreased by 15 days ($P < 0.05$), and *RL* increased from 0.03 to 0.05 day^{-1} ($P < 0.05$) for the 50 mm when compared to the 12.5 mm treatments. The effect of the size of chunks was not significant, except for *Xmid* at a rainfall frequency of 8 days with 12.5 mm, with the largest chunks retaining more K than the smallest ($P < 0.05$, not shown).

Table 4.2: Significance (probability of Wald F-tests) of the effects of rainfall frequency, rainfall amount, and size of the chunks on K leaching patterns from cocoa pod husks in a scheduled leaching (experiment 2).

Main and Interaction terms of regression	Estimated parameters		
	Asymptotic leachability	Time to half K (*Xmid*)	Leaching rate (*RL*)
Intercept	< 0.001	< 0.001	< 0.001
Rain frequency (‘Frequency’)		< 0.001	< 0.001
Rainfall		ns	ns
Size		ns	
Frequency × Rainfall		< 0.05	< 0.05
Frequency × Size		< 0.01	
Rainfall × Size		ns	
Frequency × Rainfall × Size		< 0.01	

ns: non-significant. Empty cells indicate terms for which selected coefficients were not available as a consequence of constraints imposed on the model structure.

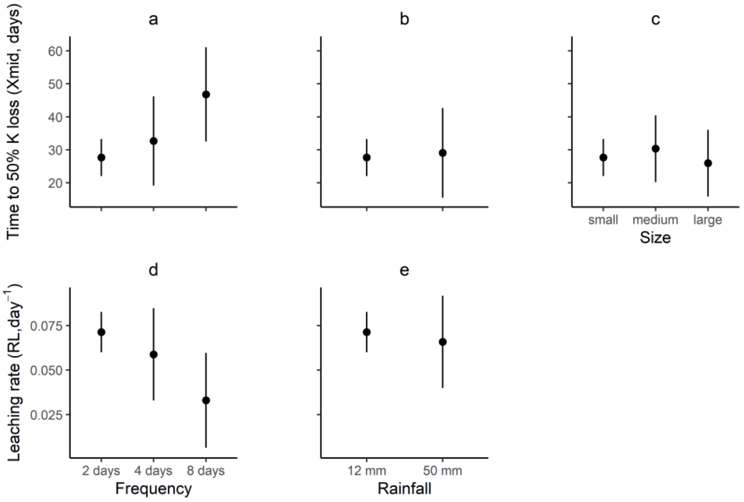

Figure 4.5: Estimated main effects (±95% confidence intervals) of rainfall frequency (a, d), rainfall amount (b, e), and size of chunks (c) on time to 50% K loss (a, b, c) and K loss rate (d, e) from cocoa pod husks in a scheduled leaching experiment (experiment2). All interaction effects are displayed in Appendix Table 4.6.

4.3.4. Effect of decomposition on K leaching from cocoa pod husks under water-saturated conditions

Fresh husks under water retained most of their K with less than 11% of K lost after 48 h (Figure 4.6), partially accounting for nutrient release due to bruising during chunk slicing. The observed K loss followed an exponential pattern, with a small leaching constant ($k = 0.03$ day^{-1}). A protective jellified layer of hydrated pectates was formed around the chunks immersed in water, temporarily preventing husks from further water absorption. In comparison, K leaching from husks was much faster, with 81% and 92% losses recorded within 24 and 48 h respectively when inundated after a period of 3 weeks of decay (Figure 4.6), corresponding to a weight loss of only 28% in aerobic conditions (Figure 4.2). The estimated values for both the k and a coefficients were significantly larger ($P < 0.001$, not shown) for these partly decayed husks when compared with fresh husks.

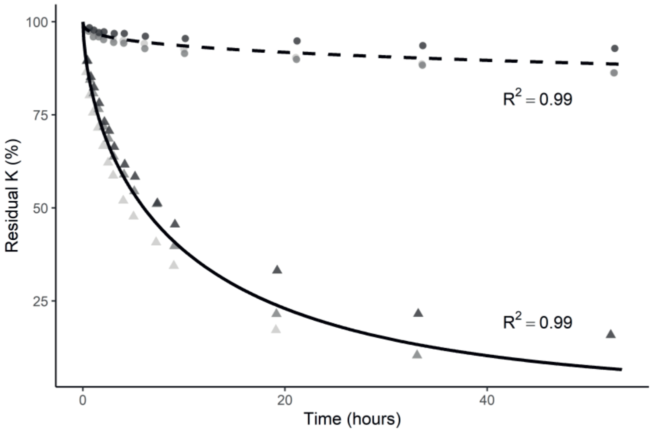

Figure 4.6: Changes in the residual K under saturated conditions for fresh and partially decomposed cocoa pod husks after a 3-week incubation at 20oC and 100% humidity. The changes in the percentage of residual K as a function of time were described with a second-order exponential model. Circles and triangles (replicates in grey-scale) represent fresh and partially decayed (3-week) husks, respectively. Fitted models are shown with dashed and solid lines for fresh and partially decayed husks, respectively. Coefficients are estimated in Appendix Table 4.7.

4.4. Discussion

To gain insights into the temporal availability of nutrients in cocoa pod husks, we analysed the losses of K, Mg, Ca, N and P in leaching experiments. The husks contain large amounts of K with concentrations of about 3%. Potassium is a yield-limiting nutrient in many cocoa plantations, especially in more demanding environments with limited shade conditions (Ahenkorah et al. 1987). We observed that K leached rapidly from the husks, with leaching rates varying as a function of rainfall amount and frequency (Figure 4.4). Under frequent and abundant rainfall events (2-day interval, 50 mm per event), we recorded less than 11% K losses after 10days, and up to 45% K losses after 31 days. Our fitted regression model predicted that 78% K will be lost after 50 days. By contrast, more structurally-bound nutrients in the husks (such as Ca, P and N) did not leach in large amounts during the same period (less than 15% after 31 days for all treatments, Figure 4.3). Under inundated conditions, K leaching from decomposed husks occurred rapidly when compared to fresh husks (92% versus 11% K respectively lost within 2 days, Figure 4.6). Therefore, inundation occurring during the first days after pod breaking would likely not deplete a husk pile of K. This is likely because the cocoa pod has a waxy, water repellent epicarp which needs to be broken down before K can leach rapidly. Although the artificial conditions imposed in our experiments limit extrapolation of the leaching rates to on-farm contexts, they show the relative importance of the factors tested when assessing kinetics of nutrient leaching. Our results highlight the need for a proper on-farm management of fresh husks to reduce K losses from cocoa farms, even more if there are risks of inundation.

To describe K leaching patterns under successive rainfall events, we used a logistic function (S-shape) since the exponential function (with initial drastic decrease) poorly fitted our data. We only observed an exponential K release from cocoa pod husks under water-saturated conditions, reflecting a rapid initial loss of K. Extremely rapid release of K has been reported for other crop residues (Talgre et al. 2014). We did not find literature reporting on K leaching from cocoa pod husks. Nutrient leaching from various organic materials such as cereal straw (Li et al. 2014; Lupwayi et al. 2006; Rosolem et al. 2005), legume residues (Lupwayi et al. 2006); oilseeds, roots and tubers, and farm manure (Kolahchi and Jalali 2012; Ranjbar and Jalali 2012), weeds, household compost, fruit and vegetable wastes (Ranjbar and Jalali 2012), wood chips and pruned materials (Ordóñez-Fernández et al. 2014) have been studied in the past. The associated loss kinetics varied strongly, depending on the crop residues and the experimental conditions. Potassium loss curves from cereal straw, legume residues and prunings under intermittent rainfall events were described by power or exponential functions (Lupwayi et al. 2006). Similar patterns were proposed for empty fruit bunches, the major residues from oil palm milling (Caliman et al. 2001; Lim and Zaharah 2000). However, these functions do not account for the limited initial K loss that was observed in the very first days of the second experiment we ran.

We hypothesized that waterlogging provoked fast K losses from fresh and decayed husks. Water saturation provoked substantial K release for partially decomposed husks, but not for fresh husks (Figure 4.6) suggesting that some decomposition is required to allow release of K. This is in contrast to Vanlauwe et al. (1995) and Lupwayi et al. (2006) who found that K leaching is independent of decomposition. The findings align with observations from Calonego et al. (2005) that K losses from leaves increase with senescence. Similarly, Li et al. (2014) recorded K losses of 80% in fully senesced rice straw in the first two hours and 90% after 3 days of inundation.

Potassium leaching is not restricted to pod husks in a cocoa plantation, but also occurs from canopies in forest environments (Moslehi et al. 2019). Rain droplets collected at the forest floor contain 10–40 times more K than rain droplets above the canopy (McDowell et al. 2020). Foliar K leaching (rain-wash minus direct rainfall) in 15–30 year old cocoa plantations was estimated at 23.1–39.7 kg ha^{-1} year^{-1}, two to three times more than in sole rainfall (13.6 kg ha^{-1} year^{-1}) (Dawoe et al. 2017). Although the quantity of K leached from canopies is larger than from cocoa pod husks, it remains in the system in contrast to poorly managed husks.

As hypothesized, the amount and frequency of rainfall altogether determined K loss patterns in our scheduled rainfall simulations (Appendix Table 4.2). The effect of rainfall frequency was more prominent than that of rainfall amount, and their interaction was significant. In general, rainfall has a large effect on K leaching from crop residues (Cavalli et al. 2018; Schreiber 1999). In a single rain event, K losses from millet straw gradually increased with rainfall amount and reached a plateau as from 40 mm (Rosolem et al. 2005). Our results show that rainfall amount interacted with rainfall frequency, with significant differences ($P < 0.05$) between large and small rainfall amounts at low but not high rainfall frequencies. At times of recurrent rainfall, delayed management of cocoa pod husks would result in rapid K release from the residues. Likewise, when rainfall amounts are high, regardless of the frequency, cocoa husks need to be actively managed to avoid large K losses.

We did not find significant differences in husk weight at the end of the scheduled leaching experiment ($P > 0.05$, not shown), suggesting that microbial decomposition was not affected by the amount or frequency of rainfall, contrasting with the findings of Joly et al. (2019). This similarity in decomposition rates was likely due to the constantly moist environment in the leaching tubes which Joly et al. (2019) did not observe. Since water content of the husks is high (80%, Lu et al. 2018), the conditions in heaps of cocoa pod husks are likely to be similar to our tubes with a high humidity in a moist environment, and we expect therefore that decomposition of heaped husks is not strongly affected by rainfall frequency and amounts.

Beside K, the husks also contain other nutrients which are relevant to cocoa nutrition. We found that more structurally-bound nutrients that are less abundant as free ions in the vacuole and cytosol were lost at much slower rates than K ($P < 0.05$). Macronutrients were lost in this relative order K >> Mg > Ca ≈ P > N, aligning with the findings of (Ranjbar and Jalali 2012). However, these authors found faster loss rates for Mg and Ca than we observed, which may be related to tissue composition and the state of the residues used (dryness, stage of decomposition). For cocoa pod husks, limited losses were observed for Mg, and even less for Ca. The relative immobility of Mg and Ca in the husks can be related to their abundance in cell wall pectins and sparingly soluble salts (Gerendás and Führs 2013). However, Mg appeared more mobile than Ca probably because it is also stored in ionic form in the vacuoles. Together, Mg and K also play an important role in osmotic regulation and the cation-anion charge balance (Marschner 2012), therefore their abundance in the vacuoles makes them more leachable than the other nutrients. In addition, K^+ has the lowest valence and thus moves more freely through disintegrating plant tissue.

To what extent does husk management contribute to K recycling and cocoa nutrition? For current regional mean cocoa bean yields of 400 kg ha^{-1} in west Africa, about 17–31 kg K ha^{-1} can be expected in cocoa pod husks (Hartemink 2005). These are modest amounts in relation to crop requirements (up to 300 kg K ha^{-1}, (von Uexküll and Cohen 1980) and husk recycling alone is insufficient to meet the K needs of cocoa, highlighting the importance of K fertilizer additions. Yet, over the life time of a plantation, poor husk management can remove large amounts of K. Indeed, when heaps of cocoa pod husks are piled repeatedly at the same location, the local soil K reserves will progressively be concentrated and lost, benefiting only a few neighbouring trees. Unfavourable drainage will worsen the K losses from the production system. Ideally, the husks should be redistributed over the whole plantation, although yield benefits are expected to be small while the labour required would be substantial. Instead, rotating the pod breaking station and sequential mulching of small field patches would reduce labour requirements while contributing to improved K recycling and reduce K fertilizer requirements in these resource-constrained smallholdings. In addition to the spatial aspects of cocoa pod husk management, asynchrony between nutrient release from residues and uptake by trees also needs consideration. Despite the lack of reports on the temporal dynamics of K demand in cocoa, uptake can be thought of as a continual process, characterized by steady uptake when soil moisture is satisfactory and the tree is growing actively, increased rates during pod enlargement, and declines under water stress. K supply from cocoa pod husks is primarily governed by the seasonality of production through the major and minor crops. The major crop coincides with the dry season in most production zones in West Africa, and therefore desiccation followed by rapid rewetting of the cocoa pod husks will likely provoke a fast release of K. The minor crop harvest coincides with the rainy season, and our analysis would be relevant to describe kinetics of nutrient release. As K is released from the cocoa pod husks, its availability for absorption by the root system will depend on several soil characteristics, including hydrology, sorption capacity, texture and mineralogy (Alfaro-Flores et al. 2015; Freitas et al. 2018; Najafi-Ghiri et al. 2017; Rosolem and Steiner 2017). Of these properties, the cation exchange capacity will play a strong role in buffering nutrient fluxes.

4.5. Conclusion

Cocoa pod husks are rich in potassium and their potential contribution to tree nutrition is significant. Since risks of K losses through leaching are high, optimizing nutrient cycling in cocoa requires improved management compared with current practices of heaping and abandonment. We found that early-stage decomposition of the husks, water-saturation, and rainfall regime (amount and frequency) significantly altered K leaching patterns and the resulting nutrient losses. Knowledge about the kinetics of nutrient leaching from decaying husks can guide timely management of the husks, provided that accurate meteorological predictions are accessible to farmers.

We have briefly explored innovative methods of handling and disposing the husks to improve nutrient cycling, but more insight is needed both in terms of the outcomes on nutrient budgets, technical requirements, and farm resource utilization. For instance, we suggest that on-farm estimation of nutrient leaching from the husks under diverse climatic conditions and management practices is needed to better inform field management. Further, there is a paucity of knowledge about the fate of K as it leaches from the husks into the topsoil. Effective leaching study designs are required to capture the effect of the root system, soil characteristics, and pod management on K spatial distribution in soil and its temporal availability to cocoa trees.

Acknowledgements

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Appendix

Table 4.3: Cumulative amount of water (mm) sprinkled over tubes for each treatment in Experiment 2.

Treatments	Days															
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31
2d, 12mm, small	**12.5***	**25**	**37.5**	**50**	**62.5***	**75**	**87.5**	**100**	**112.5***	**125**	**137.5**	**150**	**162.5***	**175**	**187.5**	**200**
4d, 12mm, small	**12.5***	12.5	**25**	25	**37.5***	37.5	**50**	50	**62.5***	62.5	**75**	75	**87.5***	87.5	**100**	100
8d, 12mm, small	**12.5***	12.5	12.5	12.5	**25***	25	25	25	**37.5***	37.5	37.5	37.5	**50***	50	50	50
2d, 50mm, small	**50***	**100***	**150***	**200***	**250***	**300***	**350***	**400***	**450***	**500***	**550***	**600***	**650***	**700***	**750***	**800***
4d, 50mm, small	**50***	50	**100**	100	**150***	150	**200**	200	**250***	250	**300**	300	**350***	350	**400**	400
8d, 50mm, small	**50***	50	50	50	**100***	100	100	100	**150***	150	150	150	**200***	200	200	200
2d, 12mm, medium	**12.5***	**25**	**37.5**	**50**	**62.5***	**75**	**87.5**	**100**	**112.5***	**125**	**137.5**	**150**	**162.5***	**175**	**187.5**	**200**
4d, 12mm, medium	**12.5***	12.5	**25**	25	**37.5***	37.5	**50**	50	**62.5***	62.5	**75**	75	**87.5***	87.5	**100**	100
8d, 12mm, medium	**12.5***	12.5	12.5	12.5	**25***	25	25	25	**37.5***	37.5	37.5	37.5	**50***	50	50	50
2d, 50mm, medium	**50***	**100**	**150**	**200**	**250***	**300**	**350**	**400**	**450***	**500**	**550**	**600**	**650***	**700**	**750**	**800**
4d, 50mm, medium	**50***	50	**100**	100	**150***	150	**200**	200	**250***	250	**300**	300	**350***	350	**400**	400
8d, 50mm, medium	**50***	50	50	50	**100***	100	100	100	**150***	150	150	150	**200***	200	200	200
2d, 12mm, large	**12.5***	**25***	**37.5***	**50***	**62.5***	**75***	**87.5***	**100***	**112.5***	**125***	**137.5***	**150***	**162.5***	**175***	**187.5***	**200***
4d, 12mm, large	**12.5***	12.5	**25**	25	**37.5***	37.5	**50**	50	**62.5***	62.5	**75**	75	**87.5***	87.5	**100**	100
8d, 12mm, large	**12.5***	12.5	12.5	12.5	**25***	25	25	25	**37.5***	37.5	37.5	37.5	**50***	50	50	50
2d, 50mm, large	**50***	**100**	**150**	**200**	**250***	**300**	**350**	**400**	**450***	**500**	**550**	**600**	**650***	**700**	**750**	**800**
4d, 50mm, large	**50***	50	**100**	100	**150***	150	**200**	200	**250***	250	**300**	300	**350***	350	**400**	400
8d, 50mm, large	**50***	50	50	50	**100***	100	100	100	**150***	150	150	150	**200***	200	200	200

Treatment code: For size, small, medium and large refer to chunks of 2, 5, and 25 g respectively. For rainfall amount, 12 mm and 50 mm refer to 12.5mm/leaching event and 50mm/leaching event, respectively. For rainfall frequency, 2d, 4d, and 8 8d refer to regular (every other day), intermittent (every 4 days), and irregular rainfall events (every 8 days), respectively. Cells with figures in bold correspond to effective days of leaching for a given Treatment. An asterisk (*) represents a day at which the leachate of a given treatment is analysed for other nutrients (N, P, Ca, Mg).

Table 4.4: Comparison of 1st and 2nd order exponential models used to describe cocoa pod husk decomposition with estimates (± 95% confidence intervals).

Predictor/Model evaluation criterion	1st order exponential model (Olson)	2nd order exponential model (Yang and Janssen)
Decomposition rate (k), day^{-1}	0.01 ± 0.00	0.09 ± 0.01
Ageing constant (a), unitless	NA	0.42 ±0.04
AIC	-69	-131
BIC	-60	-119
RMSE	0.11	0.05
R^2	0.71	0.77

NA: not applicable

Table 4.5: Effects of treatments (combination of rainfall frequency, rainfall amount, and size of chunks) and type of structurally-bound nutrients on the total losses (±95% confidence intervals) estimated on day 25 of the scheduled leaching experiment (experiment 2). Note that the probability indicates the P-value for differences between treatments based on the Wald F-test.

Treatments	Nutrient losses (% of initial value in the husks)				Probability across treatments
	N	P	Ca	Mg	
2d,12mm, large	0.02 ± 5.22	5.27 ± 5.22	4.91 ± 5.22	11.12 ± 5.22	0.99
2d,50mm, small	0.06 ± 5.22	5.72 ± 5.22	8.89 ± 5.22	13.36 ± 5.22	
8d,12mm, large	0.02 ± 5.22	1.56 ± 5.22	1.92 ± 5.22	1.92 ± 5.22	
8d,50mm, small	0.3 ± 5.22	14.09 ± 5.22	6.78 ± 5.22	15.47 ± 5.22	
Probability across nutrients	0.03				0.17

Table 4.6: Effect of rainfall amount, rainfall frequency, and size of chunks on K leaching model's parameters (see Eq.3 in main text). The intercept of the model were set for '2d, 12mm, small' treatment.

Parameter	Rainfall	Frequency	Size	Treatment label	Estimate (±95% confidence intervals)
Asym	All	All	All	All	1.16 ± 0.04
Xmid	12.5 mm	2 days	Small	2d, 12mm, small	27.68 ± 5.6
Xmid	12.5 mm	2 days	Medium	2d, 12mm, medium	30.35 ± 10.14
Xmid	12.5 mm	2 days	Large	2d, 12mm, large	25.95 ± 10.13
Xmid	50 mm	2 days	Small	2d, 50mm, small	29.11 ± 13.58
Xmid	50 mm	2 days	Medium	2d, 50mm, medium	28.46 ± 24.68
Xmid	50 mm	2 days	Large	2d, 50mm, large	28.04 ± 24.79
Xmid	12.5 mm	4 days	Small	4d, 12mm, small	32.67 ± 13.52
Xmid	12.5 mm	4 days	Medium	4d, 12mm, medium	31.01 ± 24.68
Xmid	12.5 mm	4 days	Large	4d, 12mm, large	36.71 ± 24.54
Xmid	50 mm	4 days	Small	4d, 50mm, small	24.25 ± 32.82
Xmid	50 mm	4 days	Medium	4d, 50mm, medium	27.51 ± 60.21
Xmid	50 mm	4 days	Large	4d, 50mm, large	25.57 ± 60.09
Xmid	12.5 mm	8 days	Small	8d, 12mm, small	46.77 ± 14.27
Xmid	12.5 mm	8 days	Medium	8d, 12mm, medium	59.86 ± 31.22
Xmid	12.5 mm	8 days	Large	8d, 12mm, large	83.87 ± 50.57
Xmid	50 mm	8 days	Small	8d, 50mm, small	33.18 ± 34.63
Xmid	50 mm	8 days	Medium	8d, 50mm, medium	32.7 ± 72.53
Xmid	50 mm	8 days	Large	8d, 50mm, large	32.13 ± 110.3
RL	12 mm	2 days	All	2d, 12mm	0.07 ± 0.01
RL	50 mm	2 days	All	2d, 50mm	0.07 ± 0.03
RL	12 mm	4 days	All	4d, 12mm	0.06 ± 0.03
RL	50 mm	4 days	All	4d, 50mm	0.07 ± 0.06
RL	12 mm	8 days	All	8d, 12mm	0.03 ± 0.03
RL	50 mm	8 days	All	8d, 50mm	0.05 ± 0.06

Table 4.7: Comparison of model coefficients and parameters (estimates ±95% confidence intervals) for fresh and partially decomposed cocoa pod husks exposed to simulated inundation (experiment 3).

Estimate/Criterion	Fresh husks	Partially decayed husks
Leaching rate (k), day^{-1}	0.03 ± 0.01	0.22 ± 0.04
Ageing constant (a), unitless	0.35 ± 0.05	0.63 ± 0.05
AIC	-252.14	-177.22
BIC	-243.53	-167.56
RMSE, %	0.22	1.32
R^2	0.995	0.992

5

Chapter 5

Lack of positive short-term responses to fertilizer application in existing cocoa crops demands a re-think of entry-points for intensification[1]

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[1] In preparation

Abstract

Nutrient requirements for cocoa and yield responses to fertilizers in smallholder fields are poorly understood. Our objective was to evaluate cocoa yield responses to fertilizer application in relation to current productivity and disease pressure under farm management. Experimental plots were established in 10 representative smallholder fields with 15-20 years old cocoa trees that had never received fertilizers. Yield responses were compared using a randomized complete block design (RCBD) in an on-farm trial located in the south-west of Nigeria in 2020 and 2021. Modest PK rates (22 kg P ha^{-1} and 42 kg K ha^{-1}) were annually applied combined with 0, 50, and 100 kg N ha^{-1}. Soil properties were measured at the start, while management practices (pruning, weeding, pest and disease management) were assessed monthly. The number of healthy and diseased pods, pod index and cocoa bean yields were determined per plot. In each plot, 25 trees were monitored over the experimental period. Linear mixed models were used to estimate the effect of management practices, field productivity and treatment on cocoa bean yield responses and yield components. Average cocoa bean yield responses were estimated to be 94, 55, and -54 kg ha^{-1} for PK fertilizer treatments combined with 0, 50, and 100 kg N ha^{-1} respectively, but these were not significantly different from the control (without fertilizer) due to large variability among the fields. Weeding, and pest and disease management inconsistently affected the yield response, the number of pods per tree, and the proportion of diseased pods per tree. We conclude that use of fertilizer in existing cocoa plantations in south-western Nigeria did not increase yield under smallholder management and should not be the first entry-point for intensification efforts.

Key-words: cacao; farm heterogeneity; soil fertility; yield response; farming practices; step-wise approach.

5.1. Introduction

Achieving balanced crop nutrition is essential to maintain soil fertility and improve cocoa (*Theobroma cacao* L.) yields (Uribe et al. 2001), especially in low-input low-output systems found in West Africa smallholder farms (Wartenberg et al. 2018; Wessel and Quist-Wessel 2015). Negative nutrient balances were observed in cocoa fields in Ghana and Nigeria (Appiah et al. 1997; Chianu et al. 2012) which threaten sustainability when offtakes are larger than inputs over longer periods of time. Nutrient offtakes with harvested beans are generally estimated at 19-39 kg N, 3-4 kg P, and 7-10 kg K per ton of dry cocoa beans (Hartemink 2005). Additional nutrients are needed to compensate offtake by cocoa pod husks and nutrient immobilization in the woody biomass. However, there is uncertainty about the right amount of nutrients that should be supplied to sustain or increase cocoa yields (van Vliet and Giller 2017).

Cocoa nutrition research has a long history in West Africa (Ahenkorah et al. 1981; Wessel 1971). Over decades, blanket recommendations (unique rates of blended fertilizers) have been proposed at country level for a large population of famers. Such recommendations usually emanate from experimentation in few locations (van Rooyen et al. 2021) followed by extrapolation to larger areas e.g. (Tesfahunegn and Wortmann 2017). For instance, "Asaase Wura" (containing 22% P_2O_5, 18 % K_20, 9% CaO, 7% S and 6% MgO) and "SuperCao" (23% P_2O_5, 19% K_2O, 10% CaO, 5% S, 6% MgO, 0.9% Zn, and 0.25% B) are recommended in Ghana and Côte d'Ivoire, respectively (Koko 2014; Amponsah-Doku et al. 2022). Other recommendations are available in Cameroon and Nigeria (Nlend-Nkott and Asare 2021). The Cocoa Research Institute of Nigeria (CRIN) recommends annual applications of 150 kg ha^{-1} of "NPK 20:10:10" (containing 20% N, 10% P_2O_5, and 10 % K_20) and 333 kg ha^{-1} of "NPK 15:15:15" (15% N, 15% P_2O_5, and 15 % K_20) for cocoa trees of 4-10 years and older than 10 years respectively (Moses O. Ogunlade, personal communication). In order to decide whether to use fertilizer, smallholders need strong evidence that it will be profitable for their farms (Denkyirah et al. 2016; Fosu-Mensah et al. 2022).

Criticism arose about the inadequacy of these blanket fertilizer recommendations for two main reasons. First, blanket fertilizers do not acknowledge the diversity among cocoa farms (Amponsah-Doku et al. 2022; Dossa et al. 2018), which would result in large variability in yield response to fertilizer application. Second, it has been suggested that the first generation of fertilizer trials was set on relatively fertile soils (van Vliet and Giller 2017). Usually, these trials were set upon cleared forest lands with high soil organic carbon (SOC) contents and a relatively large soil nutrient supply that may have been enough for cocoa demand, known as the ’forest rent’ (Ruf et al. 2015). This potentially underestimates nutrient requirements for current smallholder fields.

Site-specific fertilizer recommendations have been released (for cocoa as in other crops) that promise tailored recommendations to local conditions, intending to lower the financial risks of fertilizer investments. These tailored recommendations are suggested to be most effective at field level (Espinosa et al. 2006). However, site-specific recommendations require accurate knowledge about crop nutrient demand and soil supply at the corresponding spatial scale. Current estimates derive from soil and climate maps, but these are unavailable or unreliable because of limited observations (Zhu et al. 2015a). Moreover, physiological underpinnings for proper cocoa nutrition are still missing, which further complicates the development of field-specific recommendations. Therefore, field-specific recommendations are currently a bridge too far.

A middle-ground between nationwide poorly fitted “blanket recommendations” and “fine-tuned field-specific recommendations” is to adapt recommendations to regional requirements. In Côte d'Ivoire, currently two fertilizer rates are recommended by the “Centre National de Recherche Agricole” (CNRA): one for the Eastern and Central regions, and another for the Western region (Konan et al. 2015). In Nigeria, work is in progress to develop regional cocoa fertilizer recommendations, considering agroclimatic zones and soil types (Ogunlade et al. 2019a). Surprisingly, the Ghana cocoa board (COCOBOD) recommends a number of fertilizers that differ in composition for Ghana, but without regional specification (Cudjoe et al. 2016). These attempts to set regional fertilizer recommendations are made on the premise that regions substantially differ in crop demand or soil fertility (nutrient supply, limitations, and nutrient-related soil constraints).

Cocoa nitrogen (N) requirements have been studied since the 1970s, but current knowledge is still incomplete. N is the most frequently limiting plant nutrient (Agren et al. 2012; Sainju et al. 2019). Local N yield response curves were established mainly for cereals (e.g. Zhu et al. 2015b), but not yet for cocoa.

Cocoa requires larger N supply under low or no shade, and less under heavy shade (Evans and Murray 1953). A light shade regime is often recommended to maximize yields (Dohmen et al. 2018), resulting in a larger N uptake when compared to shaded conditions. Cocoa yields respond to N application only if other nutrient deficiencies (especially P) are eliminated (Wessel 1971). More recently, concurrent with regional cocoa fertilizer recommendations, cocoa nutrient requirement maps were developed for Côte d'Ivoire and Ghana (N'Guessan et al. 2017; Snoeck et al. 2010). A similar map is under development in Nigeria (Ogunlade et al. 2019a). The main feature of these maps is that they delineate areas where N is required and areas where it is not. However, conclusions concerning N requirements from on-farm trials set in Côte d'Ivoire (Ruf et al. 2016) contradicted the proposed map (N'Guessan et al. 2017). Such contradictions suggest that cocoa N requirements are subjected to variations even within the regions defined in the maps. In practice, the fertilizer suppliers swiftly adjusted and produce PK compound fertilizers which can be mixed with urea or other N fertilizers by individual farmers. Nevertheless, farmers have no information about whether they should apply N or not, and at what rates.

Based on the above discussion, it is clear that regional cocoa fertilizer recommendations are claimed to be better than the national blanket recommendations (e.g. Dossa et al. 2018), but have not been tested. In addition, cocoa N requirement maps lack estimates of uncertainty. Hence, it is critical to assess within-region variations of N requirements and explore their causes. We aimed to understand cocoa yield response to selected combinations of macronutrients and its variability between farmers' fields in Nigeria. Our objective was to compare yield response to PK combined with three rates of N (0, 50, and 100 kg N ha^{-1}), and to explore possible interactions among yield responses, soil fertility, and disease pressure under farmers' management. We hypothesized that in low-shade cocoa agroforestry systems and under variable field conditions, the yield response to N supply increases for application rates below 100 kg N ha^{-1}. Here, we report results from an on-farm trial under farmers' management in south-west of Nigeria.

5.2. Materials and methods

5.2.1. Study area

An on-farm fertilizer trial was initiated in 2020 in smallholder cocoa fields with 15-20 year old trees. Our aim is to continue the trial for at least five years. Crop response data for the first two years is presented here. The study area was situated in Owo Local Government Area, Ondo State, Nigeria. The climate is characterized by an annual rainfall of 1398 mm with a monthly peak in September (Appendix Figure 5.4); the annual mean temperature is 25.6°C with small seasonal fluctuations (Abatzoglou et al. 2018). Lixisols developed on quartz schists and gneisses are the dominant soils in the area (FAO 2015; Hengl et al. 2017).

Key-informant interviews revealed that cocoa has been grown in the study area for about 50 years and is the main source of cash income for smallholder famers. From these interviews, we learned that farmers usually plant “Amazon” cultivars (without a particular layout), upon selectively clearing a secondary forest. Management of cocoa fields in the production phase usually includes one or more annual rounds of manual weeding, depending on the degree of canopy closure. Pesticides (insecticides and fungicides) are typically applied 2-3 times per year, less than frequently recommended (Afoakwa 2014). Systematic pruning is performed once in 1-3 years, while lighter pruning is completed several times in a year as part of general field maintenance.

Prior to field selection, a survey was conducted in September 2019 to rapidly characterize cocoa farming the study area. The results of the survey served as a basis for field selection. The survey engaged a total of 110 farmers proposed by the ‘lead-farmers’ in 11 rural communities, and involved a structured interview and on-farm measurements. Lead-farmers were asked to prepare a list of potential candidates. The list of cocoa farms obtained from the ‘lead-farmers’ in their communities was used because registers were not available. The interview captured the types of cocoa production systems (full-sun, simplified agroforestry, low-shade, and heavy-shade complex agroforestry systems), the ages of present cocoa trees, the previous land-use, and the major perceived production constraints. Field measurements included the field perimeter using GPS receivers, cocoa tree count on three equilateral triangular assessment plots of side 20 m each, soil textural class, terrain slope, and a rapid cocoa yield estimation through a pod count on all trees in the triangular plots. Field areas and cocoa tree density were calculated.

After interviewing farmers and visiting fields, the coefficient of variation (CV) of all quantitative variables was evaluated; cocoa tree density was the most variable. Then, farms were sorted on cocoa tree density. Farms within 5-95% of the observed cocoa tree density were short-listed. The shortened list served as basis for farm sampling.

Table 5.1: Soil physical and chemical characteristics (mean ± standard deviation) for *n*=10 fields

Soil property	Unit	Estimate
Clay content	%	10.4 ± 1.36
pH		6.91 ± 0.40
SOC	%	1.41 ± 0.35
Total N	%	0.14 ± 0.05
C:N		10.82 ± 1.63
P	mg kg^{-1}	5.28 ± 2.14
K	cmol kg^{-1}	0.37 ± 0.18
Ca	cmol kg^{-1}	4.93 ± 1.95
Mg	cmol kg^{-1}	1.57 ± 0.40
Na	cmol kg^{-1}	0.14 ± 0.05

5.2.2. Selected experimental fields

Ten fields, located each on a different farm, were selected randomly from the shortened farm list. All fields were located between 7° 12’ 55” N and 7° 14’ 22” N, and between 5° 41’ 14” E and 5° 43’ 01” E, with elevation varying from 175 to 436 m.a.s.l. These fields were 15-20 years old and had never received organic or mineral fertilizers before this study. In all fields, palms and shade trees were present, most of them being remnant forest trees and a few planted species. The most frequently found species, in decreasing order of relative abundance were *Elaeis guineensis*, *Cola nitida*, *Triplochiton scleroxylon*, *Gliricidia sepium*, *Citrus* spp., and *Milicia excelsa*. The average (± standard deviation) cocoa tree density was measured at 1338 ± 188 trees ha^{-1}, while the shade tree density was 61 ± 27 trees ha^{-1} (Figure 5.2 c).

In June 2020, before fertilizer treatments were applied, composite soil samples were taken at 0-30 cm depth in each experimental plot, pooled at field level, air-dried, sieved at 2 mm, and analysed following routine procedures (Table 5.1). Soil texture was determined based on the hydrometer method. Soil pH was measured in a 1:2.5 soil-water ratio. For soil organic carbon (SOC) and total nitrogen contents, the chromic acid oxidation (Walkley-Black) and the Kjeldahl digestion methods were used respectively. Available P contents were quantified with the Olsen extraction method, while exchangeable bases (Ca, Mg, K, Na) and micro-nutrients (Zn, Cu, Mn, Fe) were determined through Mehlich III extraction and inductively coupled plasma-optical emission spectrometry (ICP-OES).

5.2.3. Experimental design and field measurements

The effects of three fertilizer treatments, differing only in their N contents, were evaluated on cocoa yield and yield components. The experimental unit was a plot of 21 m × 21 m (441 m^2). In each field, 4 plots that were at least 5 m apart were delineated and randomly assigned to treatments: "control" (no fertilizer), "P22K42" (22 kg P ha^{-1} and 42 kg K ha^{-1}), "N50P22K42" (50 kg N ha^{-1}, 22 kg P ha^{-1} and 42 kg K ha^{-1}), and "N100P22K42" (100 kg N ha^{-1}, 22 kg P ha^{-1} and 42 kg K ha^{-1}); these rates were supplied annually. Treatment N50P22K42 corresponded to the national recommendation for trees older than 10 years and assuming a cocoa tree density of 1333 trees ha^{-1}. Treatment P22K42 was required to study the response to N. It was assumed that rates of P and K in the national fertilizer recommendation were adequate to potentially suppress deficiencies for the study area. Fertilizers (urea, triple super phosphate and muriate of potash) were weighed per plot, manually mixed, and equally distributed over all present cocoa trees, in a circle of 0.7 m radius around the stem of each tree (Nlend-Nkott and Asare 2021). Following national recommendations in Nigeria, dosages were equally split between June and September. Except fertilizer application, all the farm management was implemented by farmers. The trial was laid out following a Randomized Complete Block Design (RCBD) with one complete block per farm.

Measurements were taken at both plot and tree levels. At plot level, we evaluated farming practices, counted healthy and diseased pods at harvest, and weighed sun-dried beans extracted from healthy pods. Three agronomic practices known for their influence on cocoa yields were assessed monthly: pest and disease management (Kongor et al. 2017), pruning (Leiva-Rojas et al. 2019; Vega et al. 2021), and weed management (Konlan et al. 2019). These practices were scored on a 4-point Likert scale (0-3) with the maximum score corresponding to the most desirable situation (Appendix Table 5.3). Each plot was scored separately to account for spatial heterogeneity in smallholder farmer fields (Tittonell et al. 2013).

In smallholder cocoa farming, pod harvest is spread throughout the year, with seasonal peaks. In this area, the main harvest period is from October to December. At each harvest event, all ripe pods were harvested; the number of healthy and diseased pods were counted. Counts were aggregated from September to December 2020 and from January to December 2021. Once in the October-December period, a sub-sample of healthy pods, all harvested from twenty-five trees, was counted and processed by pod breaking, cocoa bean fermentation and sun-drying. Weights of corresponding fresh cocoa beans and sun-dried beans were determined.

Data were also collected at tree level to capture the tree-to-tree variability in response to fertilizer treatment. At the beginning of the study, a subset of 25 trees located at the centre of each plot were identified and labelled for detailed measurements for each tree of the total number of harvested pods and the percentage of diseased pods. During the above-mentioned harvest events, pods plucked on these labelled trees were first gathered and counted per tree before information was recorded at plot level. Tree data were also aggregated from September to December in 2020, and from January to December in 2021.

5.2.4. Data processing

At plot level, we calculated the cocoa yields, the yield responses to fertilizer treatments, and the pod indices by summing data collected for each tree in the plot. At tree level, we assessed the total number of harvested pods per tree and the proportion of diseased pods. The “pod index” was calculated as the number of healthy pods required for 1 kg of sun-dried beans (Eq. 5.1, Maharaj et al. 2011). Dry cocoa bean yield was calculated as in Eq. 5.2.

$$PI = \frac{Number\ of\ healthy\ pods}{Mass\ of\ sun\!-\!dried\ beans} \quad \text{(Eq. 5.1)}$$

$$Y = Density\ \times N_{Pods} \times (1 - P_{diseased})\ \times \frac{1}{PI} \quad \text{(Eq. 5.2)}$$

where *Y* is the yield of sun-dried cocoa beans (kg ha^{-1}), *Density* the cocoa tree density (trees ha^{-1}), *N_Pods* the total number of harvested pods per tree, *P_diseased* the proportion of diseased pods per tree, and *PI* the pod index (pods kg^{-1} beans).

The cocoa yield response to a given fertilizer treatment was calculated per year in each field as in Eq. 5.3.

$$R_{i,j,k} = Y_{i,j,k} - Y_{control,j,k} \quad \text{(Eq. 5.3)}$$

where $R_{i,j,k}$ and $Y_{i,j,k}$ represent the yield response to fertilizer treatment *i* and the yield of the plot in which treatment *i* was applied in year *j* and field *k*, respectively. $Y_{control,j,k}$ represents the yield in the control plot, and was used to represent the field productivity.

At tree level, the total number of harvested pods resulted from a simple aggregation of all harvested healthy and diseased pods in a year. The proportion of diseased pods per tree was calculated by dividing the number of diseased pods by the total number of harvested pods.

As management practices were scored on a monthly basis, temporal variation was unavoidable as observed in other production systems (Kitchen and Clay 2018). The probability of the highest score was derived to capture the average annual management standard. It was calculated by dividing the frequency of the highest score (3) for a given practice by the number of observations (scores from 0 to 3) over a year (Eq. 5.4). All plots received the same number of visits.

$$Probability_{a,i,j,k} = \frac{N\ visits_{a,i,j,k}(score{=}3)}{N\ visits_{a,i,j,k}(score \in \{0,1,2,3\})} \quad \text{(Eq. 5.4)}$$

where *a* represents a farming practice (pruning, weeding, or pest management).

5.2.5. Statistical analysis

Neither soil properties (Table 5.1), nor tree densities strongly correlated with cocoa yield response to fertilizer application; therefore, these variables were not further considered as predictors. At plot level, linear mixed-effects models were used to analyse yields, yield responses, and pod indices. For yield, the fixed-effects factors were treatment and year, with fields used as random-effects. For the yield responses and pod indices, the explanatory variables included the treatment, the yield in the control plot ($Y_{control}$), the probability of highest score for each management practice (weeding, pruning, pest management), and the interaction between $Y_{control}$ and treatment.

At tree level, the cumulative frequency distribution (CDF) was determined for the total number of harvested pods per tree. The distribution curves were then compared between pairs of treatments, based on the two-sample Kolmogorov-Smirnov test. The 50th and the 80th quantiles of the CDF were compared among treatments, by fitting linear quantile mixed-effects model regressions (LQMM).

Generalized linear mixed models (GLMM) were also fitted to evaluate the effect of fertilizer treatment on the total number of harvested pods per tree and the proportion of diseased pods per tree. The same fixed-effects factors used for yield responses were employed: treatment, $Y_{control}$, the probability of highest score for the three management practices, year, and the interaction between $Y_{control}$ and treatment. A hierarchical structure of random-effects was adopted with, in decreasing order: the field, the plot (within the field), and the tree (within the plot). The analysis was repeated for each year, in which case tree was no longer included as a random factor. It was observed that the distribution of the number of pods per tree strongly deviated from normality and significant over-dispersion occurred. A negative binomial distribution was thus assumed in the corresponding GLMM. Poisson, quasi-Poisson, and zero-inflated distributions were tested for, but did not reduce the deviance of the models. For the proportion of diseased pods per tree, a binomial distribution was adopted as data did not show significant over-dispersion.

Models were analysed by testing significance of explanatory variables, through F test following a type III Analysis of variance (ANOVA) with a Satterthwaite's approximation of degrees of freedom. When this was not possible (GLMM), a Chi-squared test was used instead. In all models that included $Y_{control}$ as explanatory variable, we excluded the control treatment to ensure variable independence. Marginal means were computed for all response variables to compare the effect size of explanatory variables. The proportions of total variance explained by predictors were calculated using the marginal and conditional pseudo-coefficients of determination (Nakagawa et al. 2017), and the unadjusted intra-class correlation coefficients (Lüdecke et al. 2021). Predictions were made based on fitted models while all random-effects factors were set to zero. All analyses were implemented in R environment (R Core Team 2013), using mainly *glmmTMB*, and *qlmm* packages for model fitting, and *emmeans* and *performance* to calculate marginal means, pseudo-coefficients of determination, and model predictions.

5.3. Results

5.3.1. Effects of fertilizer treatments on cocoa yields

Overall, annual cocoa yields were estimated at 422, 515, 476, and 368 kg ha^{-1} for control, P22K42, N50P22K42, and N100P22K42 treatments respectively (Figure 5.1 a). There were no significant differences ($P>0.05$) in cocoa yields between treatments. However, there was a significant year effect ($P<0.001$) with higher yields in 2021 than in 2020. In both years, the highest and lowest average yields were recorded in the P22K42 and N100P22K42 treatments, respectively. The total variance in observed yields was mainly attributed to between-field differences (ICC=0.54, Table 5.2).

5.3.2. Cocoa yield response to fertilizer treatments under smallholder farm management

A score of zero was never recorded for pruning and pest control, but did occur for weed control. Following an unexpected change in rainfall patterns in August 2020 (Appendix Figure 5.4), all farmers could not maintain the experimental plots in the best possible manner between August 2020 and January

2021, resulting in scores below 3. In 2020, the probabilities of a score of 3 ranged between 0 and 0.5 for pest control and pruning, and between 0 and 0.83 for weed control. In 2021, this probability ranged between 0.36-0.91, 0.42-0.83, and 0.46-1.0 for pest control, pruning, and weed control, respectively.

Table 5.2: Estimated unstandardized coefficients, significance, and proportion of total variance explained by factors included in different GLMM.

#	Dependent variable	Unstandardized coefficicents[1] of the fixed-effect factors										R2m	ICC	R2c
		Year			Fertilizer treatment[2]				Pest	Pruning	Weeding			
		2020	2021		P22K42	N50P22K42	N100P22K42							
1	*Yield*	360	531	***	515	476	368	ns				0.10	0.54	0.64
2	*Response*	3	60	ns	80 $+0.01\ Y_{control}$	145 $-0.21\ Y_{control}$	211 $-0.60\ Y_{control}$	ns *	$-269Pr$ ns	$3.90Pr$ ns	$377Pr$ ns	0.24	0.34	0.58
3	*Pod index*	21.6	20.2	ns	21.7 $-5\times10^{-3}\ Y_{control}$	24.7 $-7\times10^{-3}\ Y_{control}$	28.2 $+1.2\times10^{-2}\ Y_{control}$	ns *	$-5.59Pr$ ns	$2.18Pr$ ns	$2.99Pr$ ns	0.29	-	0.29
4	*Nb pods*	4	8	***	4 $+1\times10^{-3}\ Y_{control}$	3 $-2\times10^{-3}\ Y_{control}$	3 $-1\times10^{-3}\ Y_{control}$	ns ns	$-0.99Pr$***	0.39Pr ns	0.08Pr ns	0.18	0.48	0.66
5	*Prop dis*	0.17	0.08	***	0.10 $+3\times10^{-4}\ Y_{control}$	0.13 $-2\times10^{-4}\ Y_{control}$	0.13 $+1\times10^{-4}\ Y_{control}$	ns ns	$1.22Pr$***	$-0.63Pr$ ns	$-0.52Pr$*	0.04	0.16	0.20

ICC: intra-class correlation coefficient (variation due to random-effects factors); R2c: conditional coefficient of determination (variation due to both fixed-effects and random-effects factors); R2m: marginal coefficient of determination (variation due to sole fixed-effects factors). *Nb pods* and *Prop dis* are the number of pods per tree and the proportion of diseased pods per tree, respectively. Pr and $Y_{control}$ are the probability of best management for a given practice and the yield on the control plot respectively. See methods section for details

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[1] Significance according to Wald F test, but Chi square test if the dependent variable is underlined. The symbols ns, *, **, *** represent P>0.05, P<0.05, P<0.01, and P<0.001 respectively.

[2] When the interaction between treatment and $Y_{control}$ is estimated, the additive effect of the treatment is evaluated on the first line while the interactive effect is evaluated on the second line.

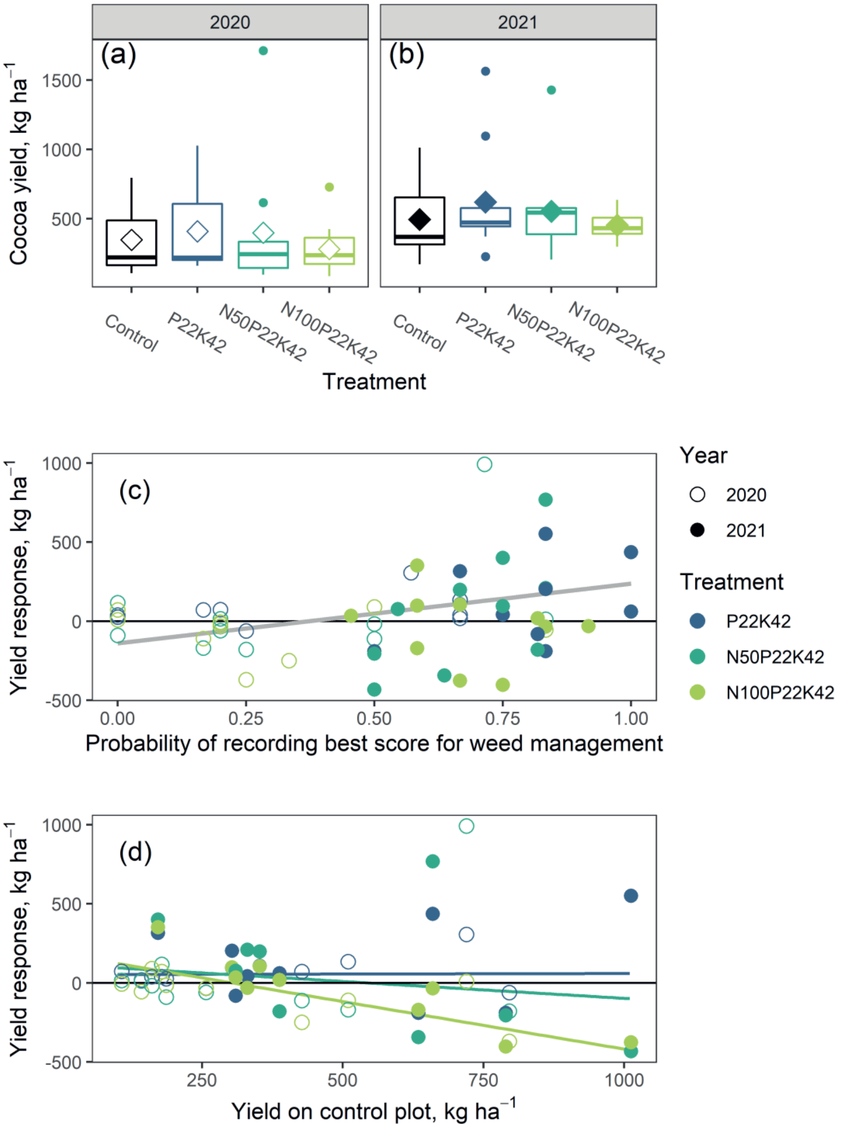

Figure 5.1: Cocoa yields (a) and yield responses (b and c) to three different fertilizer treatments. Predictions are represented with lines, while observed individual (circles) and mean values (diamonds) are represented with open (2020) and solid (2021) symbols. The treatment colours of the dots match with those of the lines; the grey line is treatment invariant.

The cocoa yields in the control plots ranged between 107 and 1012 kg ha^{-1} with a 62% coefficient of variation (CV). Despite this variation, correlation in field productivity was strong between years (r=0.68), indicating that the most productive fields in 2020 remained very productive in 2021. In comparison to field productivity, there was a larger variation in yield response to fertilizer application, with a CV=807%. Yield responses to N50P22K42 treatment were more variable (95% confidence interval between -83 and 192 kg ha^{-1}, CV=629%) than responses to P22K42 (95% confidence interval between -55 and 221 kg ha^{-1}, CV=203%) and N100P22K42 (95% confidence interval between -181 and 95 kg ha^{-1}, CV=345%).

The effects of pruning and pest and disease management on yield responses were not significant (P>0.05). There was an expected yield increase estimated at 3.8 kg ha^{-1} for every 1% increase in the probability of the highest weeding score (Figure 5.1 b). The effect of weeding on cocoa yield response was significant in 2020 (5.4 kg ha^{-1}, P<0.05), but not in 2021 (1.3 kg ha^{-1}, P>0.05, Appendix Table 5.4). The yield response to N100P22K42 significantly decreased at increasing $Y_{control}$ (P<0.05, Figure 5.1 c), meaning that an addition of 100 kg N ha^{-1} resulted in lower yields in the most productive fields, when compared to the P22K42 treatment. In a field with $Y_{control}$ of 100 kg ha^{-1}, predicted yields increased with 76 kg ha^{-1} and 160 kg ha^{-1}, for P22K42 and N100P22K42 treatments respectively. In contrast, at a $Y_{control}$ of 1000 kg ha^{-1}, the predicted yield increased with 100 kg ha^{-1} when applying P22K42 and decreased with 416 kg ha^{-1} when applying N100P22K42.

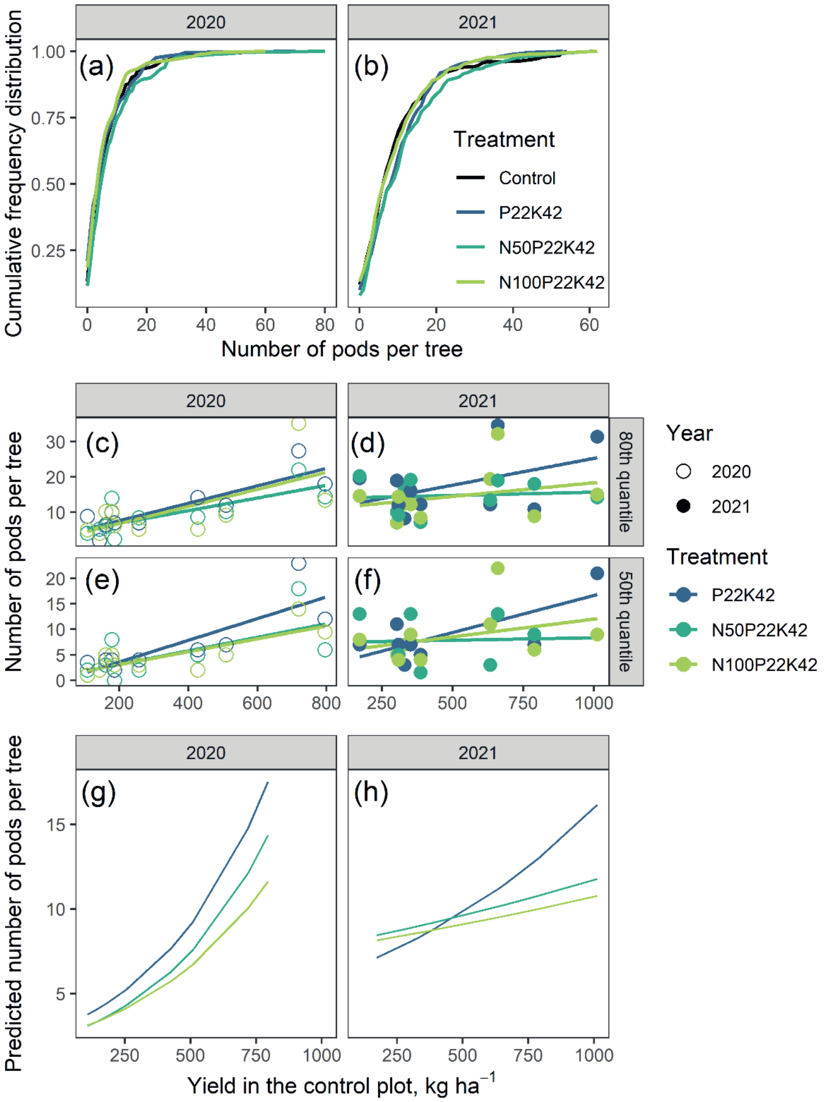

Figure 5.2: Observed (lines in a and b, and only dots in c-f) and predicted (lines in c-h) number of pods per cocoa tree under different fertilizer treatments. Open and solid symbols in c-f represent data collected in 2020 and 2021, respectively. The treatment colours of the dots match with those of the lines.

5.3.3. Effects of fertilizer treatments and management practices on yield components

Fertilizer application did not have the same effect on the different yield components. Most trees produced very few pods in all treatments. In 2020 and 2021, respectively 16% and 10% of labelled trees bore no harvestable pods (Figure 5.2 a-b). Furthermore, 2-6% of labelled trees produced no harvestable pods over the two years. Thus, applying fertilizers did not result in production of harvestable pods on all trees.

Trees in the most productive fields produced many more harvestable pods when P22K42 was applied than when N50P22K42 or N100P22K42 was applied, more so in 2021. This was not observed in the least productive fields (Figure 5.2 c-f). At all tested quantiles (50th and 80th), the number of harvestable pods per tree was significantly highest ($P<0.05$) in treatment P22K42 at increasing $Y_{control}$. The largest differences between treatments were observed at the 80th quantile, i.e. the most productive trees.

According to the GLMM (model 3, Table 5.2), the average number of pods per tree was not significantly different between treatments, even at increasing $Y_{control}$. An increased probability of the highest score for pest management was associated with a significant decrease ($P<0.001$) in the total number of pods per tree. This counter-intuitive result may have been due to the prominent role of mummified and diseased pod removal as sanitation practice: fields in which this was observed (highest scores for pest management) subsequently had a lower number of total pods at harvest. Year had a significant effect on the number of pods per tree ($P<0.001$), with more pods produced in 2021 than in 2020.

In general, the number of harvested pods that were diseased was significantly higher in 2020 (17% infected pods) than in 2021 (10%; $P<0.001$, Figure 5.3 a, b), corresponding approximately to 74 and 59 kg ha^{-1} yields losses respectively. The proportion of diseased pods was slightly larger for trees that received N100P22K42 (17%) than for trees in other treatments (14%). In 2020, the proportion of diseased pods was significantly larger for trees that received N100P22K42 than for trees in other treatments, irrespective of $Y_{control}$ ($P<0.01$). In 2021, more diseased pods were found on trees that received N100P22K42 when compared to other treatments, with significant treatment by $Y_{control}$ interaction effect (P<0.05, Figure 5.3c, d).

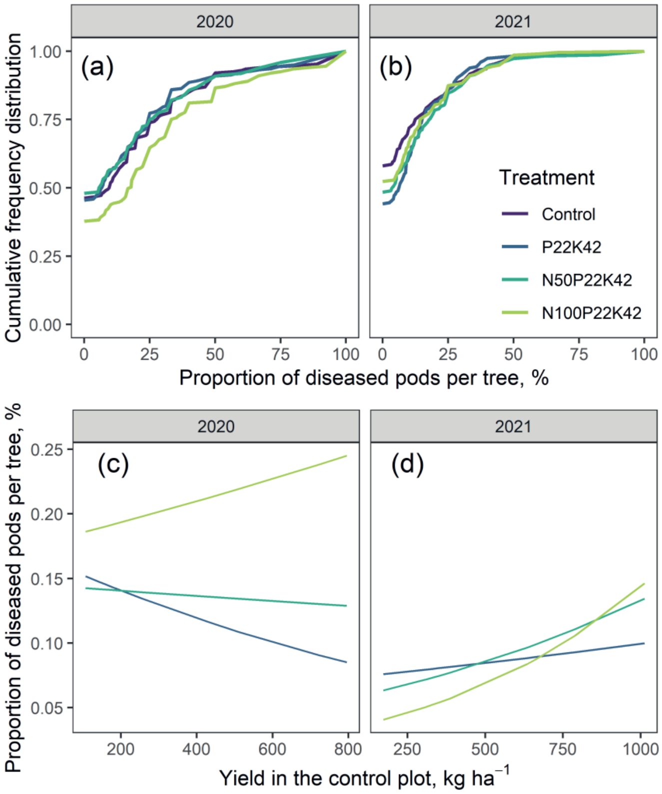

Figure 5.3: Observed (a-b) and predicted (c-d) proporitons of diseased pods calculated per cocoa tree under different fertilizer treatments. The treatment colours of the dots match with those of the lines.

Pod index significantly decreased at increasing $Y_{control}$ (P<0.05), meaning that higher yields in the most productive fields were associated with larger cocoa bean weight per pod. However, there was no significant change in the pod index as a result of fertilizer application (P>0.05). Management practices did not significantly change pod index values either.

5.4. Discussion

Overall, there were no significant differences in yield between control and fertilizer treatments (P>0.05), contrasting with our expectations. Variability between fields and between trees in a field were large. The results did clearly not support our hypothesis.

5.4.1. Unexpected lack of response to nutrient supply in low-input systems

Our results showed small positive but non-significant responses of cocoa trees to combined P and K fertilizers (applied at recommended rates in Nigeria) across years. Cocoa yield responses to various fertilizers have been assessed since the 1960s (Murray 1958). Smallholder cocoa production systems likely suffer from negative nutrient balances, and nutrient deficiency is likely the major cause of low productivity (Vaast and Somarriba 2014; Baah et al. 2011). After more than 10 years of crop growth and continuous harvest with no organic or mineral inputs, nutrient balances are expected to be negative in all the fields of our study. Most of the published work related to on-farm fertilizer trials in cocoa reported significant positive responses to fertilizer application (Uribe et al. 2001; Asare et al. 2017). Little attention was paid to variability in yield responses which may have occluded cases of no or negative responses.

Absence of response of cocoa trees to fertilizer application could be due to other constraints that are more important than nutrient deficiencies: (a) a lower than expected nutrient demand by trees, (b) sufficient supply from soil or an unbalanced or poorly-timed fertilizer application, and/or (c) a delayed response. The low nutrient demand of cocoa trees likely relates to various growth-defining, -limiting or -reducing factors. Some possible limitations on cocoa nutrient demand were: germplasm quality, constraints on flower pollination, reduced growth rate in old age, legacy-effect of past damage, and physiological adaptations to low nutrient environments. The genetic materials used are probably not the most productive since smallholder farmers generally rely on seeds from their own harvest or from neighbours as planting materials. A survey conducted in four countries in 2002 showed that 9-42% of smallholder cocoa farmers used improved varieties, with the lowest percentage for Nigerian farmers (Gockowski 2019).

A low nutrient demand for yield formation may also arise from constraints on other metabolic processes: e.g., larger resource allocation to vegetative growth or defence against bio-aggressors, failure of reproductive functions such as pollination. Visual observations of the cocoa canopy in our study hardly support the hypothesis of strong leaf biomass response instead of yield response to fertilizers. Therefore, excessive vegetative growth may not explain the lack of yield response. Total carbohydrate production and its allocation between vegetative and reproductive growth is mainly driven by genetic factors (Daymond et al. 2002), but also influenced by pruning (Gandhi et al. 2021; Leiva-Rojas et al. 2019; Susanti et al. 2017). Pod set can also be limited by a low rate of pollination irrespective the tree's nutritional status. Groeneveld et al. (2010) and Toledo-Hernández et al. (2020) suggested that a 13-40% hand-pollination had a greater potential to increase cocoa yield than improving availability of light, nutrients, or water.

Cocoa trees may have suffered irreversible damage in the past with negative legacy-effects on subsequent growth and production. Such damage includes, among others: fire, flooding, heat, drought (Medina and Laliberte 2017; Asare et al. 2017; Bar et al. 2019; Abdulai et al. 2017; Moser et al. 2010; Lahive et al. 2021; Gateau-Rey et al. 2018). From seedling establishment, several environmental shocks and stresses could have occurred with cumulative and/or delayed effect on production potential; these are insufficiently analysed in cocoa. The most studied legacy-effect is that of drought on forest tree species (Huang et al. 2018; Kannenberg et al. 2019; Wu et al. 2018), which could also occur in cocoa with expected differences between varieties (Tezara et al. 2020).

The age dependency of growth and production in tree crop could limit nutrient demand. After 15-20 years, it is expected that the tree growth rate has reduced considerably as compared to trees in the immature or young mature phase. Consequently, nutrient demand would be lower in old age than during active growth phase. Besides, Fischer et al. (2014) have proposed that organism plasticity is age-dependent. Progressive adaptation to nutrient-limited environment may result in poor response of cocoa trees to nutrient supply as tree plasticity would have decreased over time. This hypothesis seems paradoxical as strong nutrient responses are expected after long periods of starvation, but is supported by the accumulation of non-structural carbohydrates throughout the ontogeny of the tree, resulting in better acclimation to environmental shocks and stresses (Niinemets 2010).

The hypothesis of sufficient soil nutrient supply in our study is hardly supported by soil chemical properties and observed yields (lower than 2000 kg ha^{-1}). Alternatively, ineffective nutrient supply could lead to nutrients being lost, and is often linked to the 4R nutrient stewardship (Bruulsema et al. 2022; Bruulsema et al. 2019). In particular, nutrient imbalances can be expected if deficiencies are not properly identified and addressed. Nutrient imbalances have been observed in cocoa (Chinnappan 2021; Isaac and Kimaro 2011) and are proposed as a major cause of limited fertilizer response in various crops (Ndabamenye et al. 2013; Njoroge et al. 2017; Raghupathi et al. 2005). In strongly weathered tropical soils where sesquioxides are abundant (Giresse 2008), availability of P for plant uptake can be strongly limited as observed in this trial (Table 5.1). Another potential cause of ineffective supply is poor timing of fertilizer application. Timing of nutrient application was done based on a calendar, following national recommendations in Nigeria; but this could be improved provided that peaks of nutrient demands are clearly identified. For example, leaf flushing and pod enlargement in cocoa is seasonal and likely to be associated with increased nutrient demands.

Nutrient uptake by trees might be decoupled from nutrient use for growth and development (Rennenberg and Schmidt 2010). One of the mechanisms of asynchrony relates to the nutrient reserve pool in the tree that buffers future seasonal deficiencies and stress periods. As this reserve pool increases with biomass, older trees may become less dependent on environmental resources, being less responsive to environmental changes including nutrient supply. Refilling the tree reserve pool could cause delay in response to fertilizer application. Handley (2016) proposed that additional assimilates generated from enhanced photosynthesis are not immediately partitioned to pod growth, but this may occur as from the second year in younger cocoa trees. The hypothesis of delayed response needs further tests with long-term trials in which the year effect is controlled.

5.4.2. Variable yield response to nutrient supply: the role of intricately linked factors

In this study, cocoa yield responses spanned from -500 to +1000 kg ha^{-1}, with 34% of the variability explained by differences between fields, and only 24% explained by the fertilizer treatment, the management practices, the year, and the field's productivity. In total, 42% of yield response variability remained unexplained by the linear mixed-effects model. Understanding yield variability has been a constant objective of modern agronomy (Mulders et al. 2021; Maestrini and Basso 2018). Variability in yield response to fertilizer application is key information to assess farmer's economic risk to adopt fertilizer use (Laajaj et al. 2020). Average yield responses to fertilizers are often reported in cocoa (Mulia et al. 2017), but variability is often occluded. Between-farm yield variability has been found to be about 30-60% in on-farm trials (Asare et al. 2017; Hoffmann et al. 2020). Fertilizer response variability is much larger, with standard deviations as large as differences between treatments (fertilizer versus control), even with 'good agricultural practices' (Hoffmann et al. 2020). Our results indicated greater variability than observed by Hoffmann et al. (2020), and we see no scope for generalized fertilizer recommendations to smallholders due to this large variability.

Time (year) was not a significant factor influencing cocoa yield response in our study, although there were significant differences between annual yields ($P<0.001$). However, year was associated with significant differences in the number of harvested pods per tree, and significant differences in the proportion of diseased pods per tree. Temporal variation of cocoa yield was assessed in previous studies, suggesting strong limitations of climate on cocoa yields. For instance, the dependence of rainfed cocoa production on temperature and rainfall variability is clearly acknowledged (Ofori-Boateng and Insah 2014; Lahive et al. 2018; Wilson et al. 2019). Also, frequent precipitation and subsequent high air relative humidity are key drivers of black pod disease pressure (Delgado-Ospina et al. 2021).

Management explained only a small amount of cocoa yield response variability: weeding was only significant in 2020. Pest and disease management did not significantly influence the yield response to fertilizer, but was important both for the total number of harvestable pods and the number of healthy pods per tree. Pruning did not show a significant effect on any response variable measured in this study, while it is often considered a key determinant of cocoa yield (Chang et al. 2021; Laossi et al. 2022). The overarching role of pest and diseases as a major cause of yield losses was confirmed (Adomako 2007; Bailey and Meinhardt 2016); however we had no evidence that better disease management would improve the response to fertilizer *per se*. This finding supports the idea of a step-wise application of ISFM practices (Vanlauwe et al. 2010) in which weeding and pest and disease management would be a pre-requisite for improved nutrient management under the constraint of current germplasm. Weed control may additionally increase the effectiveness of fertilizer application, but evidence is weak.

5.4.3. Yield response in the most productive fields

Cocoa yield responses to N100P22K42 were negatively correlated to field productivity. N demands are larger under full-sun when compared to heavy shade (Murray 1958; Uribe et al. 2001). N requirements under low-shade conditions received less attention in previous studies. Under NPK fertilizer application, cocoa yields reached a maximum between 50-75% full daylight (Murray 1958; van Vliet and Giller 2017). The negative responses to N supply at increasing field productivity were unexpected under low shade conditions as present in this study. We found that pest management played an important role in reducing the number of harvested pods per tree in all fields. Further, the predicted number of harvested pods per tree was consistently lower at N100P22K42 when compared to the other treatments. The proportion of diseased pods was largest in trees that received 100 kg N ha^{-1}, increasing with increasing field productivity. This suggested that large N availability amplified the disease pressure on pods. Visual observations did not suggest that more leaves were produced in the canopy, which could also have increased air humidity and favoured black pod disease spread in N100P22K42 plots.

Our analysis reveals that nutrient supply is not the logical entry-point to achieve rapid improvements in cocoa yields in smallholder cocoa farms in the study area, despite the presence of negative nutrient balances. The large variability and the absence of a quick and significantly positive response contrasts with the general advice to farmers to apply fertilizers as soon as possible. This paradox calls on deeper reflections on the urgency of fertilizer application as a first step towards sustainable intensification in smallholder cocoa farms. Other farm management practices including weed control, pruning, and pest and disease management need to be addressed first to ensure healthy cocoa trees with the capacity to respond to nutrients, before NPK application.

5.5. Conclusion

There was no significant positive response to any of the three tested nutrient combinations after two years of fertilizer application, although the trees had never received nutrient inputs in the past. The yield response to fertilizers was highly variable primarily due to differences among the fields. The response to NPK fertilizer with 100 kg N ha^{-1} was absent for very unproductive fields, but was increasingly negative for the more productive fields. Diseases played a major role in reducing the number of healthy harvestable pods per tree. This yield reducing effect was amplified by large N supply, as present in the more productive fields that were fertilized with 100 kg N ha^{-1}. These results suggest that, in the short-term, fertilizer application to old cocoa trees in nutrient-limited production systems is not a viable option under smallholder management. We identified several possible explanations for this lack of response.

The observed variability in yield response highlights (a) the challenges in estimating nutrient requirements at field-scale and (b) the importance of disease as a major yield-reducing factor. Therefore, blanket fertilizer recommendations in the studied environment expose farmers to unevaluated risks of yield losses. We conclude that for the studied systems, fertilizer cannot be the entry-point for intensification in older stands of cocoa. First, other aspects of management need to be improved, including proper weeding and pruning, disease control and use of responsive germplasm.

Appendix

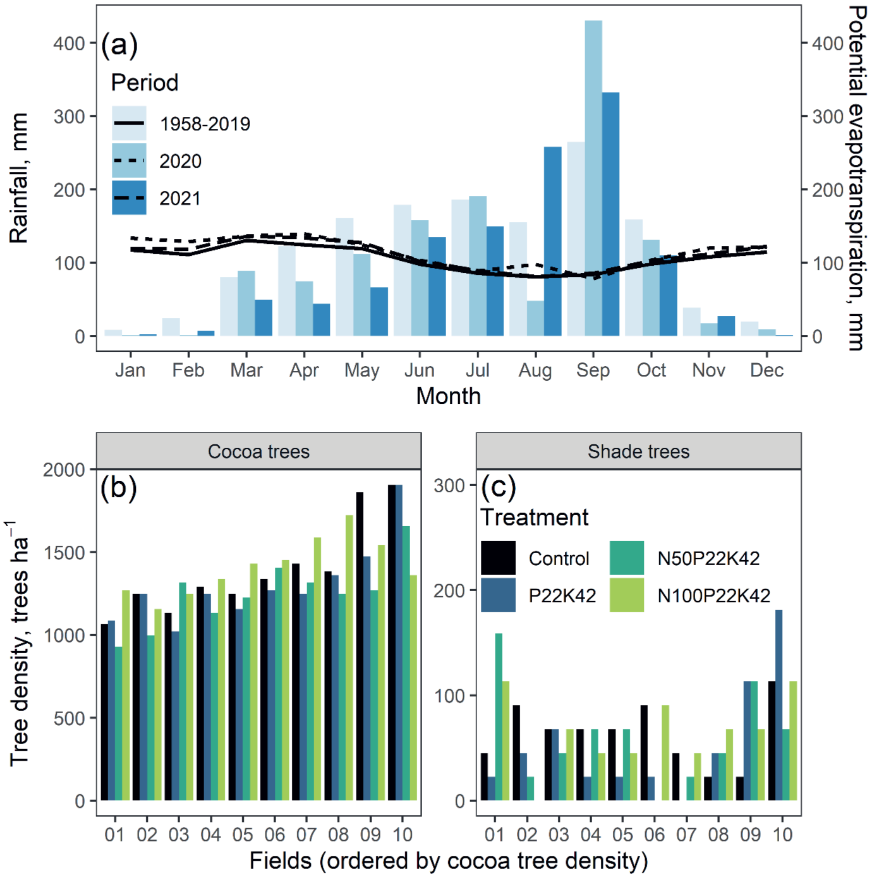

Figure 5.4: (a) Climatic conditions of experimentation with interpolated monthly rainfall (bars) and potential evapotranspiration (lines). (b) Cocoa tree density and (c) shade tree density in experimental plots.

Table 5.3: Notation scale used to score farmers' management practices in 15-20 year old cocoa plantations

Practices	Scores			
	0	1	2	3
Weeding	more than 50% weed cover	25-50% weed cover	5-25% weed cover	less than 5% weed cover
Pruning	more than 50% trees with chupons, interlocked branches, or dead branches	25-50% trees with chupons, interlocked branches, or dead branches	4 trees - 25% of trees with chupons, interlocked branches, or dead branches	less than 4 trees with chupons, interlocked branches, or dead branches
Pest control	more than 50% of trees infected with black pod or bearing mummified pods	25-50% of trees infected or bearing mummified pods	4 trees - 25% of trees infected or bearing mummified pods	less than 4 trees infected or bearing mummified pods

Table 5.4: Summary results of analysis of variance performed on different GLMM for the each year.

A: 2020

#	Dependent variable	Unstandardized coefficicents[1] of the fixed-effect factors							R2m	ICC	R2c
		Fertilizer treatment[2]				Pest	Pruning	Weeding			
		P22K42	N50P22K42	N100P22K42							
A1	*Yield*	410	399	282	ns				0.02	0.72	0.74
A2	*Response*	55 $+0.00\ Y_{control}$	-68 $+0.28\ Y_{control}$	45 $-0.23\ Y_{control}$	ns ns	-482*Pr* ns	-115*Pr* ns	540*Pr* *	0.33	0.30	0.63
A3	*Pod index*	19 $+9\times10^{-3}\ Y_{control}$	26.9 $-1.1\times10^{-2}\ Y_{control}$	29.1 $-1.3\times10^{-2}\ Y_{control}$	ns ns	1.59*Pr* ns	-7.51*Pr* ns	3.16*Pr* ns	0.27	0.12	0.40
A4	*Nb pods*	3 $+2\times10^{-3}\ Y_{control}$	2 $+2\times10^{-3}\ Y_{control}$	3 $+2\times10^{-3}\ Y_{control}$	ns ns	0.08*Pr* ns	0.55*Pr* ns	-0.32*Pr* ns	0.26	0.12	0.38
A5	*Prop dis*	0.20 $-9\times10^{-4}\ Y_{control}$	0.16 $+3\times10^{-4}\ Y_{control}$	0.19 $+7\times10^{-4}\ Y_{control}$	*** **	-0.83*Pr* ns	0.63*Pr* ns	0.44*Pr* ns	0.02	0.01	0.02

B: 2021

#	Dependent variable	Unstandardized coefficicents[1] of the fixed-effect factors							R2m	ICC	R2c
		Fertilizer treatment[2]				Pest	Pruning	Weeding			
		P22K42	N50P22K42	N100P22K42							
B1	*Yield*	621	554	454	ns				0.04	0.46	0.50
B2	*Response*	20 +0.17 $Y_{control}$	368 -0.61 $Y_{control}$	414 -0.88 $Y_{control}$	ns *	196*Pr* ns	467*Pr* ns	132*Pr* ns	0.35	0.25	0.60
B3	*Pod index*	8 -1×10^{-2} $Y_{control}$	8 -2×10^{-3} $Y_{control}$	14 -1×10^{-2} $Y_{control}$	ns ns	4.17*Pr* ns	8.31*Pr* ns	6.94*Pr* ns	0.10	-	0.10
B4	*Nb pods*	6 $+1\times10^{-3}$ $Y_{control}$	8 $+4\times10^{-4}$ $Y_{control}$	8 $+3\times10^{-4}$ $Y_{control}$	ns ns	0.41*Pr* ns	-0.63*Pr* ns	0.42*Pr* ns	0.05	0.17	0.22
B5	*Prop dis*	0.10 $+2\times10^{-4}$ $Y_{control}$	0.07 $+7\times10^{-4}$ $Y_{control}$	0.04 $+15\times10^{-4}$ $Y_{control}$	ns *	-0.80*Pr* ns	1.09*Pr* ns	0.55*Pr* ns	0.02	0.03	0.05

ICC: intra-class correlation coefficient (variation due to random-effects factors); R2c: conditional coefficient of determination (variation due to both fixed-effects and random-effects factors); R2m: marginal coefficient of determination (variation due to sole fixed-effects factors). *Nb pods* and *Prop dis* are the number of pods per tree and the proportion of diseased pods per tree, respectively. *Pr* and $Y_{control}$ are the probability of best management for a given practice and the yield on the control plot respectively. See methods section for details.

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[1] Significance according to Wald F test, but Chi square test if the dependent variable is underlined. The symbols ns, *, **, *** represent P>0.05, P<0.05, P<0.01, and P<0.001 respectively.

[2] When the interaction between treatment and $Y_{control}$ is estimated, the additive effect of the treatment is evaluated on the first line while the interactive effect is evaluated on the second line.

6

Chapter 6

General discussion

6.1. Overview

The demand for cocoa, the main ingredient of chocolate, is increasing by 1-3% per year (ICCO 2021). The bulk of cocoa is produced by smallholder farmers in West Africa who are often confronted with low productivity, ageing of tree stocks, and declining soil fertility (Matissek et al. 2012; Macek et al. 2018). Since cocoa production has long been associated with deforestation (Barima et al. 2016; Sassen et al. 2022), actors in the industry have committed to increase production in a sustainable manner (Carodenuto and Buluran 2021; Castro-Nunez et al. 2020; Drew and Boal 2019). Their objective is to meet the increasing demand, not through expansion of cultivated area, but through higher land productivity. Yield gaps are currently large in cocoa (Asante et al. 2022; Abdulai et al. 2020), which offers opportunities for yield improvement and production increase. The limited and inadequate use of organic and mineral fertilizers by smallholder farmers (Nunoo et al. 2014; Ali et al. 2018) leads to poor crop nutrition which is postulated as one of the most important constraints to cocoa yield increase (Kongor et al. 2017; Wessel and Quist-Wessel 2015). Therefore, implementing integrated soil fertility management (ISFM) in cocoa is attractive, and proposed as a path to sustainable intensification (SI). However, since the paradigm of ISFM was initially developed for maize-based production systems, the knowledge required to apply it to tropical perennial crops is lacking (Vanlauwe 2020). Implementation of ISFM in tropical tree crops was understudied when compared to annual crops (Agegnehu and Amede 2017; Tabo et al. 2007; Bayu 2020; Chivenge et al. 2010; Pincus et al. 2016; Pypers et al. 2011). The aim of this thesis was to explore the potential of ISFM to increase yields and to better understand nutrient cycling in cocoa. Focusing on existing smallholder cocoa farms in West Africa, three research questions were addressed:

- Do the principles of ISFM apply to smallholder cocoa production systems in West Africa?
- What is the contribution of litter production and decomposition and of cocoa pod husk management to soil nutrient availability?
- What is the expected yield response to fertilizer application in mature cocoa fields under current farmer management?

In this chapter, I first summarize the key findings of the thesis (section 2). Reflections on the methodological choices made throughout the studies are then presented to inform future research. A distinction was necessary between constraints peculiar to this research (section 3.2) and more generic limitations that apply to any field trial in mature smallholder cocoa fields (section 4.1). Since the latter limitations had no obvious solutions, it spurred a discussion on alternative approaches to advance cocoa nutrition knowledge (section 4.2). The limits of practising ISFM in cocoa are discussed by integrating implications of key results with current views on ISFM and alternative or complementary approaches to deliver sustainable intensification in cocoa (sections 5 and 6).

6.2. Key findings

The potential of ISFM to rapidly increase cocoa yields has not been demonstrated with experiments on farms in this thesis. The relevance and applicability of ISFM principles were discussed in the context of smallholder cocoa farming (Chapter 2), emphasizing the importance of carbon and nutrient stocks and flows within tree crop systems. The large C stocks in mature cocoa, and the limited scope for smallholder cocoa farmers to produce and collect additional on-farm organic resources question the relevance of organic fertilizer use and application in cocoa. In addition, several knowledge gaps (e.g., crop nutrient demand, optimization of pruning) were identified which limit our ability to precisely define fertilizer needs in each context and to provide undisputed "sound agronomic" recommendations to current smallholder farmers. The use of low-performance germplasms and sub-optimal management by smallholders are not conceptual constraints but do limit the yield benefits expected from applying ISFM practices in the current cocoa production systems. To achieve the desired yield increases, both knowledge gaps and current practices need to be addressed; but above all, I advocate for a thorough re-interpretation of ISFM principles in tree crop systems as a first step towards a meaningful implementation of the paradigm.

To improve nutrient cycling, organic residues generated in cocoa fields need to be managed efficiently (Turmel et al. 2015; Yadvinder et al. 2004). In Chapters 2 and 3, we showed that substantial amounts of C were stored in various components of mature cocoa crops, with significant above- to below-ground flows (through e.g., litterfall, pruning, root mortality and decay), which ultimately influence nutrient return to soil. While Chapter 2 suggests that internal stocks of C and nutrients are large, it does not provide mechanistic understanding of the observed flows and their drivers. Chapters 3 and 4 partly address this gap, by evaluating the effects of natural processes on two above-to-belowground nutrient transfer paths. In both chapters, evidence was provided that the transfer rates from residues to soil were nutrient specific. In particular, N and P were slowly released from the litter layer, which was attributed to the poor quality of senescent cocoa leaves; however, soil macrofauna played a significant role in the subsequent nutrient removal from the litter (Chapter 3). Unlike N and P whose cycles were tied to that of C, potassium (K) flowed rapidly between system components, especially as leachates were lost from decaying cocoa pod husks often abandoned in piles by smallholder farmers (Chapter 4). These studies altogether show that different mechanisms govern N, P, and K flows from trees to soil, suggesting that when residue management is possible, this should be nutrient-oriented. Hence, understanding nutrient cycling is deepened by showing the role of some essential drivers which were previously overlooked in cocoa: macrofauna for N and P release from litter, and rainfall patterns for K leaching from cocoa pod husks. The main difference between Chapters 3 and 4 is related to the degree of control a farmer could have over the nutrients contained in the residues: nutrient flows through litterfall (over which farmers have no control) were larger than the moderate flows through cocoa pod husks.

Unlike Chapters 3 and 4 which were dedicated to cycling of nutrients within the system, Chapter 5 focused on nutrient addition to the system. A key point of Chapter 2 was that ISFM could only be sub-optimal in current smallholder cocoa production systems because many prerequisites were not met. Therefore, it was urgent to estimate the profit a farmer could expect from applying a single or any combination of ISFM recommendations. In Chapter 5, we focused on fertilizer application, from which we expected the largest response in farms that never received additional nutrient inputs from the from organic or mineral sources since establishment phase. We evaluated the yield response to fertilizers in 15 to 20-year-old cocoa trees under farmer management in south-western Nigeria. Among the tested treatments was the national fertilizer recommendation for trees of more than 10 years of age. After two years of fertilizer application, we were surprised by a lack of response and the large between-field variation in yield responses found. Further, an imbalanced combination of nutrients (including a supply of 100 kg N ha^{-1}) was counter-productive and resulted in yield reductions when compared to PK only. It was concluded that, in this case, fertilizer application was not the first entry-point of ISFM to achieve larger yields in smallholder cocoa fields, despite nutrient mining being a major concern.

6.3. Methodological strengths and weaknesses

6.3.1. Revisiting the principles of a paradigm

A key message of this thesis is that ISFM, despite being a prominent paradigm for soil fertility management in SSA, first needs to be questioned. Before testing isolated or combined practices in an understudied cropping system, it was important to embrace the complexity of nutrient management by analysing conceptual and practical aspects of ISFM. The necessary combination of organic and mineral nutrient resources has become the primary principle of soil fertility management paradigms, which in its interpretation, often involves an active manipulation of organic inputs (Akinnifesi et al. 2007; Kearney et al. 2012; Ghosh et al. 2022). Even if this is clear in most cropping systems exposed to chronic soil organic matter (SOM) losses, this thesis highlighted that mature cocoa stands, under certain circumstances, represent an exception due to their large C stocks. Surprisingly, the method to communicate this outcome has become a bone of contention.

During the writing process, an anonymous reviewer objected to the choice of a narrative review as presented in Chapter 2. This opposition echoes the supremacy of quantitative research methods in agronomic research. Since the development of meta-analytical tools, narrative reviews have been portrayed as old-fashioned, lacking rigour and objectivity. Narrative reviews have also become less feasible to summarize findings in fields with abundant literature (Gurevitch et al. 2018). However, the breadth of the topic addressed in Chapter 2 and a focus on the concept made it ill-suited to perform a systematic review or a meta-analysis which is more relevant to answer specific and narrow questions. In addition, earlier studies in cocoa used a wide range of methods, so that setting restrictive literature search criteria would yield fewer articles. Systematic reviews are perhaps more transparent than narrative reviews, but they are equally exposed to selection bias since literature exclusion criteria often lack critical evaluation. On the other hand, the narrative review approach is rightly exposed to critics of an unbalanced representation of the findings because the paper selection method is not reproducible (Cook 2019). Nevertheless, the risk of a biased representation of the existing knowledge would be higher if the review attempted to resolve contradictory research findings (e.g., the benefits of full-sun cocoa vs cocoa agroforestry systems). I am convinced that the choice of a narrative review was justified, and that the rigour of such a review relies on the diligence and honesty of the authors in evaluating the literature.

6.3.2. Trade-offs between internal and external validity in experimental studies

Internal validity is the extent to which a cause-effect relationship can logically be established from a study, i.e. how confidently researchers can rule out alternative causes (non-studied factors) to the observed effects (McDermott 2011). It is often associated with the degree of control exerted over the confounding factors but does not require that the mechanistic explanation of the proposed cause-effect relationship be provided. External validity refers to the generalizability of the results beyond the context in which the study has taken place (Slack and Draugalis 2001; Kennedy-Martin et al. 2015; Dehejia et al. 2019; List 2020). The study on nutrient leaching from cocoa pod husks (Chapter 4) was the most internally valid of this thesis, because artificial conditions were provided in the laboratory experiments to isolate treatment effects. No potential confounder or mediator variable which could alter the conclusion was foreseen. Conversely, the degree of artificialization led to a poor external validity: the simulated regimes of rainfall are unlikely to be observed in real world, nor do the size and number of chunks in the tubes truly represent cocoa husk piles.

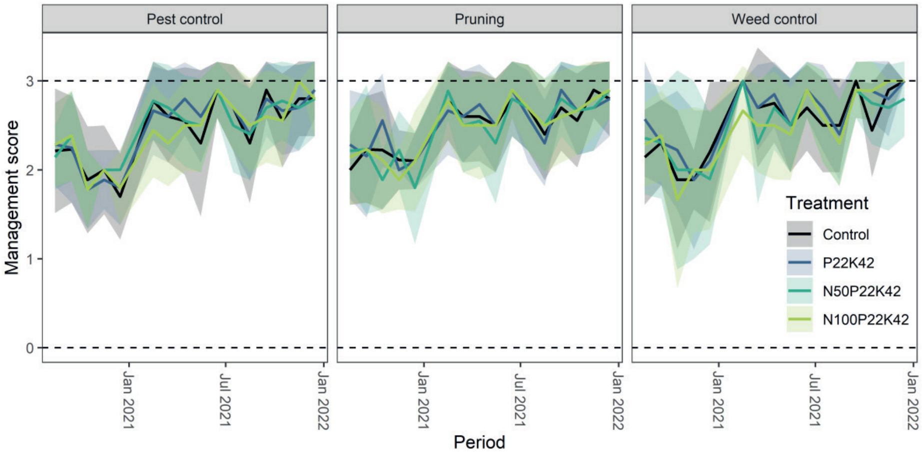

Figure 6.1: Temporal and spatial (within-field) average (± standard deviation) management scores

At the other extreme, the fertilizer trial (Chapter 5) deliberately minimized researcher involvement in the trial management which resulted in a lack of control over several sources of variation affecting yields. Representing farmer's real conditions in a trial is a constant challenge to agronomists, and failure to do so has often been identified as a symptom of limited external validity and a main cause of poor innovation adoption (Laajaj et al. 2020; de Roo et al. 2017; Stevenson et al. 2019). The confounding factors in this study were accounted for by measuring soil properties at the start of the trial and assessing management practices throughout. However, an appropriate analytical method to grasp the complexity of the data was lacking. There were several simplifications: (a) outcomes of farmer practices were recorded as monthly scores and used to compute annual probabilities of best management, (b) linear regression models were adopted, and (c) interactions between management variables were ignored. Scoring farmer practices on a Likert-scale was a practical compromise between precision and cost of data collection; but criteria and thresholds developed were arbitrary, needing further evaluation and adjustment. Subjective scoring cannot be entirely ruled out. As expected, plots were not consistently managed over time (Figure 6.1), but the temporal variation in management was not captured while computing the probability of best management (see Chapter 5, section 5.2.4). Therefore, loss of precision was inevitable as scores of 0, 1, and 2 indistinctly represented as sub-optimal management while a score of 3 represented the best possible management. To illustrate, a score of 2 for pest management during the dry season (with little or no crop expected) has the same value as a score of 0 in September (wet season with large risks of disease spread and large crop expected). The expected yield loss due to a benign incidence of black pod in March (scored 2) is intuitively less than a severe attack (scored 0) observed in September; this is why fungicide spraying is usually recommended during the rainy season (Afoakwa 2014). The adopted regression models implied linear relationships between independent and response variables. Generic yield response curves to various production factors (water, nutrients, soil properties, pest control) have proved non-linear for various crops (e.g. Wang et al. 2015; van Dijk et al. 2017). Besides, interactions between management practices were ignored, mainly because these are still poorly documented in cocoa, as in other crops (e.g. Kaur et al. 2018). Another internal validity-related constraint is the possible selection bias due to the project-restriction over study areas and relying on lead-farmers as key-informants during sampling. Therefore, external validity threats have not being completely addressed despite low research involvement in trial management. Conclusions from the fertilizer trial can hardly be generalized to other places and different production systems. In addition, the small number of participants (10) limited generalizability even within the study area. "Experimentation at scale" and "stratified experimentation" approaches (Kool et al. 2020) will potentially improve generalizability of future cocoa nutrition research. More generic constraints that are not peculiar to Chapter 5, but touch upon all field trials in cocoa are discussed in section 4.

6.4. The role of experimentation in advancing cocoa nutrition

6.4.1. Inherent challenges to measure yield response to fertilizers in smallholder cocoa

Experimentation remains an important way to generate knowledge on crop nutrition. However, measuring yields and yield responses to agronomic interventions are quite complex in smallholder cocoa fields. Several sources of heterogeneity are common and occur simultaneously in smallholder cocoa fields: tree age, germplasm, spatial variation of microclimate and soil. In Chapter 5, there was also some within-field (spatial) and temporal variation in management (Figure 6.1). Because of the field heterogeneity, yields were highly variable as already was observed in uniformity trials in which significant differences arose between adjacent plots (Lotodé and Muller 1974). Heterogeneity in the average number of pods per tree and incidence of black pod disease were observed on both small and large size plots (10 versus 200 trees per plot), challenging accurate estimations of yield and disease incidence. Even if heterogeneity cannot be eliminated, defining an optimal plot size helps to find a compromise between a better estimate of the mean (through increase in plot size) and logistical constraints. Lotodé and Muller (1974) indicated that the error variance reduction beyond 20-25 trees per plot is negligible. Data collected in Chapter 5 met this minimum requirement; but even with these large plots, observed variances were large obscuring potential yield responses. Calculating yield responses (as the yield difference between treated plots and control plots) proved to be problematic as uniformity trials had not been conducted before treatments were applied. Uniformity trials would better inform plot selection and thereby reduce within-field heterogeneity. Evaluating prior performances of cocoa trees in smallholder farms before establishing a new fertilizer trial must be performed over a couple of years to account for temporal variation in pod production.

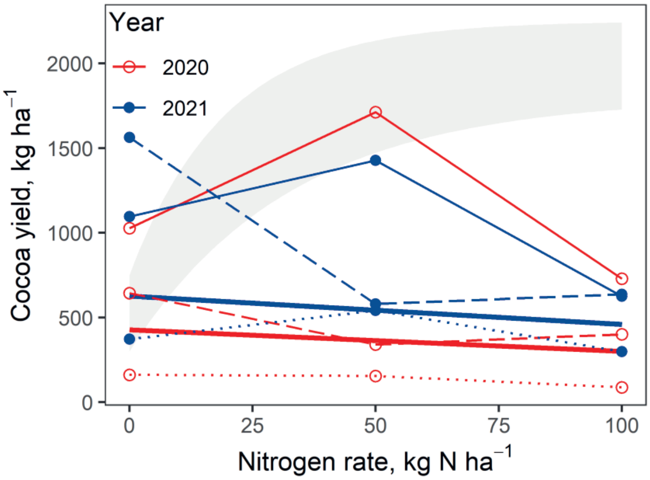

Figure 6.2: Hypothesized (grey band) versus estimated N responses (thick coloured lines) under 22 kg P ha^{-1} and 42 kg K ha^{-1} annually applied over two years in ten cocoa fields in south-western Nigeria. Individual N responses measured in three of the ten fields (represented with thin dashed, dotted, and solid lines respectively) show variations in patterns.

Three rates of N (0, 50, and 100 kg N ha^{-1}) with constant supply of P and K were tested in an on-farm trial, with the aim of deriving a N-response relationship under farmer management. However, the results were inconclusive (Figure 6.2). To my surprise, the expected yield increases due to small N application rate (50 kg N ha^{-1}) were not observed. The absence of responses (horizontal lines) suggest that the soil N supply was satisfactory to meet the actual tree demand, or the trees accumulated enough reserves before the trial started. This result supports the dominant role of tree reserves proposed in Chapter 2 (Figure 2.4). Scaling up nutrient response curves from on-farm trials is of limited relevance because of unidentified site-specific characteristics and difficulty to reduce noise in data. Alternatively, response curves may be inferred from on-station experiments with many more tested rates (e.g. at least 6, Sileshi 2021), in contrasting agroecological zones but on extremely poor soils, and under best possible management. Such on-station trials have the potential to limit or control sources of variation, thereby more accurately informing modelling studies.

6.4.2. Can modelling circumvent experimental constraints?

Since agronomic experimentation can only handle a limited number of factors affecting yield, modelling has received considerable attention to address complexity of agroecosystems (Jeuffroy et al. 2014; Reynolds et al. 2018; Meinke 2019). On the other hand, model development relies on a deep understanding of underlying mechanisms, and the capacity to formalize the existing knowledge. In cocoa, few models have been developed of which SUCROS-Cocoa or CASE-2 addressed the physiological growth and production of the crop (Zuidema et al. 2005). In the most recent development of this model, growth limitation by climatic factors have been addressed: radiation, temperature, CO_2, and water availability (Asante et al. 2022). A major limitation of CASE-2 is that it does not currently include nutrient dynamics and effects of nutrient limitations on yields (Tosto et al. 2023). How can nutrient limitations be accounted for? Here, I propose two alternative approaches.

First, the CASE-2 model can be used to estimate annual nutrient demands of a tree per climatic zone, provided that nutrient concentrations per organ are known and do not vary with age. A reasonable fraction of the water-limited cocoa yield (output of CASE-2) can further be considered as a "target yield" which is an input of the off-take model (Vasquez-Zambrano et al. in preparation) whose principles are briefly presented in Chapter 2 (section 2.4.2). Indicative target yields are most valid at coarse spatial scales (agroecological zones), but less relevant at finer scales. Another way to define target yields at sub-regional level would be to record the highest farmer yields (Tittonell and Giller 2013). At field level, target yield can be inferred from the annual pod production of the most productive trees (e.g., 80% or 90% upper percentile) corrected to some adjusted estimate of the cocoa tree density. This first proposal uses CASE-2 outputs or farm-level data to improve accuracy of the site-specific fertilizer recommendations derived from the off-take model. In the second proposal, a nutrient module can be harnessed to the CASE-2 model, provided that the physiological responses of the crop to nutrients are represented.

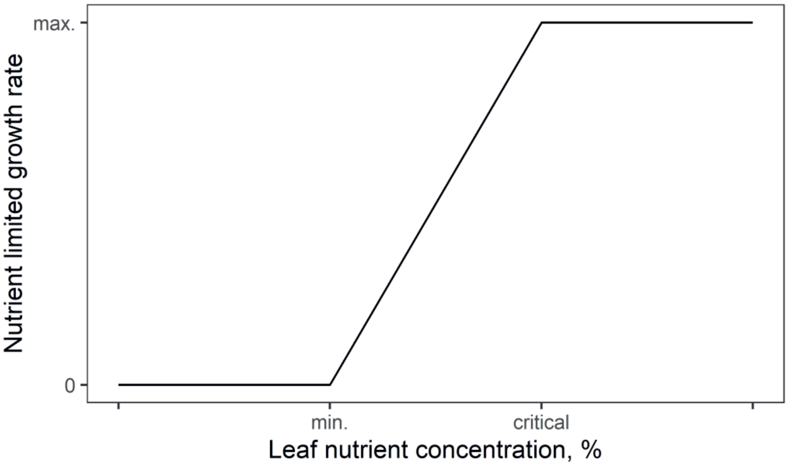

Figure 6.3: Proposed form of the simulated nutrient response curve of cocoa

A common method to include nutrient limitations in crop growth models consists of parametrizing nutrient response curves using non-linear regression analyses in distinct climatic zones (e.g. Mueller et al. 2012). However, such response curves are not yet available in cocoa; therefore an *ad hoc* approach is needed. I propose that such response curves are provisionally inferred from multi-level nutrient omission trials in which young trees are raised in nutrient-poor growth media (e.g., pure sand or glass beads), and nutrients are supplied at different rates via nutritive solutions. Based on such experiments, minimum and critical leaf nutrient concentrations[17] can be determined per cultivar. Leaf nutrient sampling in mature trees (estimated in large-scale surveys) would provide means of calibration and validation; but whole-canopy protocol development is needed (e.g., de Groot 2020). Minimum and critical nutrient concentrations in mature trees can only be approximated from measurements of extreme cases, i.e. with totally sufficient trees (demonstrating excellent growth rates) and with clearly identified single-nutrient deficient trees. The nutrient response curves would initially be represented by simple linear-plateau models in which the minimum and critical concentrations would correspond to "no

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[17] Under the minimum concentration, all growth ceases; between minimum and critical concentrations, growth is nutrient-limited.

growth” and “maximum growth” situations respectively (Figure 6.3). The nutrient-limited growth would correspond to the potential growth estimated in CASE-2 reduced by a factor proportional to the severity of leaf nutrient deficiency (only for the most limiting nutrient) if actual nutrient concentrations are comprised between the minimum and critical levels (e.g., Lemaire and Gastal 1997; Singh and Porter 2020). This approach clearly ignores the age-dependency of cocoa response to nutrient availability. It further ignores soil nutrient supply, physiological nutrient interactions, luxury consumption, mechanisms of nutrient foraging (in case of soil nutrient deficiency) and reallocation to other organs within the tree (including the existence of a tree reserve pool). Including dynamic nutrient partitioning rules and modelling soil nutrient supply can resolve some of the limitations but increase the complexity of the model.

6.5. The limits to ISFM in cocoa

6.5.1. Contested principles of ISFM

There is no consensus on a single definition of ISFM (e.g. Tittonell et al. 2008; Moshiri et al. 2021; Fairhurst 2012; Srivastava 2020), and only the combination of organic and mineral fertilizers is undisputed. The definition proposed by Vanlauwe et al. (2010) was adopted here for clarity and relevance to the geographical context (Sanginga and Woomer 2009; Vanlauwe et al. 2015a). Other aspects like the necessary use of microbial inoculants proposed (e.g. Srivastava et al. 2021) have been ignored for lack of empirical evidence in cocoa, despite growing evidence on the underlying mechanisms in other crops (Schmidt et al. 2021; Bargaz et al. 2018).

In cocoa, diverse options of combined organic and mineral nutrient supply were previously tested and proposed to farmers (Agbeniyi et al. 2011; Dogbatse et al. 2021; Lambert et al. 2020; Fidelis and Rajashekhar Rao 2017; Mulia et al. 2017), but without questioning their agronomic relevance to the crop. Chapter 2 only offers a theoretical perspective to answer this question. What is the empirical evidence that supports application of the first ISFM principle in cocoa? Two examples are reviewed for brevity. Application of cocoa pod husk compost mixed with NPK fertilizers yielded more than sole NPK and sole compost in Nigeria (Ogunlade and Orisajo 2020). The difference was attributed to increased incidence of black pod disease on trees that received either sole compost or sole mineral fertilizers; it is worth noticing that there was no significant difference in total number of pods between sole compost, sole fertilizers, and combined compost and fertilizers. It was also reported in Indonesia that yields under combined compost and fertilizers were higher than under sole fertilizers, but equal to yields under sole compost (Fungenzi et al. 2021). The effect of compost was associated with slow-release soil nutrients and improvement of soil water holding capacity. Surprisingly, the authors noted that SOM decreased the most under the compost treatment. More arguments could be stated to promote organic fertilizer application including the improvement of SOM and soil physical properties, the provision of a wider range of plant nutrients, the lower risks of acidification and salinization (Chatzistathis et al. 2021). However, some of the functions of organic matter are already covered by the existing litter addition which maintains SOM, adds nutrients (as shown in Chapter 3), and protects the soil against erosion. Therefore, the benefits of additional organic inputs still need to be evaluated in cocoa.

Analysis of these results suggests that proposed mechanisms to explain observed responses are context-specific, and experimental designs and subsequent analyses often do not allow for a fair comparison of treatments. In the above-mentioned studies, the nutrient value of the mixture was always superior to those of either component. Synergistic effects of organic and mineral fertilizer application are often claimed (Akinnifesi et al. 2007) but can only be demonstrated if compared treatments provide equal amounts of nutrients (Brunetti et al. 2019) or when the additive effects of single components are deducted from mixtures (Giller 2002; MacLaren et al. 2022). In low-input systems, SOM is the only source of nutrients. Accordingly, SOM contents and cation exchange capacity (CEC) are cited among the most critical soil properties positively associated with cocoa yield (Adeniyi et al. 2018; Kongor et al. 2019). Nevertheless, the challenge is to objectively quantify annual soil nutrient supply from measured physical and chemical soil properties (e.g., through the use of pedo-transfer functions). Poor correlations between soil properties and crop productivity are a justification for not including soil properties in the yield data analysis, as presented in Chapter 5.

Another principle of ISFM is “management following sound agronomic principles” which is often interpreted as implementation of good agricultural practices (GAP) or best management practices (BMP). Dissemination of GAPs has pervaded the whole history of agricultural extension in poor countries, with the aim of improving yields and farmers’ livelihood (Bairagi et al. 2018; Nhamo et al. 2014; Jelsma et al. 2019; Woittiez et al. 2019). The maximum locally attainable yield (often obtained in on-station trials or large-scale farms) usually serves as reference to define the GAPs which are subsequently disseminated to smallholder farmers (Caliman et al. 2005). However, defining GAPs in cocoa sometimes lacks clarity and objectivity, as shown for pruning (Obeng Adomaa et al. 2022; Tosto et al. 2022) and cocoa pod husk management (Nlend-Nkott and Asare 2021; Srivastava and Singh 2022). Such knowledge gaps justify (a) the need to assess husk management options (Chapter 4) and (b) the use of a management scoring method in the field trial (Chapter 5). Moreover, applying GAPs may not be economically viable or feasible to smallholder farmers (Srisopaporn et al. 2015; Veisi et al. 2021; Woittiez 2019). If ISFM depends on practices which do not ensure maximum returns of scarce resources or bears entry-barriers (Amekawa 2009; Burrell 2011), its adoption will certainly be hampered. The search of an optimum for all resources used at field or farm level is desirable, but likely not associated with the maximum use efficiency of a single resource (N-fertilizer for instance).

6.5.2. Practicing ISFM despite the current knowledge gap

Despite considerable knowledge gaps on cocoa nutrition, there is a growing demand for ISFM recommendations in cocoa to improve current practices (e.g. Nlend-Nkott and Asare 2021). Here, I discuss (a) adequate timing of fertilizer application, (b) increasing land productivity through management based on individual tree performances, (c) management that influences natural processes governing nutrient cycling, and (d) management of cocoa pod husks.

Even if we lack precise knowledge of the cocoa tree growth curve, it is likely that nutrient requirements are largest during the establishment period and soon after during a period of active vegetative growth

(Thong and Ng 1980; Snoeck et al. 2016). Therefore, moderate application of fertilizers at this stage could stimulate root growth and soil exploration, preparing the tree to express subsequently large nutrient demand. On the other hand, it is unknown if and to what extent stronger vegetative growth during the establishment phase may affect cocoa production in later developmental stages.

An approach to increase nutrient use efficiency at plot level is to reduce nutrient uptake by the least productive trees. In Chapter 5, a large between-tree variability was observed for annual pod production, with approximately 1% of the trees producing no pods over two years. Long-term identification of unproductive and over-productive trees can serve as entry-point for a tree-based management. A simple rule would be to replace the unproductive trees with new cocoa plants or compatible shade-trees or some shade-tolerant crops while maintaining the productivity of the most productive trees (e.g., through moderate nutrient supply, enhanced crop protection).

The ecological significance of litterfall and litter decomposition was demonstrated in nutrient cycling (Chapter 3). Farmers have no control over litterfall *per se*, but what are the implications of ISFM practices on such nutrient flows? Fertilizer application potentially modifies litter chemistry and influences decomposition rates and nutrient release, but its significance depends on initial litter quality, nutrient types, and rates. Both N-inhibition and N-stimulation of soil processes were previously observed in tropical forests (Camenzind et al. 2018; Knorr et al. 2005). In cocoa, in addition to nutrient application rates, fertilizer placement will potentially influence the outcome on soil microbiology and activity. Another practice that could alter cocoa leaf biomass and leaf longevity is pruning, with consequences on above to belowground nutrient flows. Finally, resistant pesticide residues are expected to accumulate in soil (Vaikosen et al. 2019; Afrane and Ntiamoah 2011), but the effects on soil macrofauna are poorly studied, with only negative effects of cuprous oxide fungicides reported on earthworm casts after four years of treatment (Norgrove 2007). The balance between immediate benefits of crop protection and long-term disturbance of soil biota deserves more research to define optimal pesticide application practices.

As shown in Chapter 1 (Figure 1.3), abandonment in heaps and mulching to cocoa trees are the two most common options of managing cocoa pod husks among West African smallholder farmers. A way of improving nutrient cycling proposed in Chapter 4 is to rotate the pod breaking station with sequential mulching of small patches of cocoa trees. This option would improve K recycling with little additional labour cost; however, the trade-offs between nutrient recycling and disease spread would remain unaddressed (Chapter 2). The decision to recycle nutrients contained in pod husks (e.g. through mulching) can only be taken when risks of black pod disease spread are minimized. There are other options of managing cocoa pod husks, each with its trade-offs. For instance, incineration involves unavoidable N losses (Menzies and Gillman 2003; Kauffman et al. 1993; Kuhlbusch et al. 1991), reduction of P bioavailability in the ashes (Pesonen et al. 2017; Sharifi et al. 2013), and greenhouse gas (GHG) emissions (N'Dri et al. 2018; Keywood et al. 2011), but the ashes are a local ingredient in cosmetics. Cocoa pod husk application to other crops or use as animal feed represents a model of system integration with on-farm nutrient transfers, which often implies some losses during handling and additional labour costs. When offtakes occur, it is important to compensate for the loss of nutrients in the cocoa fields which must be ensured at the farm level. Balancing nutrient budgets in cocoa fields is the key to prevent land degradation in the long-term through nutrient mining.

6.6. Options for sustainable intensification in cocoa

Sustainable intensification, defined as a means to increase yields in an environmentally-friendly way (Pretty and Bharucha 2014), has become a commonly accepted goal for agricultural development in SSA (Schut and Giller 2020; Petersen and Snapp 2015; Vanlauwe et al. 2014). Sustainable intensification can also be achieved through a reduced environmental impact (e.g. lower use of agrochemicals) even if levels of outputs (yields, revenues) are maintained (Heidenreich et al. 2022). A third path to sustainable intensification in cocoa is to increase socio-ecological benefits (e.g., resilience to shocks and stresses, increased biodiversity, income diversification) including “total system yields” even at current levels of input-output ratios for cocoa production. Planting timber trees or fruit trees in a full-sun cocoa without severe cocoa yield decrease falls under the latter path (e.g., Niether et al. 2020; Niether et al. 2019). Therefore, objectives must clearly be specified when sustainable intensification is considered in cocoa.

Following Pretty and Bharucha’s (2014) definition, ISFM was selected by the CocoaSoils programme as the pathway to sustainable cocoa intensification, as it proved to be effective in various other cropping systems (Timsina 2019; Pypers et al. 2011; Bayu 2020). Nutrient supply is not always conducive to immediate yield increase in existing smallholder farms (Chapter 5). Nevertheless, nutrient mining is undesirable but prevails in traditional cocoa farms. The extent to which mining threatens production remains questionable given the large internal nutrient flows compared to offtakes in low-output systems (approximately 10 kg N ha^{-1}, 2 kg P ha^{-1} and 5 kg K ha^{-1} for 500 kg cocoa beans), the soil nutrient supply through mineral weathering, and the unevaluated changes in nutrient bioavailability under trees (Liu et al. 2017; Yang et al. 2020). While biogeochemical nutrient cycles are still poorly understood in cocoa, a cautious measure of sustainability (third path) is to replenish offtakes knowing that major tropical soils under cocoa cultivation, i.e. Ferralsols and Acrisols (Bationo et al. 2012a), are typically strongly weathered, and soil capital is limited and often already deteriorated. Building up soil capital can require additional nutrients, depending on the extent at which nutrient losses to the environment are prevented.

Beside poor nutrition, other factors are responsible for low cocoa yields: in Chapter 5, black pod disease incidence on harvested pods in control plots was estimated at 17 and 10% in 2020 and 2021, respectively. Reducing this incidence to e.g., 5% would have contributed to yield improvement, even in absence of fertilizer application. As ISFM focuses on maximizing nutrient use efficiency, Integrated Pest Management (IPM) aims at an efficient use of pesticides. In addition to yield increase, there are clear concerns to reduce environmental and health costs (Aidoo et al. 2019). In cocoa, the emphasis has been on the use of biopesticides (Dormon et al. 2007), the adequate use of synthetic pesticides (Adu-Acheampong et al. 2014), as well as the combination of several methods (Guastella et al. 2017) to control main pests. Understanding the spatial and temporal dynamics of major pests and diseases is still in its infancy (Ndoungue Djeumekop et al. 2021), but is required to develop effective early-warning systems. The profitability of cocoa production and impact on the environment of ISFM or IPM practices will need to be assessed (Scudder et al. 2022). Other paths to sustainable cocoa intensification include rehabilitation of existing plantations, optimizing cocoa agroforestry systems, and value-chain based system transformation.

A major sustainability issue faced by the global cocoa industry is deforestation intertwined with poverty. A strategy to limit deforestation in cocoa production areas is to prevent crop expansion by increasing productivity of existing plantations (land sparing). But as yields increase, the crop becomes more profitable, and farmers are likely to expand areas to reap larger benefits (Jevons' paradox). If many farmers can increase their production capacity, there is a risk of over-production that may cause price collapse, and disincentivize production. Loss of interest in production, characterized by poor maintenance and abandonment, will again create shortage and another boom-bust cycle. On the other hand, cocoa agroforestry systems are proposed to increase biodiversity and ecosystem services on farmland (land sharing). It is unclear whether and under what circumstances cocoa yields are improved under agroforestry systems, but benefits associated with maintaining economic shade-trees (e.g., timber or fruit trees) has often outweighed incomes from full-sun in comparative studies (Niether et al. 2020). The on-farm diversification pathway (intercropping) may leave less room for cocoa yield improvement, as resources (e.g. land, labour, nutrients) are utilized to produce other goods than cocoa beans (Aboah and Setsoafia 2022). Synergies between tree species can also be beneficial to cocoa production if shade-trees are kept at reasonable density. It has been suggested that the optimum canopy cover of shade-trees cannot realistically exceed 30% without impeding productivity, biodiversity conservation and/or adaptation to climate change (Blaser et al. 2018). Even if yields of cocoa are reduced in cocoa agroforestry systems, the total economic and ecological benefits often outweigh that of monocrop, especially when the associated trees are carefully selected (Asitoakor et al. 2022; Blaser-Hart et al. 2021; Notaro et al. 2021) and the farm design is optimized.

Another intensification pathway for old unproductive cocoa plantations is rehabilitation whereby production capacity of old cocoa trees is enhanced (Riedel et al. 2019; Yaconnelo-Hernandez et al. 2021). Rehabilitation is opposed to renovation which entails a complete replanting of cocoa (Somarriba et al. 2021) either at once or in sequence. At a regional scale, promoting speciality cocoa for a niche market (e.g., fine flavour cocoa) is viewed as a path to sustainable intensification (Tscharntke et al. 2022). There are sustainable intensification options that focus on on-farm and off-farm diversification to improve the livelihood portfolio, spread labour and risks, and secure additional financial resources for cocoa farming (van Vliet et al. 2021). An emerging idea in line with the land sparing strategy is to discourage inefficient cocoa production by raising entry-barriers so that fewer producers may continue operating efficiently to meet market needs (quantity and quality). For instance, in Côte d'Ivoire, distribution of improved cocoa varieties at no cost to farmers has been suspended. All these pathways are associated with long-term and multifaceted decisions determined by social and economic aspects of the farmers (Toledo-Hernandez et al. 2021) and the enabling environment (Effendy et al. 2019).

6.7. Concluding remarks

The potential of ISFM to boost cocoa yields is not obvious in current smallholder West African farms. First of all, interpretation of the core principle of integration of mineral and organic fertilizers must be adapted to the characteristics of the tree crop system to ensure meaningful implementation. Second, nutrient cycling which is central to ISFM in cocoa depends on both natural processes (including litterfall) and farming practices such as pruning and pod husk management. Finally, nutrient addition to the system is required as a sustainability measure, but fertilizer application is not the first action that guarantees short-term yield increase in south-western Nigeria.

The use of unimproved germplasms, heterogeneous soils and climates, unevaluated legacy effects, varying management practices, and the large ignorance of their respective limits to crop nutrient demand currently prevent formulation of fertilizer recommendations to smallholder farmers operating similar cocoa production systems. Past field experiments (Fageria 2007) were often poorly designed and studies lacked analytical tools to disentangle the various confounding effects. Controlled experiments are urgently needed to identify overarching mechanisms that can inform modelling work to advance understanding of cocoa nutrition.

Sustainability of cocoa production can readily be improved by moderate nutrient supply to compensate offtakes, but not with the promise of a systematic yield increase in the short term. When positive fertilizer response is observed, long-term nutrient management should account for effects on major C and nutrient cycles. Internal nutrient flows can additionally be altered through pruning and cocoa pod husk management but need careful consideration of the implications to broader crop management and farm resource availability. Even when nature-inclusive cocoa farming provides ecological benefits to the society, it will further need to demonstrate direct benefits to farmers (Tennhardt et al. 2022) or will need to be incentivized, calling for careful policies.

Alternative paths to ISFM deserve further research efforts to precede or complement balanced cocoa nutrition. Such alternatives in the current production systems include IPM, rehabilitation, and income-oriented agroforestry. The prospect of complete implementation of ISFM in cocoa can only be realized in the future. In order to achieve zero deforestation in the sector, agronomy of cocoa replanting and new cocoa planting on previous farmland must be considered for the next generation of cocoa farms. Key issues to address under the cocoa replanting scheme will include management of old tree stumps, management of soil organic matter during periods of bare soil and open canopy, avoidance of pest build-up, and livelihood transition options. In case of cocoa planting on previous farmland, implications to food security must further be considered.

References

Abatzoglou JT, Dobrowski SZ, Parks SA, Hegewisch KC (2018) TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958-2015. Sci Data 5:170191. doi:10.1038/sdata.2017.191

Abdulai I, Hoffmann MP, Jassogne L, Asare R, Graefe S, Tao H-H, Muilerman S, Vaast P, Van Asten P, Läderach P, Rötter RP (2020) Variations in yield gaps of smallholder cocoa systems and the main determining factors along a climate gradient in Ghana. Agric Syst 181. doi:10.1016/j.agsy.2020.102812

Abdulai I, Vaast P, Hoffmann MP, Asare R, Jassogne L, Van Asten P, Rotter RP, Graefe S (2017) Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. Glob Chang Biol 24 (1):273-286. doi:10.1111/gcb.13885

Aboah J, Setsoafia ED (2022) Examining the synergistic effect of cocoa-plantain intercropping system on gross margin: A system dynamics modelling approach. Agric Syst 195. doi:10.1016/j.agsy.2021.103301

Abou Rajab Y, Hölscher D, Leuschner C, Barus H, Tjoa A, Hertel D (2018) Effects of shade tree cover and diversity on root system structure and dynamics in cacao agroforests: the role of root competition and space partitioning. Plant Soil 422 (1-2):349-369. doi:10.1007/s11104-017-3456-x

Abou Rajab Y, Leuschner C, Barus H, Tjoa A, Hertel D (2016) Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses. PLoS One 11 (2):e0149949. doi:10.1371/journal.pone.0149949

Acheampong K, Daymond AJ, Adu-Yeboah P, Hadley P (2019) Improving field establishment of cacao (Theobroma cacao) through mulching, irrigation and shading. Exp Agric 55 (6):898-912. doi:10.1017/s0014479718000479

Acheampong K, Hadley P, Daymond A (2013) Photosynthetic activity and early growth of four cacao genotypes as influenced by different shade regimes under West African dry and wet season conditions. Exp Agric 49 (1):31-42

Adamou A, Tabo R, Fatondji D, Hassane O, Bationo A, Adam T (2012) Effect of integrated soil fertility management technologies on the performance of millet in Niger: understanding the processes using simulation. In: Kihara J, Fatondji D, Jones JW, Hoogenboom G, Tabo R, Bationo A (eds) Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer, Dordrecht, pp 101-117. doi:10.1007/978-94-007-2960-5_7

Adebayo ST, Oyawole FP, Sanusi RA, Afolami CA (2021) Technology adoption among cocoa farmers in Nigeria: what drives farmers' decisions? For Trees Livelihoods 31 (1):1-12. doi:10.1080/14728028.2021.2011789

Adeniyi SA, de Clercq WP, van Niekerk A (2018) Assessing the relationship between soil quality parameters of Nigerian alfisols and cocoa yield. Agrofor Syst 93 (4):1235-1250. doi:10.1007/s10457-018-0238-2

Adewale BD, Nduka BA (2020) Genotype and within-pod bean position microenvironment effect on seed choice for raising cocoa (Theobroma cacao L.) seedlings. Acta Agric Slov 115 (2):247-259. doi:10.14720/aas.2020.115.2.1345

Adiyah F, Fuchs M, Michéli E, Dawoe E, Kovács E (2021) 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):714-725. doi:10.5897/ajar2020.15320

Adjin-Tetteh M, Asiedu N, Dodoo-Arhin D, Karam A, Amaniampong PN (2018) Thermochemical conversion and characterization of cocoa pod husks a potential agricultural waste from Ghana. Ind Crops Prod 119:304-312. doi:10.1016/j.indcrop.2018.02.060

Adomako B (2007) Causes and extent of yield losses in cocoa progenies. Trop Sci 47 (1):22-25. doi:10.1002/ts.187

Adu-Acheampong R, Jiggins J, van Huis A, Cudjoe AR, Johnson V, Sakyi-Dawson O, Ofori-Frimpong K, Osei-Fosu P, Tei-Quartey E, Jonfia-Essien W, Owusu-Manu M, Nana Karikari Addo MS, Afari-Mintah C, Amuzu M, Nyarko Eku-X N, Quarshie ETN (2014) The cocoa mirid (Hemiptera: Miridae) problem: evidence to support new recommendations on the timing of insecticide application on cocoa in Ghana. Int J Trop Insect Sci 34 (01):58-71. doi:10.1017/s1742758413000441

Afoakwa EO (2014) Pests and diseases of cocoa. In: Afoakwa EO (ed) Cocoa production and processing technology. CRC Press, Boca Raton, Florida, USA, pp 125-132

Afolabi OO, Muoghalu JI (2018) Effect of pesticides on microorganisms involved in litter decomposition in cacao plantation in Ile-Ife, Nigeria. Agrofor Syst 92:511-524. doi:10.1007/s10457-016-0032-y

Afrane G, Ntiamoah A (2011) Use of pesticides in the cocoa industry and their impact on the environment and the food chain. Pesticides in the modern world-risks and benefits InTech:51-68

Agbeniyi SO, Oluyole KA, Ogunlade MO (2011) Impact of cocoa pod husk fertilizer on cocoa production in Nigeria. World J Agric Sci 7 (2):113-116

Agegnehu G, Amede T (2017) Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: A review. Pedosphere 27 (4):662-680. doi:10.1016/s1002-0160(17)60382-5

Agele S, Famuwagun B, Ogunleye A (2016) Effects of shade on microclimate, canopy characteristics and light integrals in dry season field-grown cocoa (Theobroma cacao L.) seedlings. J Hortic Sci 11 (1):47-56

Aggangan NS, Cortes AD, Opulencia RB, Jomao-as JG, Yecyec RP (2019a) Effects of mycorrhizal fungi and bamboo biochar on the rhizosphere bacterial population and nutrient uptake of cacao (Theobroma cacao L.) Seedlings. Philippine Journal of Crop Science (PJCS) 44 (1):1-9

Aggangan NS, Cortes AD, Reaño CE (2019b) Growth response of cacao (Theobroma cacao L.) plant as affected by bamboo biochar and arbuscular mycorrhizal fungi in sterilized and unsterilized soil. Biocatal Agric Biotechnol 22:101347. doi:10.1016/j.bcab.2019.101347

Agren GI, Wetterstedt JAM, Billberger MFK (2012) Nutrient limitation on terrestrial plant growth-modeling the interaction between nitrogen and phosphorus. New Phytol 194 (4):953-960. doi:10.1111/j.1469-8137.2012.04116.x

Ahenkorah Y, Halm BJ, Appiah MR, Akrofi GS Fertilizer use on cacao rehabilitation projects in Ghana. In: 8th International Cocoa Research Conference, Cartagena, Colombia, 18-23 Oct 1981. Cocoa Producers' Alliance, pp 165-170

Ahenkorah Y, Halm BJ, Appiah MR, Akrofi GS, Yirenkyi JEK (1987) Twenty years' results from a shade and fertilizer trial on Amazon cocoa (Theobroma cacao) in Ghana. Exp Agric 23 (1):31-39

Aidoo AK, Arthur S, Bolfrey-Arkur G, Mochiah BM (2019) Pesticides abuse and health implications in Ghana: a review. Int J Environ Agric Biotechnol 4 (3):874-883. doi:10.1302/2046-3758.43.2000339

Akinnifesi FK, Makumba W, Sileshi G, Ajayi OC, Mweta D (2007) Synergistic effect of inorganic N and P fertilizers and organic inputs from Gliricidia sepium on productivity of intercropped maize in Southern Malawi. Plant Soil 294 (1):203-217. doi:10.1007/s11104-007-9247-z

Akrofi-Atitianti F, Ifejika Speranza C, Bockel L, Asare R (2018) Assessing climate smart agriculture and its determinants of practice in Ghana: a case of the cocoa production system. Land 7 (1). doi:10.3390/land7010030

Alagele SM, Jose S, Anderson SH, Udawatta RP (2021) Hydraulic lift: processes, methods, and practical implications for society. Agrofor Syst 95 (4):641-657. doi:10.1007/s10457-021-00614-w

Alfaro-Flores A, Morales-Belpaire I, Schneider M (2015) Microbial biomass and cellulase activity in soils under five different cocoa production systems in Alto Beni, Bolivia. Agrofor Syst 89 (5):789-798. doi:10.1007/s10457-015-9812-z

Ali EB, Awuni JA, Danso-Abbeam G, Yildiz F (2018) Determinants of fertilizer adoption among smallholder cocoa farmers in the Western Region of Ghana. Cogent Food Agric 4 (1). doi:10.1080/23311932.2018.1538589

Amekawa Y (2009) Reflections on the growing influence of good agricultural practices in the global south. J Agric Environ Ethics 22 (6):531-557. doi:10.1007/s10806-009-9171-8

Amon-Armah F, Domfeh O, Baah F, Owusu-Ansah F (2021) Farmers’ adoption of preventive and treatment measures of cocoa swollen shoot virus disease in Ghana. J Agric Food Res 3. doi:10.1016/j.jafr.2021.100112

Amponsah-Doku B, Daymond A, Robinson S, Atuah L, Sizmur T (2022) Improving soil health and closing the yield gap of cocoa production in Ghana – A review. Sci Afr 15. doi:10.1016/j.sciaf.2021.e01075

Anda M, Shamshuddin J, Fauziah CI (2013) Increasing negative charge and nutrient contents of a highly weathered soil using basalt and rice husk to promote cocoa growth under field conditions. Soil Tillage Res 132:1-11. doi:10.1016/j.still.2013.04.005

Anderson JM, Ingram JSI (1993) Tropical soil biology and fertility: a handbook of methods. 2nd edn. CABI, Wallingford, Oxfordshire, UK

Andivia E, Vázquez-Piqué J, Fernández M, Alejano R (2012) Litter production in Holm oak trees subjected to different pruning intensities in Mediterranean dehesas. Agrofor Syst 87 (3):657-666. doi:10.1007/s10457-012-9586-5

Aneani F, Ofori-Frimpong K (2013) An analysis of yield gap and some factors of cocoa (Theobroma cacao) yields in Ghana. Sustain Agric Res 2 (4):117-127. doi:10.5539/sar.v2n4p117

Anten NPR, Ackerly DD (2001) Canopy-level photosynthetic compensation after defoliation in a tropical understorey palm. Funct Ecol 15 (2):252-262

Appiah MR, Sackey ST, Ofori-Frimpong K, Afrifa AA (1997) The consequences of cocoa production on soil fertility in Ghana: a review. Ghana J Agric Sci 30 (2):183-190

Aranguren J, Escalante G, Herrera R (1982) Nitrogen cycle of tropical perennial crops under shade trees. Plant Soil 67 (1):259-269. doi:10.1007/BF02182773

Arnholt AT, Evans B (2017) BSDA: basic statistics and data analysis. R package version 1.2.0.

Arthur A, Acquaye S, Cheng W, Dogbatse JA, Konlan S, Domfeh O, Quaye AK (2022) Soil carbon stocks and main nutrients under cocoa plantations of different ages. Soil Sci Plant Nutr 68 (1):99-103. doi:10.1080/00380768.2022.2029219

Asante PA, Rahn E, Zuidema PA, Rozendaal DMA, van der Baan MEG, Läderach P, Asare R, Cryer NC, Anten NPR (2022) The cocoa yield gap in Ghana: a quantification and an analysis of factors that could narrow the gap. Agric Syst 201. doi:10.1016/j.agsy.2022.103473

Asante PA, Rozendaal DMA, Rahn E, Zuidema PA, Quaye AK, Asare R, Läderach P, Anten NPR (2021) Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana. Agric Syst 193. doi:10.1016/j.agsy.2021.103214

Asante WA, Acheampong E, Kyereh E, Kyereh B (2017) Farmers' perspectives on climate change manifestations in smallholder cocoa farms and shifts in cropping systems in the forest-savannah transitional zone of Ghana. Land Use Policy 66:374-381. doi:10.1016/j.landusepol.2017.05.010

Asare R, Asare RA, Asante WA, Markussen BO, Raebild A (2017) Influences of shading and fertilization on on-farm yields of cocoa in Ghana. Exp Agric 53 (3):416-431

Asare R, David S (2011) Good agricultural practices for sustainable cocoa production: A guide for farmer training. Manual no 1: Planting, replanting and tree diversification in cocoa systems. Forest & Landscape Denmark - University of Copenhagen, Copenhagen

Ashiagbor G, Asante WA, Forkuo EK, Acheampong E, Foli E (2022) Monitoring cocoa-driven deforestation: The contexts of encroachment and land use policy implications for deforestation free cocoa supply chains in Ghana. Appl Geogr 147. doi:10.1016/j.apgeog.2022.102788

Asigbaase M, Dawoe E, Lomax BH, Sjogersten S (2021a) Biomass and carbon stocks of organic and conventional cocoa agroforests, Ghana. Agric Ecosyst Environ 306. doi:10.1016/j.agee.2020.107192

Asigbaase M, Dawoe E, Lomax BH, Sjogersten S (2021b) Temporal changes in litterfall and potential nutrient return in cocoa agroforestry systems under organic and conventional management, Ghana. Heliyon 7 (10):e08051. doi:10.1016/j.heliyon.2021.e08051

Asigbaase M, Dawoe E, Sjogersten S, Lomax BH (2021c) Decomposition and nutrient mineralisation of leaf litter in smallholder cocoa agroforests: a comparison of organic and conventional farms in Ghana. J Soils Sediments 21 (2):1010-1023. doi:10.1007/s11368-020-02844-4

Asitoakor BK, Vaast P, Ræbild A, Ravn HP, Eziah VY, Owusu K, Mensah EO, Asare R (2022) Selected shade tree species improved cocoa yields in low-input agroforestry systems in Ghana. Agric Syst 202. doi:10.1016/j.agsy.2022.103476

Ayeni LS (2011) Integrated plant nutrition management: a panacea for sustainable crop production in Nigeria. Int J Soil Sci 6 (1):19-24

Baah F, Anchirinah VM, Amon-Armah F (2011) Soil fertility management practices of cocoa farmers in the Eastern Region of Ghana. Agriculture and Biology Journal of North America 2:173-181

Bado VB, Bationo A (2018) Integrated management of soil fertility and land resources in sub-saharan Africa: involving local communities. Adv Agron 150:1-33. doi:10.1016/bs.agron.2018.02.001

Bai SH, Gallart M, Singh K, Hannet G, Komolong B, Yinil D, Field DJ, Muqaddas B, Wallace HM (2022) Leaf litter species affects decomposition rate and nutrient release in a cocoa plantation. Agric Ecosyst Environ 324. doi:10.1016/j.agee.2021.107705

Bai SH, Trueman SJ, Nevenimo T, Hannet G, Bapiwai P, Poienou M, Wallace HM (2017) Effects of shade-tree species and spacing on soil and leaf nutrient concentrations in cocoa plantations at 8 years after establishment. Agric Ecosyst Environ 246:134-143. doi:10.1016/j.agee.2017.06.003

Bailey BA, Meinhardt LW (eds) (2016) Cacao diseases: a history of old enemies and new encounters. Springer, Cham, Switzerland. doi:10.1007/978-3-319-24789-2

Bairagi S, Mishra AK, Giri A (2018) Good agricultural practices, farm performance, and input usage by smallholders: empirical evidence from Nepal. Agribusiness 35 (3):471-491. doi:10.1002/agr.21577

Balasimha D, Daniel EV, Bhat PG (1991) Influence of environmental factors on photosynthesis in cocoa trees. Agric For Meteorol 55 (1):15-21. doi:10.1016/0168-1923(91)90019-M

Baligar VC, Fageria NK (2005) Soil aluminum effects on growth and nutrition of cacao. Soil Sci Plant Nutr 51 (5):709-713. doi:10.1111/j.1747-0765.2005.tb00097.x

Bar A, Michaletz ST, Mayr S (2019) Fire effects on tree physiology. New Phytol 223 (4):1728-1741. doi:10.1111/nph.15871

Bargaz A, Lyamlouli K, Chtouki M, Zeroual Y, Dhiba D (2018) Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. Front Microbiol 9:1606. doi:10.3389/fmicb.2018.01606

Barima YSS, Kouakou ATM, Bamba I, Sangne YC, Godron M, Andrieu J, Bogaert J (2016) Cocoa crops are destroying the forest reserves of the classified forest of Haut-Sassandra (Ivory Coast). Glob Ecol Conserv 8:85-98. doi:10.1016/j.gecco.2016.08.009

Barnes P, Wilson BR, Reid N, Koen TB, Lockwood P, Lamb DW (2011) Litterfall and associated nutrient pools extend beyond the canopy of scattered eucalypt trees in temperate pastures. Plant Soil 345 (1):339-352

Barreto PAB, Gama-Rodrigues EF, Gama-Rodrigues AC, Fontes AG, Polidoro JC, Moço MKS, Machado RCR, Baligar VC (2011) Distribution of oxidizable organic C fractions in soils under cacao agroforestry systems in Southern Bahia, Brazil. Agrofor Syst 81 (3):213-220. doi:10.1007/s10457-010-9300-4

Bationo A, Hartemink A, Lungu O, Naimi M, Okoth P, Smaling E, Thiombiano L, Waswa B (2012a) Knowing the African soils to improve fertilizer recommendations. In: Kihara J, Fatondji D, Jones JW, Hoogenboom G, Tabo R, Bationo A (eds) Improving soil fertility recommendations in Africa using the decision support system for agrotechnology transfer (DSSAT). Springer, Dordrecht, pp 19-42. doi:10..1007/978-94-007-2960-5

Bationo A, Waswa B, Abdou A, Bado BV, Bonzi M, Iwuafor E, Kibunja C, Kihara J, Mucheru M, Mugendi D (2012b) Overview of long term experiments in Africa. In: Bationo A, Waswa B, Kihara J, Adolwa I, Vanlauwe B, Saidou K (eds) Lessons learned from long-term soil fertility management experiments in Africa. Springer, Dordrecht, pp 1-26

Bationo A, Waswa B, Kihara J, Kimetu J (2007) Advances in integrated soil fertility management in sub Saharan Africa: challenges and opportunities. Nutr Cycl Agroecosystems 77:1-2

Bayu T (2020) Review on contribution of integrated soil fertility management for climate change mitigation and agricultural sustainability. Cogent Environ Sci 6 (1):1823631

Beer J (1988) Litter production and nutrient cycling in coffee (Coffea arabica) or cacao (Theobroma cacao) plantations with shade trees. Agrofor Syst 7 (2):103-114

Beer J, Bonnemann A, Chávez W, Fassbender HW, Imbach AC, Martel I (1990) Modelling agroforestry systems of cacao (Theobroma cacao) with laurel (Cordia alliodora) or poro (Erythrina poeppigiana) in Costa Rica. 5 Productivity indices, organic material models and sustainability over ten years. Agrofor Syst 12 (3):229-249

Bekele F, Phillips-Mora W (2019) Cacao (Theobroma cacao L.) breeding. In: Al-Khayri JM, Jain SM, Johnson DV (eds) Advances in plant breeding strategies: industrial and food crops. Springer, Cham, pp 409-487

Bekunda M, Odhong J, Hoeschle-Zeledon I (2022) Combining multiple technologies: integrated soil fertility management. In: Bekunda M, Odhong J, Hoeschle-Zeledon I (eds) Sustainable agricultural intensification: a handbook for practitioners in east and southern Africa. CABI, pp 134-144. doi:10.1079/9781800621602.0010

Benoit M, Veysset P (2021) Livestock unit calculation: a method based on energy requirements to refine the study of livestock farming systems. INRAE Productions Animales. doi:10.20870/productions-animales.2021.34.2.4855

Berg Br, McClaugherty C (2014) Plant litter : decomposition, humus formation, carbon sequestration. Third edition. edn. Springer, Heidelberg. doi:10.1007/978-3-642-38821-7

Bernal MP, Alburquerque JA, Moral R (2009) Composting of animal manures and chemical criteria for compost maturity assessment. A review. Bioresour Technol 100 (22):5444-5453. doi:10.1016/j.biortech.2008.11.027

Blaser-Hart WJ, Hart SP, Oppong J, Kyereh D, Yeboah E, Six J (2021) The effectiveness of cocoa agroforests depends on shade-tree canopy height. Agric Ecosyst Environ 322. doi:10.1016/j.agee.2021.107676

Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J (2018) Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat Sustain 1 (5):234-239. doi:10.1038/s41893-018-0062-8

Blesh J, Isaac ME, Schipanski ME, Vanek SJ (2022) Editorial: ecological nutrient management as a pathway to zero hunger. Front Sustain Food Syst 6. doi:10.3389/fsufs.2022.1079973

Borden KA, Anglaaere LCN, Adu-Bredu S, Isaac ME (2019) Root biomass variation of cocoa and implications for carbon stocks in agroforestry systems. Agrofor Syst 93 (2):369-381. doi:10.1007/s10457-017-0122-5

Boroughs H, Bornemisza E, da Silva Cardoso A (1963) The foliar absorption by cacao of P32-labelled sodium, potassium, and ammonium phosphate as influenced by pH. Plant Soil 19 (2):241-248

Brant AN, Chen HYH (2015) Patterns and mechanisms of nutrient resorption in plants. Critical Reviews in Plant Sciences 34 (5):471-486. doi:10.1080/07352689.2015.1078611

Bray RH, Kurtz LT (1945) Determination of total, organic, and available forms of phosphorus in soils. Soil Sci 59 (1):39-46

Brobbey LK, Agyei FK, Osei-Tutu P (2020) Drivers of cocoa encroachment into protected forests: the case of three forest reserves in Ghana. Int For Rev 22 (4):425-437. doi:10.1505/146554820831255533

Brunetti G, Traversa A, De Mastro F, Cocozza C (2019) Short term effects of synergistic inorganic and organic fertilization on soil properties and yield and quality of plum tomato. Sci Hortic 252:342-347. doi:10.1016/j.scienta.2019.04.002

Bruulsema T, Cakmak I, Dobermann A, Gerard B, Majumdar K, McLaughlin M, Reidsma P, Vanlauwe B, Wollenberg E, Zhang F (2022) Furthering 4R nutrient stewardship. Issue Brief 03, Paris

Bruulsema TW, Peterson HM, Prochnow LI (2019) The science of 4R nutrient stewardship for phosphorus management across latitudes. J Environ Qual 48 (5):1295-1299. doi:10.2134/jeq2019.02.0065

Bunn C, Lundy M, Läderach P, Castro F (2017) Global climate change impacts on cocoa. Paper presented at the International Symposium on Cocoa Research, Lima, Peru, 13-17 November 2017

Burrell A (2011) ‘Good agricultural practices’ in the agri-food supply chain. Environ Law Rev 13 (4):251-270

Bymolt R, Laven A, Tyzler M (2018a) Demystifying the cocoa sector in Ghana and Côte d’Ivoire. The Royal Tropical Institute (KIT), Amsterdam

Bymolt R, Laven A, Tyzler M (2018b) Production and yield. In: Bymolt R, Laven A, Tyzler M (eds) Demystifying the cocoa sector in Ghana and Côte d'Ivoire. The Royal Tropical Institute (KIT), Amsterdam, pp 195-206

Caliman J-P, Berthaud A, Dubos B, Tailliez B (2005) Agronomy, sustainability and good agricultural practices. Oléagineux, Corps gras, Lipides 12 (2):134-140. doi:10.1051/ocl.2005.0134

Caliman J-P, Budi M, Salètes S (2001) Dynamics of nutrient release from empty fruit bunches in field conditions and soil characteristics changes. In: Proceedings of the 2001 PIPOC International Palm Oil Congress, Bangi, 20-25 August 2001. MPOB, pp 550-556

Callesen I, Harrison R, Stupak I, Hatten J, Raulund-Rasmussen K, Boyle J, Clarke N, Zabowski D (2016) Carbon storage and nutrient mobilization from soil minerals by deep roots and rhizospheres. For Ecol Manag 359:322-331. doi:10.1016/j.foreco.2015.08.019

Calonego JC, Foloni JSS, Rosolem CA (2005) Potassium leaching from plant cover straw at different senescence stages after chemical desiccation. Revista Brasileira de Ciência do Solo 29 (1):99-108. doi:10.1590/S0100-06832005000100011

Calvo Romero F (2018) Biomass and nutrient distribution in cacao trees (Theobroma cacao): a case study in Cote d'Ivoire. Wageningen University and Research, Wageningen

Camenzind T, Hättenschwiler S, Treseder KK, Lehmann A, Rillig MC (2018) Nutrient limitation of soil microbial processes in tropical forests. Ecol Monogr 88 (1):4-21

Campos-Vega R, Nieto-Figueroa KH, Oomah BD (2018) Cocoa (*Theobroma cacao* L.) pod husk: renewable source of bioactive compounds. Trends in Food Science & Technology 81:172-184. doi:10.1016/j.tifs.2018.09.022

Carodenuto S, Buluran M (2021) The effect of supply chain position on zero-deforestation commitments: evidence from the cocoa industry. J Environ Policy Plan 23 (6):716-731. doi:10.1080/1523908x.2021.1910020

Carr MKV, Lockwood G (2011) The water relations and irrigation requirements of cocoa (Theobroma cacao L.): A review. Exp Agric 47 (4):653-676. doi:10.1017/s0014479711000421

Castro-Nunez A, Charry A, Castro-Llanos F, Sylvester J, Bax V (2020) Reducing deforestation through value chain interventions in countries emerging from conflict: the case of the Colombian cocoa sector. Appl Geogr 123. doi:10.1016/j.apgeog.2020.102280

Cavalli E, Lange A, Cavalli C, Behling M (2018) Decomposition and release of nutrients from crop residues on soybean-maize cropping systems. Revista Brasileira de Ciências Agrárias, 13:8. doi:10.5039/agraria.v13i2a5527

Centenaro G, Hudek C, Zanella A, Crivellaro A (2018) Root-soil physical and biotic interactions with a focus on tree root systems: A review. Appl Soil Ecol 123:318-327. doi:10.1016/j.apsoil.2017.09.017

Cerda R, Deheuvels O, Calvache D, Niehaus L, Saenz Y, Kent J, Vilchez S, Villota A, Martinez C, Somarriba E (2014) Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. Agrofor Syst 88 (6):957-981. doi:10.1007/s10457-014-9691-8

Chamberlin J, Jayne TS, Headey D (2014) Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. Food Policy 48:51-65. doi:10.1016/j.foodpol.2014.05.002

Chang JV, Cano CJM, Pacheco MBS (2021) Effect of pruning intensities on National and Trinitary cocoa established with three propagation methods. Revista Colombiana de Investigaciones Agroindustriales 8 (1):1-10

Chapin FS, Schulze ED, Mooney HA (1990) The ecology and economics of storage in plants. Annu Rev Ecol Syst 21 (1):423-447

Chatzistathis T, Kavvadias V, Sotiropoulos T, Papadakis IE (2021) Organic fertilization and tree orchards. Agriculture 11 (8). doi:10.3390/agriculture11080692

Chemura A (2014) The growth response of coffee (Coffea arabica L) plants to organic manure, inorganic fertilizers and integrated soil fertility management under different irrigation water supply levels. Int J Recycl Org Waste Agric 3 (2):1-9. doi:10.1007/s40093-014-0059-x

Chianu JN, Chianu JN, Mairura F (2012) Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agron Sustain Dev 32 (2):545-566. doi:10.1007/s13593-011-0050-0

Chinnappan S (2021) DRIS norms for identifying yield limiting micronutrients in cocoa under coconut intercropping systems. J Plant Nutr:1-9. doi:10.1080/01904167.2021.1994592

Chivenge P, Vanlauwe B, Six J (2010) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant Soil 342 (1-2):1-30. doi:10.1007/s11104-010-0626-5

Cho H, Kim M, Tripathi B, Adams J (2017) Changes in soil fungal community structure with increasing disturbance frequency. Microb Ecol 74 (1):62-77. doi:10.1007/s00248-016-0919-1

Cilas C, Bastide P (2020) Challenges to cocoa production in the face of climate change and the spread of pests and diseases. Agronomy 10 (9). doi:10.3390/agronomy10091232

Clough Y, Faust H, Tscharntke T (2009) Cacao boom and bust: sustainability of agroforests and opportunities for biodiversity conservation. Conserv Lett 2 (5):197-205. doi:10.1111/j.1755-263X.2009.00072.x

Coe SD, Coe MD (2013) The true history of chocolate. 3rd edn. Thames & Hudson, London

Cook DA (2019) Systematic and nonsystematic reviews: choosing an approach. In: Nestel D, Hui J, Kunkler K, Scerbo M, Calhoun A (eds) Healthcare simulation research. pp 55-60. doi:10.1007/978-3-030-26837-4_8

Cudjoe AR, Clottey EA, Wiafe WM, Akrofi A, Abu SI, Aboagye-Frimpong O, Adu-Gyamfi M (2016) Manual for cocoa extension in Ghana. COCOBOD-CHED-USAID-WCF-IDH, Accra, Ghana

Cusack DF, Chou WW, Yang WH, Harmon ME, Silver WL (2009) Controls on long-term root and leaf litter decomposition in neotropical forests. Glob Chang Biol 15 (5):1339-1355. doi:10.1111/j.1365-2486.2008.01781.x

da Silva Moço MK, da Gama-Rodrigues EF, da Gama-Rodrigues AC, Machado RCR, Baligar VC (2009) Soil and litter fauna of cacao agroforestry systems in Bahia, Brazil. Agrofor Syst 76 (1):127-138. doi:10.1007/s10457-008-9178-6

Dand R (2011) Agronomics of international cocoa production. In: Dand R (ed) The International Cocoa Trade. pp 23-64. doi:10.1016/b978-0-85709-125-3.50002-1

Dane JH, Topp GC, Campbell GS, Al-Amoodi L, Dick WA (2002) Methods of soil analysis Pt.4, Physical methods. Soil Science Society of America books series ; 5-4. Soil Science Society of America, Madison

Danso-Abbeam G, Baiyegunhi LJS (2019) Technical efficiency and technology gap in Ghana's cocoa industry: accounting for farm heterogeneity. Appl Econ 52 (1):100-112. doi:10.1080/00036846.2019.1644439

Dawoe EK, Barnes VR, Oppong SK (2017) Spatio-temporal dynamics of gross rainfall partitioning and nutrient fluxes in shaded-cocoa (Theobroma cocoa) systems in a tropical semi-deciduous forest. Agrofor Syst. doi:10.1007/s10457-017-0108-3

Dawoe EK, Isaac ME, Quashie-Sam J (2010) Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana. Plant Soil 330 (1-2):55-64. doi:10.1007/s11104-009-0173-0

Dawoe EK, Quashie-Sam J, Isaac ME, Oppong SK (2012) Exploring farmers' local knowledge and perceptions of soil fertility and management in the Ashanti Region of Ghana. Geoderma 179-180:96-103. doi:10.1016/j.geoderma.2012.02.015

Dawoe EK, Quashie-Sam JS, Oppong SK (2014) 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):87-99. doi:10.1007/s10457-013-9658-1

Dawson N, Martin A, Sikor T (2016) Green revolution in sub-Saharan Africa: Implications of imposed innovation for the wellbeing of rural smallholders. World Dev 78:204-218. doi:10.1016/j.worlddev.2015.10.008

Daymond A, Giraldo Mendez D, Hadley P, Bastide P (eds) (2022) A global review of cocoa farming systems. ICCO - Swiss foundation of the cocoa and chocolate economy, Reading

Daymond AJ, Hadley P, Machado RCR, Ng E (2002) Genetic variability in partitioning to the yield component of cacao (Theobroma cacao L.). HortScience 37 (5):799-801

Daymond AJ, Prawoto A, Abdoellah S, Susilo AW, Cryer NC, Lahive F, Hadley P (2020) Variation in Indonesian cocoa farm productivity in relation to management, environmental and edaphic factors. Exp Agric 56 (5):738-751. doi:10.1017/s0014479720000289

de Almeida J, Herrera A, Tezara W (2018) Phenotypic plasticity to photon flux density of physiological, anatomical and growth traits in a modern Criollo cocoa clone. Physiol Plant 166 (3):821-832

de Groot J (2020) Nutrient distribution in cocoa canopies: investigating foliar nutrient contents of Theobroma cacao in Ivory Coast. Wageningen University and Research, Wageningen

de Roo N, Andersson JA, Krupnik TJ (2017) On-farm trials for development impact? The organisation of research and the scaling of agricultural technologies. Exp Agric 55 (2):163-184. doi:10.1017/s0014479717000382

de Silva PM, Pathiratne A, van Straalen NM, van Gestel CA (2010) Chlorpyrifos causes decreased organic matter decomposition by suppressing earthworm and termite communities in tropical soil. Environ Pollut 158 (10):3041-3047. doi:10.1016/j.envpol.2010.06.032

de Souza Júnior JO, da Silveira FGF, dos Santos RO, Neves JCL (2019) Zinc fertilizers and additives for foliar fertilization of cocoa seedlings. J Agric Sci 11 (1):471-478

de Willigen P, Janssen BH, Heesmans HIM, Conijn JG, Velthof GL, Chardon WJ (2008) Decomposition and accumulation of organic matter in soil; comparison of some models. Wageningen University & Research, Wageningen

Deen-Swarray M, Odularu G, Adekunle B (2020) Introduction: nutrition, sustainable agriculture and climate change issues in Africa. In: Odularu G (ed) Nutrition, Sustainable Agriculture and Climate Change in Africa. Springer, Cham, Switzerland, pp 1-11. doi:10.1007/978-3-030-47875-9_1

Dehejia R, Pop-Eleches C, Samii C (2019) From local to global: External validity in a fertility natural experiment. Journal of Business & Economic Statistics 39 (1):217-243. doi:10.1080/07350015.2019.1639407

Delgado-Ospina J, Molina-Hernandez JB, Chaves-Lopez C, Romanazzi G, Paparella A (2021) The role of fungi in the cocoa production chain and the challenge of climate change. J Fungi (Basel) 7 (3). doi:10.3390/jof7030202

Denkyirah EK, Okoffo ED, Adu DT, Aziz AA, Ofori A, Denkyirah EK (2016) Modeling Ghanaian cocoa farmers' decision to use pesticide and frequency of application: the case of Brong Ahafo Region. Springerplus 5 (1):1113. doi:10.1186/s40064-016-2779-z

Diby L, Kahia J, Kouamé C, Aynekulu E (2017) Tea, coffee, and cocoa. In: Brian T, Brian GM, Denis, J. Murphy (eds) Encyclopedia of Applied Plant Sciences, vol 3. Academic Press, Oxford, UK, pp 420-425. doi:10.1016/b978-0-12-394807-6.00179-9

Dietze MC, Sala A, Carbone MS, Czimczik CI, Mantooth JA, Richardson AD, Vargas R (2014) Nonstructural carbon in woody plants. Annu Rev Plant Biol 65:667-687

Doe EK, Attua EM, Dogbatse JA, Fosu-Mensah BY (2022) Assessing the condition and capability of soils in cocoa districts of Ghana using geovisualization. Soil Security 7. doi:10.1016/j.soisec.2022.100058

Dogbatse JA, Arthur A, Awudzi GK, Quaye AK, Konlan S, Amaning AA, Serrano M (2021) Effects of organic and inorganic fertilizers on growth and nutrient uptake by young cacao (Theobroma cacao L.). Int J Agron 2021:1-10. doi:10.1155/2021/5516928

Dohmen MM, Noponen M, Enomoto R, Mensah C, Muilerman S (2018) Climate-Smart Agriculture in cocoa: a training manual for field officers. World Cocoa Foundation & Rainforest Alliance, Washington & New-York, USA

Dormon ENA, van Huis A, Leeuwis C (2007) Effectiveness and profitability of integrated pest management for improving yield on smallholder cocoa farms in Ghana. Int J Trop Insect Sci 27 (01). doi:10.1017/s1742758407727418

dos Santos EA, de Almeida A-AF, da Silva Branco MC, dos Santos IC, Ahnert D, Baligar VC, Valle RR (2018) Path analysis of phenotypic traits in young cacao plants under drought conditions. PloS one 13 (2):e0191847

Dossa EL, Arthur A, Dogbe W, Mando A, Snoeck D, Afrifa AA, Acquaye S (2018) Improving fertilizer recommendations for cocoa in Ghana based on inherent soil fertility characteristics. In: Bationo A, Ngaradoum D, Youl S, Lompo F, Fening JO (eds) Improving the profitability, sustainability and efficiency of nutrients through site specific fertilizer recommendations in West Africa agro-ecosystems. Springer, Cham, pp 287-299

Doungous O, Minyaka E, Longue EAM, Nkengafac NJ (2018) Potentials of cocoa pod husk-based compost on Phytophthora pod rot disease suppression, soil fertility, and Theobroma cacao L. growth. Environ Sci Pollut Res Int 25:25327-25335. doi:10.1007/s11356-018-2591-0

Drew D, Boal P (2019) For sustainability in cocoa production, both countries and companies need to commit. Accessed 19 January 2023

Drinkwater LE, Snapp SS (2022) Advancing the science and practice of ecological nutrient management for smallholder farmers. Front Sustain Food Syst 6. doi:10.3389/fsufs.2022.921216

Duguma B, Gockowski J, Bakala J (2001) Smallholder cacao (Theobroma cacao Linn.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities. Agrofor Syst 51 (3):177-188

Edwin J, Masters WA (2005) Genetic improvement and cocoa yields in Ghana. Exp Agric 41 (4):491-503. doi:10.1017/s0014479705002887

Edy N, Zakaria EK, Lakani I Forest conversion into cacao agroforestry and cacao plantation change the diversity of arbuscular mycorrhizal fungi. In: 1st Biennial Conference on Tropical Biodiversity, Makassar, Indonesia, 20-21 September 2019. IOP Publishing, p 012015

Effendy, Pratama MF, Rauf RA, Antara M, Basir-Cyio M, Mahfudz, Muhardi (2019) Factors influencing the efficiency of cocoa farms: A study to increase income in rural Indonesia. PLoS One 14 (4):e0214569. doi:10.1371/journal.pone.0214569

Espinosa J, Mite F, Cedeño S, Barriga S, Andino J (2006) GIS-based site-specific management of cocoa. Better Crops 90 (1):36-39

Evans H, Murray DB (1953) A shade and fertilizer experiment on young cacao. Report on cacao research 1945-1951. Imperial College of Tropical Agriculture, St. Augustine, Trinidad & Tobago

Fageria NK (2007) Soil fertility and plant nutrition research under field conditions: basic principles and methodology. J Plant Nutr 30; NUMB 2 (2):203-223

Fairhurst T (2012) Handbook for integrated soil fertility management. CTA/CABI, Pondicherry, India

FAO (2015) World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps, vol 106. World Soil Resources Report. FAO, Rome

FAO (2022) Per capita foood supply. https://www.fao.org/faostat/en/#data. Accessed 19 January 2023

FAO, IFAD, UNICEF, WFP, WHO (2021) The state of food security and nutrition in the world 2021: transforming food systems for food security, improved nutrition and affordable healthy diets for all. doi:10.4060/cb4474en

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79 (1):69-116. doi:10.1016/S0016-7061(97)00039-6

Fermeglia M (2022) Recent developments in EU environmental policy and legislation. J Eur Environ Plan Law 19 (1-2):129-137

Fidelis C, Rajashekhar Rao BK (2017) Enriched cocoa pod composts and their fertilizing effects on hybrid cocoa seedlings. Int J Recycl Org Waste Agric 6 (2):99-106. doi:10.1007/s40093-017-0156-8

Fischer B, van Doorn GS, Dieckmann U, Taborsky B (2014) The evolution of age-dependent plasticity. Am Nat 183 (1):108-125. doi:10.1086/674008

Fisher D (2018) Biomass, nutrient content and allometric relations of 1, 6 and 11 year-old, intensively grown Cocoa (Theobroma cacao) trees. Wageningen University & Research, Wageningen

Fold N, Neilson J (2016) Sustaining supplies in smallholder-dominated value chains: corporate governance of the global cocoa sector. The economics of chocolate:195-212

Fontes AG, Gama-Rodrigues AC, Gama-Rodrigues EF, Sales MVS, Costa MG, Machado RCR (2014) Nutrient stocks in litterfall and litter in cocoa agroforests in Brazil. Plant Soil 383 (1-2):313-335. doi:10.1007/s11104-014-2175-9

Fosu-Mensah BY, Okoffo ED, Darko G, Gordon C (2016) Assessment of organochlorine pesticide residues in soils and drinking water sources from cocoa farms in Ghana. Springerplus 5 (1):869. doi:10.1186/s40064-016-2352-9

Fosu-Mensah BY, Okoffo ED, Mensah M (2022) Assessment of farmers' knowledge and pesticides management in cocoa production in Ghana. Int J Adv Appl Sci 9 (3):100-110. doi:10.21833/ijaas.2022.03.012

Fowler MS (2009) Cocoa beans: from tree to factory. Industrial chocolate manufacture and use 4:137-152

Frazer GW, Canham CD, Lertzman KP (1999) Gap Light Analyzer (GLA), Version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation. Simon Fraser University & Institute of Ecosystem Studies, New-York

Freitas J, Netto AM, Correa MM, Xavier BTL, Assis FX (2018) Potassium adsorption in soil cultivated with sugarcane. An Acad Bras Cienc 90 (1):541-555. doi:10.1590/0001-3765201720160910

Fungenzi T, Sakrabani R, Burgess PJ, Lambert S, McMahon P (2021) Medium-term effect of fertilizer, compost, and dolomite on cocoa soil and productivity in Sulawesi, Indonesia. Exp Agric 57 (3):185-202. doi:10.1017/s0014479721000132

Gandhi A, Ala A, Nasaruddin (2021) Effectivity of biofertilizer and shoot pruning on yield of cocoa (Theobroma cacao L). IOP Conference Series: Earth and Environmental Science 807 (4). doi:10.1088/1755-1315/807/4/042060

Gateau-Rey L, Tanner EVJ, Rapidel B, Marelli JP, Royaert S (2018) Climate change could threaten cocoa production: Effects of 2015-16 El Nino-related drought on cocoa agroforests in Bahia, Brazil. PLoS One 13 (7):e0200454. doi:10.1371/journal.pone.0200454

Gebreyohannes G, Reda G (2019) Climate-smart integrated soil fertility management (CS-ISFM). Climate-smart agriculture: enhancing resilient agricultural systems, landscapes, and livelihoods in Ethiopia and beyond:49-57

Geng A, Tu Q, Chen J, Wang W, Yang H (2022) Improving litterfall production prediction in China under variable environmental conditions using machine learning algorithms. J Environ Manage 306:114515. doi:10.1016/j.jenvman.2022.114515

Gerendás J, Führs H (2013) The significance of magnesium for crop quality. Plant Soil 368 (1-2):101-128. doi:10.1007/s11104-012-1555-2

Ghosh D, Brahmachari K, Skalicky M, Roy D, Das A, Sarkar S, Moulick D, Brestic M, Hejnak V, Vachova P, Hassan MM, Hossain A (2022) The combination of organic and inorganic fertilizers influence the weed growth, productivity and soil fertility of monsoon rice. PLoS One 17 (1):e0262586. doi:10.1371/journal.pone.0262586

Giller KE (2002) Targeting management of organic resources and mineral fertilizers: can we match scientists' fantasies with farmers' realities? In: Vanlauwe B, Diels J, Sangiga N, Merckx R (eds) Integrated plant nutrient management in sub-Saharan Africa: From concept to practice. CABI Publishing Wallingford UK, pp 155-171

Giresse P (2008) Characteristics of the soils and present day vegetation of tropical West Africa. In: Giresse P (ed) Developments in Quaternary Sciences, vol 10. Elsevier, pp 15-18. doi:10.1016/S1571-0866(08)80005-X

Gockowski J (2019) The tree crop farming system: stagnation, innovation and forest degradation. In: Dixon J, Garrity DP, Boffa JM, Williams TO, Amede, T., Auricht, C., Lott, R. and Mburathi, G. (eds) Farming Systems and Food Security in Africa. Routledge, Oxon, pp 282-317

Goh KJ, Po SB Fertilizer recommendation systems for oil palm: estimating the fertilizer rates. In: MOSTA Best practices workshops-agronomy and crop management, Petaling Jaya, Selangor, Malaysia, 27 March-14 August 2004. Malaysian Oil Scientists and Technologists Association, pp 1-37

Goswami R, Ray K, Ghosh S, Dutta S, Mandal S, Nayak J, Chakraborty S, Banerjee H (2022) Multiple pathways of legume-based systems towards environmental, social, and economic sustainability in smallholder systems. In: Meena RS, Kumar S (eds) Advances in legumes for sustainable intensification. Academic Press, London, pp 657-678. doi:10.1016/b978-0-323-85797-0.00017-3

Gram G, Roobroeck D, Pypers P, Six J, Merckx R, Vanlauwe B (2020) Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. PLoS One 15 (9):e0239552. doi:10.1371/journal.pone.0239552

Groeneveld JH, Tscharntke T, Moser G, Clough Y (2010) Experimental evidence for stronger cacao yield limitation by pollination than by plant resources. Perspect Plant Ecol Evol Syst 12 (3):183-191. doi:10.1016/j.ppees.2010.02.005

Grossman RB, Reinsch TG (2002) Bulk density and linear extensibility. In: Dane JH, Topp GC (eds) Methods of soil analysis: Part 4 physical methods, vol 5. Wiley Online Library, Madison, pp 201-228

Guastella D, Cocuzza GEM, Rapisarda C (2017) Integrated pest management in tea, cocoa and coffee. In: Rapisarda C, Cocuzza GEM (eds) CABI Books. CABI, Wallingford, pp 285-312. doi:10.1079/9781780648002.0285

Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis. Glob Chang Biol 8 (4):345-360

Gurevitch J, Koricheva J, Nakagawa S, Stewart G (2018) Meta-analysis and the science of research synthesis. Nature 555 (7695):175-182. doi:10.1038/nature25753

Gutzler C, Koehler S, Gerold G (2010) A comparison of throughfall rate and nutrient fluxes in rainforest and cacao plantation in Central Sulawesi, Indonesia. In: Tscharntke T, Leuschner CV, Edzo Faust, Heiko, Guhardja E, Bidin A (eds) Tropical rainforests and agroforests under global change. Springer-Verlag, Berlin, pp 309-326

Handley LR (2016) The effects of climate change on the reproductive development of Theobroma cacao L. University of Reading, Reading

Hartemink AE (2005) Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: a review. Adv Agron 86:227-253. doi:10.1016/s0065-2113(05)86005-5

Hartemink AE (2006) Assessing soil fertility decline in the tropics using soil chemical data. Adv Agron 89:179-225

Hebbar P, Bittenbender HC, O'Doherty D (2011) Farm and forestry production and marketing profile for cacao (Theobroma cacao). In: Elevitch CR (ed) Specialty crops for Pacific island agroforestry. Permanent Agriculture Resources, Holualoa, Hawaii, p 23

Heidenreich A, Grovermann C, Kadzere I, Egyir IS, Muriuki A, Bandanaa J, Clottey J, Ndungu J, Blockeel J, Muller A, Stolze M, Schader C (2022) Sustainable intensification pathways in sub-Saharan Africa: assessing eco-efficiency of smallholder perennial cash crop production. Agric Syst 195. doi:10.1016/j.agsy.2021.103304

Hengl T, Mendes de Jesus J, Heuvelink GB, Ruiperez Gonzalez M, Kilibarda M, Blagotic A, Shangguan W, Wright MN, Geng X, Bauer-Marschallinger B, Guevara MA, Vargas R, MacMillan RA, Batjes NH, Leenaars JG, Ribeiro E, Wheeler I, Mantel S, Kempen B (2017) SoilGrids250m: Global gridded soil information based on machine learning. PLoS One 12 (2):e0169748. doi:10.1371/journal.pone.0169748

Hengl T, Miller MAE, Krizan J, Shepherd KD, Sila A, Kilibarda M, Antonijevic O, Glusica L, Dobermann A, Haefele SM, McGrath SP, Acquah GE, Collinson J, Parente L, Sheykhmousa M, Saito K, Johnson JM, Chamberlin J, Silatsa FBT, Yemefack M, Wendt J, MacMillan RA, Wheeler I, Crouch J (2021) African soil properties and nutrients mapped at 30 m spatial resolution using two-scale ensemble machine learning. Sci Rep 11 (1):6130. doi:10.1038/s41598-021-85639-y

Hertel D, Harteveld MA, Leuschner C (2009) Conversion of a tropical forest into agroforest alters the fine root-related carbon flux to the soil. Soil Biol Biochem 41 (3):481-490. doi:0.1016/j.soilbio.2008.11.020

Hoffmann MP, Cock J, Samson M, Janetski N, Janetski K, Rötter RP, Fisher M, Oberthür T (2020) Fertilizer management in smallholder cocoa farms of Indonesia under variable climate and market prices. Agric Syst 178. doi:10.1016/j.agsy.2019.102759

Hossain MZ, Bahar MM, Sarkar B, Donne SW, Ok YS, Palansooriya KN, Kirkham MB, Chowdhury S, Bolan N (2020) Biochar and its importance on nutrient dynamics in soil and plant. Biochar 2 (4):379-420. doi:10.1007/s42773-020-00065-z

Houba VJG, Temminghoff EJM, Gaikhorst GA, van Vark W (2008) Soil analysis procedures using 0.01 M calcium chloride as extraction reagent. Commun Soil Sci Plant Anal 31 (9-10):1299-1396. doi:10.1080/00103620009370514

Hougni DGJM, Schut AGT, Woittiez LS, Vanlauwe B, Giller KE (2021) How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching. Plant Soil 463 (1-2):155-170. doi:10.1007/s11104-021-04885-1

Huang M, Wang X, Keenan TF, Piao S (2018) Drought timing influences the legacy of tree growth recovery. Glob Chang Biol 24 (8):3546-3559. doi:10.1111/gcb.14294

ICCO (2020) Quarterly bulletin of cocoa statistics, vol. XLVI, No.1, cocoa year 2019/20. https://www.icco.org/about-us/international-cocoa-agreements/doc_download/4566-production-qbcs-xlvi-no-1.html Accessed 22 June 2020

ICCO (2021) Quaterly bulletin of cocoa statistics: cocoa year 2020/21. vol XLVII.

Iqbal N, Masood A, Khan NA (2012) Analyzing the significance of defoliation in growth, photosynthetic compensation and source-sink relations. Photosynthetica 50 (2):161-170. doi:10.1007/s11099-012-0029-3

Isaac ME, Borden KA (2019) Nutrient acquisition strategies in agroforestry systems. Plant Soil 444 (1-2):1-19. doi:10.1007/s11104-019-04232-5

Isaac ME, Gordon AM, Thevathasan N, Oppong SK, Quashie-Sam J (2005) Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: a chronosequence of pools and fluxes. Agrofor Syst 65 (1):23-31. doi:10.1007/s10457-004-4187-6

Isaac ME, Kimaro AA (2011) Diagnosis of nutrient imbalances with vector analysis in agroforestry systems. J Environ Qual 40 (3):860-866

Isaac ME, Timmer VR, Quashie-Sam SJ (2007a) Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of Theobroma cacao by vector analysis. Nutr Cycl Agroecosystems 78 (2):155-165. doi:10.1007/s10705-006-9081-3

Isaac ME, Ulzen-Appiah F, Timmer VR, Quashie-Sam SJ (2007b) Early growth and nutritional response to resource competition in cocoa-shade intercropped systems. Plant Soil 298 (1-2):243-254. doi:10.1007/s11104-007-9362-x

Jagoret P, Michel-Dounias I, Snoeck D, Ngnogué HT, Malézieux E (2012) Afforestation of savannah with cocoa agroforestry systems: a small-farmer innovation in central Cameroon. Agrofor Syst 86 (3):493-504. doi:10.1007/s10457-012-9513-9

Jagoret P, Ngnogue HT, Malézieux E, Michel I (2018) Trajectories of cocoa agroforests and their drivers over time: Lessons from the Cameroonian experience. Eur J Agron 101:183-192. doi:10.1016/j.eja.2018.09.007

Jaimez RE, Amores Puyutaxi F, Vasco A, Gastón Loor R, Tarqui O, Quijano G, Jimenez JC, Tezara W (2018) Photosynthetic response to low and high light of cacao growing without shade in an area of low evaporative demand. Acta Biol Colomb 23 (1):95-103

Jelsma I, Woittiez LS, Ollivier J, Dharmawan AH (2019) Do wealthy farmers implement better agricultural practices? An assessment of implementation of Good Agricultural Practices among different types of independent oil palm smallholders in Riau, Indonesia. Agric Syst 170:63-76. doi:10.1016/j.agsy.2018.11.004

Jeuffroy M-H, Casadebaig P, Debaeke P, Loyce C, Meynard J-M (2014) Agronomic model uses to predict cultivar performance in various environments and cropping systems. A review. Agron Sustain Dev 34 (1):121-137

Johnston AM, Bruulsema TW (2014) 4R Nutrient Stewardship for Improved Nutrient Use Efficiency. Procedia Eng 83:365-370. doi:10.1016/j.proeng.2014.09.029

Joly F-X, Weibel AK, Coulis M, Throop HL (2019) Rainfall frequency, not quantity, controls isopod effect on litter decomposition. Soil Biol Biochem 135:154-162. doi:10.1016/j.soilbio.2019.05.003

Juhrbandt J, Duwe T, Barkmann J, Gerold G, Marggraf R (2010) Structure and management of cocoa agroforestry systems in Central Sulawesi across an intensification gradient. In: Tscharntke T, Leuschner CV, Edzo

Faust, Heiko, Guhardja E, Bidin A (eds) Tropical rainforests and agroforests under global change. Springer-Verlag, Berlin, pp 115-140

Kaba JS, Yamoah FA, Acquaye A (2021) Towards sustainable agroforestry management: harnessing the nutritional soil value through cocoa mix waste. Waste Manage 124:264-272. doi:10.1016/j.wasman.2021.02.021

Kähkölä A-K, Nygren P, Leblanc HA, Pennanen T, Pietikäinen J (2012) Leaf and root litter of a legume tree as nitrogen sources for cacaos with different root colonisation by arbuscular mycorrhizae. Nutr Cycl Agroecosystems 92 (1):51-65. doi:10.1007/s10705-011-9471-z

Kalus K, Koziel J, Opaliński S (2019) A review of biochar properties and their utilization in crop agriculture and livestock production. Appl Sci 9 (17). doi:10.3390/app9173494

Kannenberg SA, Novick KA, Alexander MR, Maxwell JT, Moore DJP, Phillips RP, Anderegg WRL (2019) Linking drought legacy effects across scales: From leaves to tree rings to ecosystems. Glob Chang Biol 25 (9):2978-2992. doi:10.1111/gcb.14710

Kasran R, Sandrang AK, Kamaruddin SW, Syed Effects of foliar fertilizers on cherelle wilt in cocoa. In: Lazan H, Wan Chik GM, Adul Ghani AK, Abdul Aziz Z, Abdul Halim MR, Mohamed Tamin MS (eds) Tropical Plant Physiology Development Workshop: Physiological & Environmental Constraints, Kuala Lumpur, Malaysia, 27-28 August 1991. University Pertanian, pp 103-108

Kauffman JB, Sanford Jr RL, Cummings DL, Salcedo IH, Sampaio E (1993) Biomass and nutrient dynamics associated with slash fires in neotropical dry forests. Ecology 74 (1):140-151

Kaur S, Kaur R, Chauhan BS (2018) Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. Crop Prot 103:65-72. doi:10.1016/j.cropro.2017.09.011

Kayser M, Benke M, Isselstein J (2012) Potassium leaching following silage maize on a productive sandy soil. Plant Soil Environ 58 (12):545-550

Kearney S, Fonte SJ, Salomon A, Six J, Scow KM (2012) Forty percent revenue increase by combining organic and mineral nutrient amendments in Ugandan smallholder market vegetable production. Agron Sustain Dev 32 (4):831-839. doi:10.1007/s13593-012-0097-6

Kebenei MC, Mucheru-Muna M, Muriu-Ng'ang'a F, Ndung'u CK (2021) Zai technology and integrated nutrient management for improved soil fertility and increased sorghum yields in Kitui county, Kenya. Front Sustain Food Syst 5. doi:10.3389/fsufs.2021.714212

Kenfack Essougong UP, Slingerland M, Mathé S, Vanhove W, Tata Ngome PI, Boudes P, Giller KE, Woittiez LS, Leeuwis C (2020) Farmers' perceptions as a driver of agricultural practices: Understanding soil fertility management practices in cocoa agroforestry systems in Cameroon. Hum Ecol 48 (6):709-720. doi:10.1007/s10745-020-00190-0

Kennedy-Martin T, Curtis S, Faries D, Robinson S, Johnston J (2015) A literature review on the representativeness of randomized controlled trial samples and implications for the external validity of trial results. Trials 16:495. doi:10.1186/s13063-015-1023-4

Keywood M, Kanakidou M, Stohl A, Dentener F, Grassi G, Meyer CP, Torseth K, Edwards D, Thompson AM, Lohmann U, Burrows J (2011) Fire in the air: biomass burning impacts in a changing climate. Crit Rev Environ Sci Technol 43 (1):40-83. doi:10.1080/10643389.2011.604248

Khanahmadi S, Yusof F, Chyuan Ong H, Amid A, Shah H (2016) Cocoa pod husk: a new source of CLEA-lipase for preparation of low-cost biodiesel: an optimized process. J Biotechnol 231:95-105. doi:10.1016/j.jbiotec.2016.05.015

Kihara J, Manda J, Kimaro A, Swai E, Mutungi C, Kinyua M, Okori P, Fischer G, Kizito F, Bekunda M (2022) Contributions of integrated soil fertility management (ISFM) to various sustainable intensification impact domains in Tanzania. Agric Syst 203. doi:10.1016/j.agsy.2022.103496

Kirchmann H, Witter E (1989) Ammonia volatilization during aerobic and anaerobic manure decomposition. Plant Soil 115 (1):35-41

Kirchmann H, Witter E (1992) Composition of fresh, aerobic and anaerobic farm animal dungs. Bioresour Technol 40 (2):137-142. doi:10.1016/0960-8524(92)90199-8

Kitchen NR, Clay SA (2018) Understanding and identifying variability. Precis Agric Basics:13-24

Knorr M, Frey SD, Curtis PS (2005) Nitrogen additions and litter decomposition: a meta-analysis. Ecology 86 (12):3252-3257

Koko L (2014) Teractiv Cacao as a new fertilizer based reactive phosphate rock for cocoa productivity in côte d'ivoire: A participatory approach to update fertilization recommendation. Procedia Eng 83:348-353. doi:10.1016/j.proeng.2014.09.027

Kolahchi Z, Jalali M (2012) Kinetics of nutrient release from different organic residues using a laboratory system. Arch Agron Soil Sci 58 (9):1013-1031. doi:10.1080/03650340.2011.559227

Konan A, Yameogo I, Assiri Assiri A, Ehougban V (2015) Manuel technique de cacaoculture durable a l'attention du technicien. FIRCA - CCC - WCF - USAID - IDH, Abidjan

Kongor JE, Boeckx P, Vermeir P, Van de Walle D, Baert G, Afoakwa EO, Dewettinck K (2019) Assessment of soil fertility and quality for improved cocoa production in six cocoa growing regions in Ghana. Agrofor Syst 93 (4):1455-1467

Kongor JE, De Steur H, Van de Walle D, Gellynck X, Afoakwa EO, Boeckx P, Dewettinck K (2017) Constraints for future cocoa production in Ghana. Agrofor Syst 92 (5):1373-1385. doi:10.1007/s10457-017-0082-9

Konlan S, Quaye AK, Pobee P, Amon-Armah F, Dogbatse JA, Arthur A, Fiakpornu R, Dogbadzi R (2019) Effect of weed management with glyphosate on growth and early yield of young cocoa (Theobroma cacao L.) in Ghana. Afr J Agric Res 14 (28):1229-1238. doi:10.5897/ajar2018.13555

Kool H, Andersson JA, Giller KE (2020) Reproducibility and external validity of on-farm experimental research in Africa. Exp Agric 56 (4):587-607. doi:10.1017/s0014479720000174

Kozlowski TT, Pallardy SG (2002) Acclimation and adaptive responses of woody plants to environmental stresses. Bot Rev 68 (2):270-334. doi:10.1663/0006-8101(2002)068[0270:AAAROW]2.0.CO;2

Kuhlbusch TA, Lobert JM, Crutzen PJ, Warneck P (1991) Molecular nitrogen emissions from denitrification during biomass burning. Nature 351 (6322):135-137

Laajaj R, Macours K, Masso C, Thuita M, Vanlauwe B (2020) Reconciling yield gains in agronomic trials with returns under African smallholder conditions. Sci Rep 10 (1):14286. doi:10.1038/s41598-020-71155-y

Lahive F, Hadley P, Daymond AJ (2018) The physiological responses of cacao to the environment and the implications for climate change resilience. A review. Agron Sustain Dev 39 (1). doi:10.1007/s13593-018-0552-0

Lahive F, Handley LR, Hadley P, Daymond AJ (2021) Climate change impacts on cacao: genotypic variation in responses of mature cacao to elevated CO2 and water deficit. Agronomy 11 (5). doi:10.3390/agronomy11050818

Lambert S, bin Purung H, Syawaluddin, McMahon P (2020) Growth and flowering of young cocoa plants is promoted by organic and nitrate-based fertiliser amendments. Exp Agric 56 (6):794-814. doi:10.1017/s0014479720000320

Laossi K-R, Kone S, Marchetti M, Broun P (2022) Impact of pruning intensities on cocoa tree productivity, pest (mirids) and disease (black pod disease) infestations on farmer field trials in Côte d'Ivoire. Paper presented at the International Symposium on Cocoa Research, Montpellier, 5-7 December 2022

Lavelle P, Decaëns T, Aubert M, Barot S, Blouin M, Bureau F, Margerie P, Mora P, Rossi JP (2006) Soil invertebrates and ecosystem services. Eur J Soil Biol 42:S3-S15. doi:10.1016/j.ejsobi.2006.10.002

Lecerf A (2017) Methods for estimating the effect of litterbag mesh size on decomposition. Ecol Modell 362:65-68. doi:10.1016/j.ecolmodel.2017.08.011

Lehmann J (2003) Subsoil root activity in tree-based cropping systems. Plant Soil 255:319-331

Leiva-Rojas EI, Gutiérrez-Brito EE, Pardo-Macea CJ, Ramírez-Pisco R (2019) Vegetative and reproductive behavior of cocoa (Theobroma cacao L.) due to pruning. Rev Fitotec Mex 42 (2):137-146

Lemaire G, Gastal F (1997) N uptake and distribution in plant canopies. In: Lemaire G (ed) Diagnosis of the nitrogen status in crops. Springer, Berlin, pp 3-44. doi:10.1007/978-3-642-60684-7

Leuschner C, Moser G, Hertel D, Erasmi S, Leitner D, Culmsee H, Schuldt B, Schwendenmann L (2013) Conversion of tropical moist forest into cacao agroforest: consequences for carbon pools and annual C sequestration. Agrofor Syst 87 (5):1173-1187. doi:10.1007/s10457-013-9628-7

Li J, Lu J, Li X, Ren T, Cong R, Zhou L (2014) Dynamics of potassium release and adsorption on rice straw residue. PLoS One 9 (2):e90440. doi:10.1371/journal.pone.0090440

Lim KC, Zaharah AR (2000) Decomposition and N & K release by oil palm empty fruit bunches applied under mature palms. J Oil Palm Res 12 (2):55-62

List JA (2020) Non est disputandum de generalizability?: A glimpse into the external validity trial.

Liu Y, Bortier MF, De Boeck HJ, Nijs I (2017) Root distribution responses to three-dimensional soil heterogeneity in experimental mesocosms. Plant Soil 421 (1-2):353-366. doi:10.1007/s11104-017-3472-x

Lokin M (2020) Integrated soil fertility management: understanding cocoa farmers' motivations and unpacking adoption. Wageningen University and Research, Wageningen

Lorenz K, Lal R, Ehlers K (2019) Soil organic carbon stock as an indicator for monitoring land and soil degradation in relation toUnitedNations'SustainableDevelopmentGoals. Land Degrad Dev 30 (7):824-838. doi:10.1002/ldr.3270

Lotodé R, Muller RA (1974) Problems of experimentation with cocoa trees. Phytophthora Diseases of Cocoa:348

Lu F, Rodriguez-Garcia J, Van Damme I, Westwood NJ, Shaw L, Robinson JS, Warren G, Chatzifragkou A, McQueen Mason S, Gomez L, Faas L, Balcombe K, Srinivasan C, Picchioni F, Hadley P, Charalampopoulos D (2018) Valorisation strategies for cocoa pod husk and its fractions. Curr Opin Green Sustain Chem 14:80-88. doi:10.1016/j.cogsc.2018.07.007

Lüdecke D, Ben-Shachar M, Patil I, Waggoner P, Makowski D (2021) performance: an R package for assessment, comparison and testing of statistical models. J Open Source Softw 6 (60). doi:10.21105/joss.03139

Lupwayi NZ, Clayton GW, O'Donovan JT, Harker KN, Turkington TK, Soon YK (2006) Potassium release during decomposition of crop residues under conventional and zero tillage. Can J Soil Sci 86 (3):473-481. doi:10.4141/S05-049

Macek P, Husain U, Werner K (2018) Supporting smallholders in achieving more sustainable cocoa cultivation: the case of West Africa. In: Umaharan P (ed) Achieving sustainable cultivation of cocoa. Burleigh Dodds Series in Agricultural Science. Burleigh Dodds Science Publishing, Cambridge, UK, pp 541-558. doi:10.19103/as.2017.0021.32

MacLaren C, Mead A, van Balen D, Claessens L, Etana A, de Haan J, Haagsma W, Jäck O, Keller T, Labuschagne J, Myrbeck Å, Necpalova M, Nziguheba G, Six J, Strauss J, Swanepoel PA, Thierfelder C, Topp C, Tshuma F, Verstegen H, Walker R, Watson C, Wesselink M, Storkey J (2022) Long-term evidence for ecological intensification as a pathway to sustainable agriculture. Nat Sustain 5 (9):770-779. doi:10.1038/s41893-022-00911-x

Madountsap Tagnang N, Zapfack L, Chimi Djomo C, Kabelong Banoho L-P, Forbi Preasious F, Tsopmejio Temfack I, Tajeukem Vice C, Ntonmen Yonkeu FA, Tabue Mboba BR, Nasang JM (2018) Carbon storage potential of cacao agroforestry systems of different age and management intensity. Clim Dev 11 (7):543-554. doi:10.1080/17565529.2018.1456895

Maestrini B, Basso B (2018) Predicting spatial patterns of within-field crop yield variability. Field Crops Res 219:106-112. doi:10.1016/j.fcr.2018.01.028

Maharaj K, Maharaj P, Bekele FL, Ramnath D, Bidaisee GG, Bekele I, Persad C, Jennings K, Sankar R (2011) Trinidad selected hybrids: an investigation of the phenotypic and agro-economic traits of 20 selected cacao cultivars. Trop Agric 88 (4):175-185

Maney C, Sassen M, Hill SLL (2022) Modelling biodiversity responses to land use in areas of cocoa cultivation. Agric Ecosyst Environ 324. doi:10.1016/j.agee.2021.107712

Mansur D, Tago T, Masuda T, Abimanyu H (2014) Conversion of cacao pod husks by pyrolysis and catalytic reaction to produce useful chemicals. Biomass Bioenerg 66:275-285. doi:10.1016/j.biombioe.2014.03.065

Margate RZ, Secretaria MI, Padrones GD, Maravilla JN, Magat SS, Mantiquilla JA, Silva EC, Corsame R, Borromeo J, Rivera V (nd) Integrated soil fertility management of hybrid coconut grown in different agro climatic conditions of the Philippines. CORD 13 (01):7-18. doi:10.37833/cord.v13i01.306

Maria de Aquino A, Ferreira da Silva R, Mercante FM, Fernandes Correia ME, de Fátima Guimarães M, Lavelle P (2008) Invertebrate soil macrofauna under different ground cover plants in the no-till system in the Cerrado. Eur J Soil Biol 44 (2):191-197. doi:10.1016/j.ejsobi.2007.05.001

Marschner H (2012) Marschner's mineral nutrition of higher plants, vol 89. 3rd edn. Academic Press, San Diego, USA. doi:10.1016/B978-0-12-384905-2.00030-3

Marsden C, Martin-Chave A, Cortet J, Hedde M, Capowiez Y (2020) How agroforestry systems influence soil fauna and their functions-a review. Plant Soil 453 (1):29-44

Matissek R, Reinecke J, von Hagen O, Manning S (2012) Sustainability in the cocoa sector - review, challenges and approaches. Moderne Ernaehrung Heute:1-27

Matusso JMM, Mugwe JN, Mucheru-Muna M (2014) Potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of Sub-Saharan Africa. J Agric Environ Sci 3 (3):162-174

Mbuthia LW, Acosta-Martínez V, DeBruyn J, Schaeffer S, Tyler D, Odoi E, Mpheshea M, Walker F, Eash N (2015) Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. Soil Biol Biochem 89:24-34. doi:10.1016/j.soilbio.2015.06.016

McDermott R (2011) Internal and external validity. In: Druckman JN, Green DP, Kuklinski JH, Lupia A (eds) Cambridge handbook of experimental political science. Cambridge University Press, New-York, pp 27-40

McDowell WH, Pérez-Rivera KX, Shaw ME (2020) Assessing the ecological significance of throughfall in forest ecosystems. In: Levia DF, Carlyle-Moses DE, Iida S, Michalzik B, Nanko K, Tischer A (eds) Forest-Water Interactions. Ecological Studies. Springer, Cham, Switzerland, pp 299-318. doi:10.1007/978-3-030-26086-6_13

McLean EO (1983) Soil pH and lime requirement. Methods of soil analysis: Part 2 Chemical and microbiological properties 9:199-224

Medina V, Laliberte B (2017) A review of research on the effects of drought and temperature stress and increased CO2 on Theobroma cacao L., and the role of genetic diversity to address climate change. Bioversity International, Rome

Meinke H (2019) The role of modeling and systems thinking in contemporary agriculture. In: Accorsi R, Manzini R (eds) Sustainable food supply chains: planning, design, and control through interdisciplinary methodologies. pp 39-47. doi:10.1016/b978-0-12-813411-5.00003-x

Menzies NW, Gillman GP (2003) Plant growth limitation and nutrient loss following piled burning in slash and burn agriculture. Nutr Cycl Agroecosystems 65:23-33

Miao Y, Stewart BA, Zhang F (2010) Long-term experiments for sustainable nutrient management in China. A review. Agron Sustain Dev 31 (2):397-414. doi:10.1051/agro/2010034

Michel FC, Pecchia JA, Rigot J, Keener HM (2004) Mass and nutrient losses during the composting of dairy manure amended with sawdust or straw. Compost Sci Util 12 (4):323-334. doi:10.1080/1065657x.2004.10702201

Miller CR, Guiltinan MJ Perspectives on rapid vegetative multiplication for orthotropic scion and rootstock varieties of cocoa. In: Bekele FL, End M, Eskes A (eds) International workshop on cocoa breeding for improved production systems, Accra, Ghana, 19-21 October 2003. INGENIC-COCOBOD, pp 189-194

Mohammed AM, Robinson JS, Midmore DJ, Verhoef A (2019) Leaf litter decomposition and mitigation of CO2 emissions in cocoa ecosystems. CO2 sequestration:28

Mommer L (1999) The water relations in cacao (Theobroma cacao L.): modelling root growth and evapotranspiration. Wageningen Agricultural University, Wageningen

Monteiro WR, Lopes UV, Clement D (2009) Genetic improvement in cocoa. In: Jain SM, Priyadarshan PM (eds) Breeding plantation tree crops: tropical species. Springer, New-York, pp 589-626. doi:10.1007/978-0-387-71201-7_16

Morel AC, Adu Sasu M, Adu-Bredu S, Quaye M, Moore C, Ashley Asare R, Mason J, Hirons M, McDermott CL, Robinson EJZ, Boyd E, Norris K, Malhi Y (2019) Carbon dynamics, net primary productivity and human-appropriated net primary productivity across a forest-cocoa farm landscape in West Africa. Glob Chang Biol 25 (8):2661-2677. doi:10.1111/gcb.14661

Mortimer R, Saj S, David C (2017) Supporting and regulating ecosystem services in cacao agroforestry systems. Agrofor Syst 92 (6):1639-1657. doi:10.1007/s10457-017-0113-6

Moser G, Leuschner C, Hertel D, Hölscher D, Köhler M, Leitner D, Michalzik B, Prihastanti E, Tjitrosemito S, Schwendenmann L (2010) Response of cocoa trees (Theobroma cacao) to a 13-month desiccation period in Sulawesi, Indonesia. Agrofor Syst 79 (2):171-187. doi:10.1007/s10457-010-9303-1

Moshiri F, Balali MR, Rejali F, Sedaghat A (2021) A framework for integrated soil fertility and plant nutrition management in Iran. Land Manag J

Moslehi M, Habashi H, Khormali F, Ahmadi A, Brunner I, Zimmermann S (2019) Base cation dynamics in rainfall, throughfall, litterflow and soil solution under oriental beech (*Fagus orientalis* Lipsky) trees in northern Iran. Ann For Sci 76 (2). doi:10.1007/s13595-019-0837-8

Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA (2012) Closing yield gaps through nutrient and water management. Nature 490 (7419):254-257

Mugwe J, Ngetich F, Otieno EO (2019) Integrated soil fertility management in sub-saharan africa: evolving paradigms toward integration. In: Leal Filho W, Azul A, Brandli L, Özuyar P, Wall T (eds) Zero Hunger. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham, pp 1-12. doi:10.1007/978-3-319-69626-3_71-1

Mulders PJAM, van den Heuvel ER, van den Borne J, van de Molengraft R, Heemels WPMH, Reidsma P (2021) Data science at farm level: Explaining and predicting within-farm variability in potato growth and yield. Eur J Agron 123. doi:10.1016/j.eja.2020.126220

Mulia S, McMahon PJ, Purwantara A, Bin Purung H, Djufry F, Lambert S, Keane PJ, Guest DI (2017) Effect of organic and inorganic amendments on productivity of cocoa on a marginal soil in Sulawesi, Indonesia. Exp Agric 55 (1):1-20. doi:10.1017/s0014479717000527

Muñoz F, Beer J (2001) Fine root dynamics of shaded cacao plantations in Costa Rica. Agrofor Syst 51 (2):119-130

Munroe JW, Isaac ME (2014) N2-fixing trees and the transfer of fixed-N for sustainable agroforestry: a review. Agron Sustain Dev 34 (2):417-427. doi:10.1007/s13593-013-0190-5

Muoghalu JI, Odiwe AI (2011) Litter production and decomposition in cacao (Theobroma cacao) and kolanut (Cola nitida) plantations. Ecotropica 17 (1):79-90

Murray DB (1958) Response of cacao to fertilizers. Nature 182 (4649):1613-1613. doi:10.1038/1821613a0

Mutsaers H, Coyne D, Hauser S, Huising J, Generose N, Pieter P, Godfrey T, Bernard V (2017) Soil and soil fertility management research in sub-Saharan Africa: fifty years of shifting visions and chequered achievements. Routledge, London. doi:10.4324/9781315518855

N'Dri AB, Kone AW, Loukou SKK, Barot S, Gignoux J (2018) Carbon and nutrient losses through biomass burning, and links with soil fertility and yam (Dioscorea alata) production. Exp Agric 55 (5):738-751. doi:10.1017/s0014479718000327

N'Guessan KJ-C, Traore MJ, Snoeck D, Kassin KE, Koko L, Camara M, Yao Kouame A (2017) Mapping cacao fertiliser requirements in Cote d'Ivoire. Imp J Interdiscip Res 3 (6):504-515

N’Gbala FNG, Guéi AM, Tondoh JE (2017) Carbon stocks in selected tree plantations, as compared with semi-deciduous forests in centre-west Côte d’Ivoire. Agric Ecosyst Environ 239:30-37. doi:10.1016/j.agee.2017.01.015

Nadelhoffer KJ, Blair JM (1999) Measuring decomposition, nutrient turnover, and stores in plant litter. In: Robertson GP (ed) Standard soil methods for long-term ecological research. Long-term ecological research network series. Oxford University Press, Oxford, UK, pp 202-240

Nair KPP (2009) The agronomy and economy of some important industrial crops. Adv Agron 101:183-313. doi:10.1016/s0065-2113(08)00804-3

Nair KPP (2010) Cocoa (Theobroma cacao L.). In: Nair KPP (ed) The agronomy and economy of important tree crops of the developing world. Elsevier, Amsterdam, pp 131-180. doi:10.1016/b978-0-12-384677-8.00005-9

Najafi-Ghiri M, Niksirat SH, Soleimanpour L, Nowzari S (2017) Comparison of different organic amendments on potassium release from two fine-textured soils. Org Agric 8 (2):129-140. doi:10.1007/s13165-017-0179-5

Nakagawa S, Johnson PCD, Schielzeth H (2017) The coefficient of determination R(2) and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. J R Soc Interface 14 (134). doi:10.1098/rsif.2017.0213

Ndabamenye T, Van Asten PJA, Blomme G, Vanlauwe B, Uzayisenga B, Annandale JG, Barnard RO (2013) Nutrient imbalance and yield limiting factors of low input East African highland banana (Musa spp. AAA-EA) cropping systems. Field Crops Res 147:68-78

Ndoumbe Nkeng M, Efombagn Mousseni IB, Bidzanga Nomo L, Sache I, Cilas C (2016) Spatio-temporal dynamics on a plot scale of cocoa black pod rot caused by Phytophthora megakarya in Cameroon. Eur J Plant Pathol 147 (3):579-590. doi:10.1007/s10658-016-1027-2

Ndoungue Djeumekop MM, Ngo Bieng MA, Ribeyre F, Bonnot F, Cilas C, Neema C, Ten Hoopen GM (2021) Spatial and temporal analysis of Phytophthora megakarya epidemic in newly established cacao plantations. Plant Dis 105 (5):1448-1460. doi:10.1094/PDIS-09-19-2024-RE

Ndoungue M, Petchayo S, Techou Z, Nana WG, Nembot C, Fontem D, Hoopen GMT (2018) The impact of soil treatments on black pod rot (caused by Phytophthora megakarya) of cacao in Cameroon. Biol Control 123:9-17. doi:10.1016/j.biocontrol.2018.04.016

Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. Methods of soil analysis: Part 3 Chemical methods 5:961-1010

Nhamo N, Rodenburg J, Zenna N, Makombe G, Luzi-Kihupi A (2014) Narrowing the rice yield gap in East and Southern Africa: using and adapting existing technologies. Agric Syst 131:45-55. doi:10.1016/j.agsy.2014.08.003

Niemenak N, Cilas C, Rohsius C, Bleiholder H, Meier U, Lieberei R (2010) Phenological growth stages of cacao plants (Theobroma sp.): codification and description according to the BBCH scale. Ann Appl Biol 156 (1):13-24. doi:10.1111/j.1744-7348.2009.00356.x

Niether W, Jacobi J, Blaser WJ, Andres C, Armengot L (2020) Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environ Res Lett 15 (10):104085

Niether W, Schneidewind U, Armengot L, Adamtey N, Schneider M, Gerold G (2017) Spatial-temporal soil moisture dynamics under different cocoa production systems. Catena 158:340-349. doi:10.1016/j.catena.2017.07.011

Niether W, Schneidewind U, Fuchs M, Schneider M, Armengot L (2019) Below- and aboveground production in cocoa monocultures and agroforestry systems. Sci Total Environ 657:558-567. doi:10.1016/j.scitotenv.2018.12.050

Niinemets Ü (2010) Responses of forest trees to single and multiple environmental stresses from seedlings to mature plants: Past stress history, stress interactions, tolerance and acclimation. For Ecol Manag 260 (10):1623-1639. doi:10.1016/j.foreco.2010.07.054

Nijmeijer A, Lauri P-E, Harmand J-M, Freschet GT, Essobo Nieboukaho J-D, Fogang PK, Enock S, Saj S (2019a) Long-term dynamics of cocoa agroforestry systems established on lands previously occupied by savannah or forests. Agric Ecosyst Environ 275:100-111. doi:10.1016/j.agee.2019.02.004

Nijmeijer A, Lauri P-É, Harmand J-M, Saj S (2019b) Carbon dynamics in cocoa agroforestry systems in Central Cameroon: afforestation of savannah as a sequestration opportunity. Agrofor Syst 93 (3):851-868. doi:10.1007/s10457-017-0182-6

Njira KOW, Semu E, Mrema JP, Nalivata PC (2020) Integrated soil fertility management based on pigeon pea and cowpea cropping systems influences nitrogen use efficiency, yields and quality of subsequent maize on Alfisols in central Malawi. In: Singh BR, Safalaoh A, Amuri NAE, Lars Olav, Sitaula BK, Lal R (eds) Climate impacts on agricultural and natural resource sustainability in africa. Springer, Cham, Switzerland, pp 93-113. doi:10.1007/978-3-030-37537-9_5

Njoroge R, Otinga AN, Okalebo JR, Pepela M, Merckx R (2017) Occurrence of poorly responsive soils in western Kenya and associated nutrient imbalances in maize (Zea mays L.). Field Crops Res 210:162-174. doi:10.1016/j.fcr.2017.05.015

Nlend-Nkott J-P, Asare R (2021) Managing soils for increased productivity and decreased deforestation in cocoa: a training manual for field officers. CocoaSoils, Ibadan, Nigeria

Norgrove L (2007) Effects of different copper fungicide application rates upon earthworm activity and impacts on cocoa yield over four years. Eur J Soil Biol 43:S303-S310. doi:10.1016/j.ejsobi.2007.08.031

Norgrove L, Hauser S (2013) Carbon stocks in shaded Theobroma cacao farms and adjacent secondary forests of similar age in Cameroon. Trop Ecol 54 (1):15-22

Notaro M, Collado C, Depas JK, Dumovil D, Denis AJ, Deheuvels O, Tixier P, Gary C (2021) The spatial distribution and height of associated crops influence cocoa tree productivity in complex agroforestry systems. Agron Sustain Dev 41 (5). doi:10.1007/s13593-021-00716-w

Nunoo I, Frimpong BN, Frimpong FK (2014) Fertilizer use among cocoa farmers in Ghana: the case of Sefwi Wiawso District. Int J Environ 3 (1):22-31

Nye PH, Greenland DJ (1960) The soil under shifting cultivation. Commonwealth Agricultural Bureaux, Harpenden, UK.

Nygren P, Leblanc HA, Lu M, Gómez Luciano CA (2013) Distribution of coarse and fine roots of Theobroma cacao and shade tree Inga edulis in a cocoa plantation. Ann For Sci 70 (3):229-239. doi:10.1007/s13595-012-0250-z

Obeng Adomaa F, Vellema S, Slingerland M, Asare R (2022) The adoption problem is a matter of fit: tracing the travel of pruning practices from research to farm in Ghana’s cocoa sector. Agric Human Values:1-15

Oberthür T, Samson M, Janetski N, Janetski K, Fisher M (2018) Response of cacao seedlings to fertilizer. Better Crops with Plant Food 102 (4):20-23. doi:10.24047/bc102420

Obiri BD, Bright GA, McDonald MA, Anglaaere LCN, Cobbina J (2007) Financial analysis of shaded cocoa in Ghana. Agrofor Syst 71 (2):139-149. doi:10.1007/s10457-007-9058-5

Öborn I, Vanlauwe B, Phillips M, Thomas R, Brooijmans W, Atta-Krah K (2017) Sustainable intensification in smallholder agriculture: an integrated systems research approach. Earthscan Food and Agriculture series. Routledge, London & New-York

Ofori-Boateng K, Insah B (2014) The impact of climate change on cocoa production in West Africa. Int J Clim Change Strateg Manag 6 (3):296-314. doi:10.1108/ijccsm-01-2013-0007

Ofori-Frimpong K, Asase A, Mason J, Danku L Shaded versus unshaded cocoa: implications on litter fall, decomposition, soil fertility and cocoa pod development. In: Symposium on multi-strata agroforestry systems with perennial crops: making ecosystem service count for farmers, consumers, and the environment, Turrialba, Costa-Rica, 17-21 September 2007. IUFRO-CIRAD-CATIE, Tur, p 9

Ofori A, Konlan S, Dadzie MA, Amoah FM (2014) Genotypic performance of cocoa (Theobroma cacao L.) during establishment under natural drought stress. J Crop Improv 28 (6):804-824. doi:10.1080/15427528.2014.947529

Ogunlade M, Obatolu B, Uponi J, Adejobi KB, Tunrayo A, Ogundijo DS, Aduramigba-Modukpe V, Aikpokpodion PE, Lawal JO, Okafor BN, Adeoye G, van Asten P (2019a) Soil fertility evaluation for formulation of appropriate cocoa fertilizer in Nigeria. IDH - IITA - OCP Africa - CRIN, Ibadan, Nigeria

Ogunlade MO, Adeoye GO, Ogeh JS (2012) Studies on nutrient release pattern of neem fortified cocoa pod husk fertilizer in an Alfisol. J Trop Soils 17 (2):129-134

Ogunlade MO, Bello OS, Agbeniyi SO, Adeniyi DO (2019b) Microbiota assay of cocoa pod husk – based compost as organic fertilizer. Int J Curr Microbiol Appl Sci 8 (06):3182-3192. doi:10.20546/ijcmas.2019.806.380

Ogunlade MO, Iloyanomon CI (2009) Leaf litter fall and soil nutrient status under cocoa plantation of different ages in Ibadan, Nigeria. Nig J Soil Sci 19 (1):25-28

Ogunlade MO, Orisajo SB (2020) Integrated soil fertility management for smallholder cocoa farms: using combination of cocoa pod husk based compost and mineral fertilizers. Int J Plant Soil Sci 32 (2):68-77. doi:10.9734/IJPSS/2020/v32i230248

Oikeh SO, Houngnandan P, Abaidoo RC, Rahimou I, Touré A, Niang A, Akintayo I (2008) Integrated soil fertility management involving promiscuous dual-purpose soybean and upland NERICA enhanced rice productivity in the savannas. Nutr Cycl Agroecosystems 88 (1):29-38. doi:10.1007/s10705-008-9185-z

Olasoji HO, Ojetade JO, Muda SA, Amusan AA (2022) Characterisation, classification and suitability assessment of soils formed in granite and gneiss in humid area of southwestern Nigeria for cacao (Theobroma cacao) production. Trop Agric 99 (1):11-26

Olson JS (1963) Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44 (2):322-331

Olujide MG, Adeogun SO (2006) Assessment of cocoa growers' farm management practices in Ondo State, Nigeria. Span J Agric Res 4 (2):173-179

Oomes N, Tieben B, Laven A, Ammerlaan T, Appelman R, Biesenbeek C, Buunk E (2016) Market concentration and price formation in the global cocoa value chain. SEO-rapport. SEO Economisch Onderzoek,

Ordóñez-Fernández R, Repullo-Ruibérriz De Torres MA, Román-Vázquez J, González-Fernández P, Carbonell-Bojollo R (2014) Macronutrients released during the decomposition of pruning residues used as plant cover and their effect on soil fertility. J Agric Sci 153 (4):615-630. doi:10.1017/s0021859614000458

Ordway EM, Asner GP, Lambin EP (2017) Deforestation risk due to commodity crop expansion in sub-Saharan Africa. Environ Res Lett 12 (4):13. doi:10.1088/1748-9326/aa6509

Ossohou M, Galy-Lacaux C, Yoboué V, Adon M, Delon C, Gardrat E, Konaté I, Ki A, Zouzou R (2020) Long-term atmospheric inorganic nitrogen deposition in West African savanna over 16 year period (Lamto, Côte d'Ivoire). Environ Res Lett 16 (1):015004

Otsuka K, Muraoka R (2017) A green revolution for sub-Saharan Africa: past failures and future prospects. Journal of African Economies 26 (suppl_1):i73-i98. doi:10.1093/jae/ejx010

Owusu-Sekyere E, Cobbina J, Wakatsuki T (2006) Nutrient cycling in primary, secondary forests and cocoa plantation in the Ashanti Region, Ghana. West Afr J Appl Ecol 9 (1):10-18

Padi FK, Adu-Gyamfi P, Akpertey A, Arthur A, Ofori A, Weber WE (2013) Differential response of cocoa (Theobroma cacao) families to field establishment stress. Plant Breed 132 (2):229-236. doi:10.1111/pbr.12039

Perez-Flores J, Perez AA, Suarez YP, Bolaina VC, Quiroga AL (2018) Leaf litter and its nutrient contribution in the cacao agroforestry system. Agrofor Syst 92 (2):365-374. doi:10.1007/s10457-017-0096-3

Pesonen J, Kuokkanen T, Rautio P, Lassi U (2017) Bioavailability of nutrients and harmful elements in ash fertilizers: Effect of granulation. Biomass Bionerg 100:92-97. doi:10.1016/j.biombioe.2017.03.019

Peter I, Lehmann J (2000) Pruning effects on root distribution and nutrient dynamics in an acacia hedgerow planting in northern Kenya. Agrofor Syst 50 (1):59-75

Petersen B, Snapp S (2015) What is sustainable intensification? Views from experts. Land Use Policy 46:1-10. doi:10.1016/j.landusepol.2015.02.002

Picchioni F, Warren GP, Lambert S, Balcombe K, Robinson JS, Srinivasan C, D. Gomez L, Faas L, Westwood NJ, Chatzifragkou A, Charalampopoulos D, Shaw LJ (2020) Valorisation of natural resources and the need for economic and sustainability assessment: The case of cocoa pod husk in Indonesia. Sustainability 12 (21). doi:10.3390/su12218962

Pincus L, Margenot A, Six J, Scow K (2016) On-farm trial assessing combined organic and mineral fertilizer amendments on vegetable yields in central Uganda. Agric Ecosyst Environ 225:62-71. doi:10.1016/j.agee.2016.03.033

Pinheiro JC, Bates D, DebRoy S, Sarkar D, R Core Team (2019) nlme: Linear and nonlinear mixed effects models. R package version 3.1-142.

Pinheiro JC, Bates DM (1996) Unconstrained parametrizations for variance-covariance matrices. Stat Comput 6 (3):289-296

Poelmans E, Swinnen J (2016) A brief economic history of chocolate. In: Squicciarini MP, Swinnen J (eds) The economics of chocolate. Oxford University Press, Oxford, UK, pp 11-42. doi:10.1093/acprof:oso/9780198726449.003.0002

Pouangam Ngalani G, Dzemze Kagho F, Peguy NNC, Prudent P, Ondo JA, Ngameni E (2022) Effects of coffee husk and cocoa pods biochar on the chemical properties of an acid soil from West Cameroon. Arch Agron Soil Sci:1-15. doi:10.1080/03650340.2022.2033733

Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Philos Trans R Soc Lond B Biol Sci 363 (1491):447-465. doi:10.1098/rstb.2007.2163

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114 (8):1571-1596. doi:10.1093/aob/mcu205

Puentes-Páramo YJ, Menjivar-Flores JC, Aranzazu-Hernández F (2016) Nutrient concentration in leaves, a tool for nutritional diagnosis in cocoa. Agron Mesoam 27 (2):329-336

Pypers P, Sanginga J-M, Kasereka B, Walangululu M, Vanlauwe B (2011) Increased productivity through integrated soil fertility management in cassava–legume intercropping systems in the highlands of Sud-Kivu, DR Congo. Field Crops Res 120 (1):76-85. doi:10.1016/j.fcr.2010.09.004

Quansah E (2021) The quality of cocoa pod husk biochar produced with the "Kon-tiki" kiln technology, and its effect as a soil enhancer on the growth rate of cocoa seedlings. Norwegian University of Life Sciences, Ås,

Quaye AK, Doe EK, Amon-Armah F, Arthur A, Dogbatse JA, Konlan S (2021a) Predictors of integrated soil fertility management practice among cocoa farmers in Ghana. J Agric Food Res 5. doi:10.1016/j.jafr.2021.100174

Quaye AK, Doe EK, Attua EM, Yiran G, Arthur A, Dogbatse JA, Konlan S, Nkroma YD, Addo D (2021b) Geospatial distribution of soil organic carbon and soil pH within the cocoa agroecological zones of Ghana. Geoderma 386. doi:10.1016/j.geoderma.2020.114921

R Core Team (2013) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Raghupathi HB, Reddy YTN, Reju MK, Bhargava BS (2005) Diagnosis of nutrient imbalance in mango by DRIS and PCA approaches. J Plant Nutr 27 (7):1131-1148

Raju J, Jayalakshmi K, Sonavane PS, Raghu S (2021) Major diseases of cocoa or chocolate (Theobroma cacao L.) and their management. In: Srivastava JN, Singh AK (eds) Diseases of horticultural crops: diagnosis and management. CRC Press, Boca Raton, USA, pp 51-71

Ramtahal G, Umaharan P, Davis C, Roberts C, Hanuman A, Ali L (2022) Mitigation of cadmium uptake in Theobroma cacao L: efficacy of soil application methods of hydrated lime and biochar. Plant Soil. doi:10.1007/s11104-022-05422-4

Ranjbar F, Jalali M (2012) Calcium, magnesium, sodium, and potassium release during decomposition of some organic residues. Commun Soil Sci Plant Anal 43 (4):645-659. doi:10.1080/00103624.2012.644005

Renier C, Vandromme M, Meyfroidt P, Ribeiro V, Kalischek N, zu Ermgassen EKHJ (2022) Transparency, traceability and deforestation in the Ivorian cocoa supply chain. CABI Wallingford, UK

Rennenberg H, Schmidt S (2010) Perennial lifestyle--an adaptation to nutrient limitation? Tree Physiol 30 (9):1047-1049. doi:10.1093/treephys/tpq076

Reynolds M, Kropff M, Crossa J, Koo J, Kruseman G, Molero Milan A, Rutkoski J, Schulthess U, Balwinder S, Sonder K, Tonnang H, Vadez V (2018) Role of modelling in international crop research: overview and some case studies. Agronomy 8 (12). doi:10.3390/agronomy8120291

Ribeiro MAQ, Almeida A-AFd, Mielke MS, Gomes FP, Pires MV, Baligar VC (2013) Aluminum effects on growth, photosynthesis, and mineral nutrition of cacao genotypes. J Plant Nutr 36 (8):1161-1179. doi:10.1080/01904167.2013.766889

Riedel J, Kägi N, Armengot L, Schneider M (2019) Effects of rehabilitation pruning and agroforestry on cacao tree development and yield in an older full-sun plantation. Exp Agric 55 (6):849-865

Rietra RPJJ, Heinen M, Dimkpa CO, Bindraban PS (2017) Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. Commun Soil Sci Plant Anal 48 (16):1895-1920. doi:10.1080/00103624.2017.1407429

Rojas-Molina J, Ortiz-Cabralez L, Escobar-Pachajoa L, Rojas-Buitrago M, Jaimes-Suarez Y (2021) Decomposition and release of nutrients in biomass generated by cocoa (Theobroma cacao L.) pruning in Rionegro, Santander, Colombia. Agron Mesoam 32 (3):888-900. doi:10.15517/am.v32i3.41608

Rosolem CA, Calonego JC, Foloni JSS (2005) Potassium leaching from millet straw as affected by rainfall and potassium rates. Commun Soil Sci Plant Anal 36 (7-8):1063-1074. doi:10.1081/css-200050497

Rosolem CA, Steiner F (2017) Effects of soil texture and rates of K input on potassium balance in tropical soil. Eur J Soil Sci 68 (5):658-666. doi:10.1111/ejss.12460

Ross C (2017) Cultivating the colonies: agriculture, development, and environment. In: Ross C (ed) Ecology and power in the age of empire: Europe and the transformation of the tropical world. Oxford University Press, Oxford, UK, pp 307-347

Ruf F, Schroth G, Doffangui K (2015) Climate change, cocoa migrations and deforestation in West Africa: what does the past tell us about the future? Sustain Sci 10 (1):101-111. doi:10.1007/s11625-014-0282-4

Ruf F, Tanoh R, Galo AK (2016) Tests of fertilizers with and without nitrogen on cocoa farms in Côte d'Ivoire.

Rufino MC, Tittonell P, Van Wijk MT, Castellanos-Navarrete A, Delve RJ, De Ridder N, Giller KE (2007) Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livest Sci 112 (3):273-287

Ruseani NS, Vanhove W, Susilo AW, Van Damme P (2022) Macro-nutrient uptake by cocoa seedlings (Theobroma cacao L.) as influenced by clone and soil-applied nitrogen levels. Acta Hortic (1333):69-74. doi:10.17660/ActaHortic.2022.1333.9

Rynk R (ed) (2022) The composting handbook : a how-to and why manual for farm, municipal, institutional and commercial composters. Elsevier Academic Press, London, UK. doi:10.1016/B978-0-323-85602-7.01001-3

Sainju UM, Ghimire R, Pradhan GP (2019) Nitrogen fertilization I: Impact on crop, soil, and environment. Nitrogen Fixation, vol 9. IntechOpen, London

Saj S, Nijmeijer A, Nieboukaho J-DE, Lauri P-E, Harmand J-M (2021) Litterfall seasonal dynamics and leaf-litter turnover in cocoa agroforests established on past forest lands or savannah. Agrofor Syst 95:583-597. doi:10.1007/s10457-021-00602-0

Salètes S, Caliman J-P, Raham D (2004) Study of mineral nutrient losses from oil palm empty fruit bunches during temporary storage. J Oil Palm Res 16:11-21

Salifu A, Amedor EN, Afetsu JY (2020) Effects of biochar and compost on cocoa (Theobroma cacao) seedlings growth. Int J Environ Agric Res 6 (8):6-12

Sanginga N, Woomer PL (2009) Integrated soil fertility management in Africa: principles, practices, and developmental process. TSBF-CIAT, Nairobi

Santoso TI, Zakariyya F (2019) Several physiological changes of cocoa (Theobroma cacao L.) in response to vascular streak dieback diseases. AGRIVITA, Journal of Agricultural Science 41 (1):129-138

Saputra DD, Sari RR, Hairiah K, Roshetko JM, Suprayogo D, van Noordwijk M (2020) Can cocoa agroforestry restore degraded soil structure following conversion from forest to agricultural use? Agrofor Syst 94 (6):2261-2276. doi:10.1007/s10457-020-00548-9

Saquet AA, Streif J, Almeida DPF (2019) Mineral composition and distribution within 'Rocha' pear in relation to internal storage disorders. Postharvest Biol Technol 158. doi:10.1016/j.postharvbio.2019.111002

Sari RR, Rozendaal D, Saputra DD, Hairiah K, Roshetko JM, van Noordwijk M (2022) Balancing litterfall and decomposition in cacao agroforestry systems. Plant Soil 473 (1-2):251-271

Sari RR, Saputra DD, Hairiah K, Rozendaal DMA, Roshetko JM, van Noordwijk M (2020) Gendered species preferences link tree diversity and carbon stocks in cacao agroforest in Southeast Sulawesi, Indonesia. Land 9 (4). doi:10.3390/land9040108

Sassen M, van Soesbergen A, Arnell AP, Scott E (2022) Patterns of (future) environmental risks from cocoa expansion and intensification in West Africa call for context specific responses. Land Use Policy 119. doi:10.1016/j.landusepol.2022.106142

Sauvadet M, Saj S, Freschet GT, Essobo JD, Enock S, Becquer T, Tixier P, Harmand JM (2020) Cocoa agroforest multifunctionality and soil fertility explained by shade tree litter traits. J Appl Ecol 57 (3):476-487. doi:10.1111/1365-2664.13560

Schmidt JE, DuVal A, Puig A, Tempeleu A, Crow T (2021) Interactive and dynamic effects of rootstock and rhizobiome on scion nutrition in cacao seedlings. Front Agron 3. doi:10.3389/fagro.2021.754646

Schmidt JE, Firl A, Hamran H, Imaniar NI, Crow TM, Forbes SJ (2022) Impacts of shade trees on the adjacent cacao rhizosphere in a young diversified agroforestry system. Agronomy 12 (1). doi:10.3390/agronomy12010195

Schneidewind ULF, Niether W, Armengot L, Schneider M, Sauer D, Heitkamp F, Gerold G (2018) Carbon stocks, litterfall and pruning residues in monoculture and agroforestry cacao production systems. Exp Agric 55 (3):452-470. doi:10.1017/s001447971800011x

Schreefel L, Schulte RPO, de Boer IJM, Schrijver AP, van Zanten HHE (2020) Regenerative agriculture – the soil is the base. Glob Food Sec 26. doi:10.1016/j.gfs.2020.100404

Schreiber JD (1999) Nutrient leaching from corn residues under simulated rainfall. J Environ Qual 28 (6):1864-1870. doi:10.2136/sssaj1993.03615995005700010037x

Schroth G, Laderach P, Martinez-Valle AI, Bunn C, Jassogne L (2016) Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation. Sci Total Environ 556:231-241. doi:10.1016/j.scitotenv.2016.03.024

Schroth G, Lehmann J, Rodrigues MRL, Barros E, Macêdo JLV (2001) Plant-soil interactions in multistrata agroforestry in the humid tropics. Agrofor Syst 53 (2):85-102

Schroth G, Sinclair FL (2003) Trees, crops, and soil fertility: concepts and research methods. CABI, Wallingford-Cambridge

Schut AGT, Giller K (2020) Sustainable intensification of agriculture in Africa. Front Agric Sci Eng 0 (0). doi:10.15302/j-fase-2020357

Schwendenmann L, Veldkamp E, Moser G, HÖLscher D, KÖHler M, Clough Y, Anas I, Djajakirana G, Erasmi S, Hertel D, Leitner D, Leuschner C, Michalzik B, Propastin P, Tjoa A, Tscharntke T, van Straaten O (2010) Effects of an experimental drought on the functioning of a cacao agroforestry system, Sulawesi, Indonesia. Glob Chang Biol 16 (5):1515-1530. doi:10.1111/j.1365-2486.2009.02034.x

Scudder M, Wampe N, Waviki Z, Applegate G, Herbohn J (2022) Smallholder cocoa agroforestry systems; is increased yield worth the labour and capital inputs? Agric Syst 196:103350

Shamshuddin J, Anda M, Fauziah CI, Omar SRS (2011) Growth of cocoa planted on highly weathered soil as affected by application of basalt and/or compost. Commun Soil Sci Plant Anal 42 (22):2751-2766. doi:10.1080/00103624.2011.622822

Sharifi M, Cheema M, McVicar K, LeBlanc L, Fillmore S (2013) Evaluation of liming properties and potassium bioavailability of three Atlantic Canada wood ash sources. CanJ Plant Sci 93 (6):1209-1216. doi:10.1139/CJPS2013-168

Shimeles A, Verdier-Chouchane A, Boly A (2018) Understanding the challenges of the agricultural sector in sub-Saharan Africa. In: Shimeles AV-C, Audrey, Boly A (eds) Building a resilient and sustainable agriculture in sub-Saharan Africa. Palgrave Macmillan, Cham, pp 1-12. doi:10.1007/978-3-319-76222-7_1

Sileshi GW (2021) Dose-response models to guide site-specific nutrient management and lessons for fertiliser trial design in sub-Saharan Africa. Exp Agric 58. doi:10.1017/s0014479721000193

Singh U, Porter C (2020) Improving modeling of nutrient cycles in crop cultivation. In: Boote K (ed) Advances in crop modelling for a sustainable agriculture. Burleigh Dodds, Cambridge, UK, pp 69-99

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241 (2):155-176

Slack MK, Draugalis JR (2001) Establishing the internal and external validity of experimental studies. American Journal of Health System Pharmacy 58 (22):2173-2181

Smaling EMA, Nandwa SM, Janssen BH (1997) Soil fertility in Africa is at stake. Replenishing soil fertility in Africa 51:47-61

Smiley GL, Kroschel J (2008) Temporal change in carbon stocks of cocoa–gliricidia agroforests in Central Sulawesi, Indonesia. Agrofor Syst 73 (3):219-231

Smith R, McSwiney C, Grandy A, Suwanwaree P, Snider R, Robertson G (2008) Diversity and abundance of earthworms across an agricultural land-use intensity gradient. Soil Tillage Res 100 (1-2):83-88. doi:10.1016/j.still.2008.04.009

Snoeck D, Afrifa AA, Ofori-Frimpong K, Boateng E, Abeoke MK (2010) Mapping fertilizer recommendations for cocoa production in Ghana using soil diagnostic and GIS tools. West Afr J Appl Ecol 17:97-107

Snoeck D, Koko L, Joffre J, Bastide P, Jagoret P (2016) Cacao nutrition and fertilization. In: Lichtfouse E (ed) Sustainable Agriculture Reviews, vol 19. Sustainable Agriculture Reviews. Springer International Publishing, pp 155-202. doi:10.1007/978-3-319-26777-7_4

Sodré GA, Gomes ARS (2019) Cocoa propagation, technologies for production of seedlings. Revista Brasileira de Fruticultura 41 (2). doi:10.1590/0100-29452019782

Somarriba E, Cerda R, Orozco L, Cifuentes M, Dávila H, Espin T, Mavisoy H, Ávila G, Alvarado E, Poveda V, Astorga C, Say E, Deheuvels O (2013) Carbon stocks and cocoa yields in agroforestry systems of Central America. Agric Ecosyst Environ 173:46-57. doi:10.1016/j.agee.2013.04.013

Somarriba E, Peguero F, Cerda R, Orozco-Aguilar L, López-Sampson A, Leandro-Muñoz ME, Jagoret P, Sinclair FL (2021) Rehabilitation and renovation of cocoa (Theobroma cacao L.) agroforestry systems. A review. Agron Sustain Dev 41 (5):64. doi:10.1007/s13593-021-00717-9

Sonwa DJ, Weise SF, Schroth G, Janssens MJJ, Shapiro H-Y (2019) Structure of cocoa farming systems in West and Central Africa: a review. Agrofor Syst 93 (5):2009-2025. doi:10.1007/s10457-018-0306-7

Sreekala NV, George M, John PS, Nair RV (2001) Seasonal variation in elemental composition of cocoa litter under shaded and open conditions. Journal of Tropical Agriculture 39 (2):186-189

Srisopaporn S, Jourdain D, Perret SR, Shivakoti G (2015) Adoption and continued participation in a public good agricultural practices program: The case of rice farmers in the central plains of Thailand. Technological Forecasting and Social Change 96:242-253. doi:10.1016/j.techfore.2015.03.016

Srivastava AK (2020) Climate-smart integrated soil fertility management in fruit crops: an overview. In: Srivastava AK, Chengxiao H (eds) Fruit crops: diagnosis and management of nutrient constraints. Elsevier, Amsterdam, pp 521-540. doi:10.1016/B978-0-12-818732-6.00037-X

Srivastava AK, Wu Q-S, Mousavi SM, Hota D (2021) Integrated soil fertility management in fruit crops: an overview. International Journal of Fruit Science 21 (1):413-439. doi:10.1080/15538362.2021.1895034

Srivastava JN, Singh AK (2022) Diseases of horticultural crops: diagnosis and management: important plantation crops, medicinal crops, and mushrooms, vol 4. CRC Press, Boca Raton

Stevenson J, Vanlauwe B, Macours K, Johnson N, Krishnan L, Place F, Spielman D, Hughes K, Vlek P (2019) Farmer adoption of plot- and farm-level natural resource management practices: Between rhetoric and reality. Glob Food Sec 20:101-104. doi:10.1016/j.gfs.2019.01.003

Stewart CE, Paustian K, Conant RT, Plante AF, Six J (2007) Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86 (1):19-31. doi:10.1007/s10533-007-9140-0

Subler S (1994) Allometric equations for estimating the above-ground biomass of cacao stands in the eastern Amazon Basin. Agrotropica (Brazil) 6 (3):65-72

Surujdeo-Maharaj S, Sreenivasan TN, Motilal LA, Umaharan P (2016) Black pod and other Phytophthora induced diseases of cacao: history, biology, and control. In: Bailey BA, Meinhardt LW (eds) Cacao diseases: A history of old enemies and new encounters. Springer, pp 213-266

Susanti RA, Hadley P, Daymond AJ, Bastide P, Lambert S, Ingram K, Motamayor JC (2017) The effect of pruning on photosynthetic rate of cacao tree in a novel cropping system. Paper presented at the International Symposium on Cocoa Research (ISCR), Lima, 13-17 November 2017

Sylvester-Bradley R, Roques S, Baxter C, Kendall S (2022) Nutrient harvests: the essential yardstick to transform crop nutrition. Paper presented at the Annual IFS Conference, Cambridge, UK, 8 December

Tabo R, Bationo A, Gerard B, Ndjeunga J, Marchal D, Amadou B, Garba Annou M, Sogodogo D, Taonda J-BS, Hassane O (2007) Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa. In: Bationo A, Waswa B, Kihara J, Kimetu J (eds) Advances in integrated soil fertility management in sub-Saharan Africa: Challenges and opportunities. Springer, the Netherlands, pp 201-208

Talgre L, Lauringson E, Roostalu H, Makke A (2014) Phosphorus and potassium release during decomposition of roots and shoots of green manure crops. Biol Agric Hortic 30 (4):264-271. doi:10.1080/01448765.2014.953582

Tennhardt L, Lazzarini G, Weisshaidinger R, Schader C (2022) Do environmentally-friendly cocoa farms yield social and economic co-benefits? Ecol Econ 197. doi:10.1016/j.ecolecon.2022.107428

Tesfahunegn GB, Wortmann CS (2017) Maize [Zea Mays (L.)] crop-nutrient response functions extrapolation for Sub-Saharan Africa. Nutr Cycl Agroecosystems 109 (3):269-289. doi:10.1007/s10705-017-9887-1

Tezara W, Pereyra G, Ávila-Lovera E, Herrera A (2020) Variability in physiological responses of Venezuelan cacao to drought. Exp Agric 56 (3):407-421. doi:10.1017/S0014479720000058

Thomazini A, Spokas K, Hall K, Ippolito J, Lentz R, Novak J (2015) GHG impacts of biochar: predictability for the same biochar. Agric Ecosyst Environ 207:183-191. doi:10.1016/j.agee.2015.04.012

Thomsen ST, Kádár Z, Schmidt JE (2014) Compositional analysis and projected biofuel potentials from common West African agricultural residues. Biomass Bionerg 63:210-217. doi:10.1016/j.biombioe.2014.01.045

Thong KC, Ng WL Growth and nutrients composition of monocrop cocoa plants on inland Malaysian soils. In: International conference on cocoa and coconuts, Dunlop Research Centre, Kuala-Lumpur, Malaysia, 1980. Malaysian Agricultural Research and Development Institute & Incorporated Society of Planters, pp 262-286

Timsina J (2019) Fertilizer application on crop yield. MDPI-Multidisciplinary Digital Publishing Institute, Basel

Titiloye JO, Abu Bakar MS, Odetoye TE (2013) Thermochemical characterisation of agricultural wastes from West Africa. Ind Crops Prod 47:199-203. doi:10.1016/j.indcrop.2013.03.011

Tittonell P, Corbeels M, van Wijk MT, Vanlauwe B, Giller KE (2008) Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of kenya: Explorations using the crop-soil model FIELD. Agronomy Journal 100 (5):1511-1526. doi:10.2134/agronj2007.0355

Tittonell P, Giller KE (2013) When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res 143:76-90

Tittonell P, Muriuki A, Klapwijk CJ, Shepherd KD, Coe R, Vanlauwe B (2013) Soil heterogeneity and soil fertility gradients in smallholder farms of the east African highlands. Soil Sci Soc Am J 77 (2):525-538. doi:10.2136/sssaj2012.0250

Toledo-Hernandez M, Lander TA, Bao C, Xie K, Atta-Boateng A, Wanger TC (2021) Genome-edited tree crops: mind the socioeconomic implementation gap. Trends Ecol Evol 36 (11):972-975. doi:10.1016/j.tree.2021.08.007

Toledo-Hernández M, Tscharntke T, Tjoa A, Anshary A, Cyio B, Wanger TC (2020) Hand pollination, not pesticides or fertilizers, increases cocoa yields and farmer income. Agric Ecosyst Environ 304. doi:10.1016/j.agee.2020.107160

Tosto A, Morales A, Rahn E, Evers JB, Zuidema PAA, Niels P.R. (2023) Simulating cocoa production: a review of modelling approaches and gaps. Agric Syst 206. doi:10.1016/j.agsy.2023.103614

Tosto A, Zuidema PA, Goudsmit E, Evers JB, Anten NPR (2022) The effect of pruning on yield of cocoa trees is mediated by tree size and tree competition. Sci Hortic 304. doi:10.1016/j.scienta.2022.111275

Tovar MDL, Guzman JA, Ramirez LE, Garcia J (2022) Architecture of cocoa genotypes in Colombia as affected by bud type, grafting technique, and pruning. Pelita Perkebunan (a Coffee and Cocoa Research Journal) 38 (1):29-42

Tsai W-T, Huang P-C (2018) Characterization of acid-leaching cocoa pod husk (CPH) and its resulting activated carbon. Biomass Conversion and Biorefinery 8 (3):521-528. doi:10.1007/s13399-018-0302-1

Tscharntke T, Ocampo-Ariza C, Vansynghel J, Ivañez-Ballesteros B, Aycart P, Rodriguez L, Ramirez M, Steffan-Dewenter I, Maas B, Thomas E (2022) Socio-ecological benefits of fine-flavor cacao in its center of origin. Conserv Lett. doi:10.1111/conl.12936

Tully K, Sullivan C, Weil R, Sanchez P (2015) The state of soil degradation in sub-Saharan Africa: baselines, trajectories, and solutions. Sustainability 7 (6):6523-6552. doi:10.3390/su7066523

Turmel M-S, Speratti A, Baudron F, Verhulst N, Govaerts B (2015) Crop residue management and soil health: A systems analysis. Agric Syst 134:6-16. doi:10.1016/j.agsy.2014.05.009

Uke A, Nakazono-Nagaoka E, Chuah JA, Zain NA, Amir HG, Sudesh K, Abidin N, Hashim Z, Kosugi A (2021) Effect of decomposing oil palm trunk fibers on plant growth and soil microbial community composition. J Environ Manage 295:113050. doi:10.1016/j.jenvman.2021.113050

Umaharan P (2018) Achieving sustainable cultivation of cocoa. Burleigh Dodds Series in Agricultural Science. Burleigh Dodds Science Publishing, Cambridge, UK. doi:10.19103/AS.2017.0021

Umeh BC, Avicor SW, Dankyi E, Kyerematen R (2022) Farmers’ knowledge and practices on pollination and insecticide use in cocoa farming in Ghana. Int J Agric Sustain:1-13. doi:10.1080/14735903.2022.2106656

Uribe A, Méndez H, Mantilla J (2001) Effect of balanced fertilization on cocoa yield. Better Crops 15 (2):3

Vaast P, Somarriba E (2014) Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. Agrofor Syst 88 (6):947-956. doi:10.1007/s10457-014-9762-x

Vaikosen EN, Olu-Owolabi BI, Gibson LT, Adebowale KO, Davidson CM, Asogwa U (2019) Kinetic field dissipation and fate of endosulfan after application on Theobroma cacao farm in tropical Southwestern Nigeria. Environ Monit Assess 191 (3):196. doi:10.1007/s10661-019-7293-7

Vail G (2009) Cacao use in Yucatán among the pre-Hispanic Maya. In: Grivetti L, Shapiro H-Y (eds) Chocolate: history, culture, and heritage. Wiley, Hoboken, USA, pp 3-15. doi:10.1002/9780470411315.ch1

van Bueren EM, Lammerts van Bueren ET, van der Zijpp AJ (2014) Understanding wicked problems and organized irresponsibility: challenges for governing the sustainable intensification of chicken meat production. Curr Opin Environ Sustain 8:1-14. doi:10.1016/j.cosust.2014.06.002

van Dijk M, Morley T, Jongeneel R, van Ittersum M, Reidsma P, Ruben R (2017) Disentangling agronomic and economic yield gaps: an integrated framework and application. Agric Syst 154:90-99. doi:10.1016/j.agsy.2017.03.004

van Rooyen AF, Bjornlund H, Pittock J (2021) Beyond fertilizer for closing yield gaps in sub-Saharan Africa. Nat Food 2 (10):756-757. doi:10.1038/s43016-021-00386-7

van Straaten O, Veldkamp E, Köhler M, Anas I (2010) Spatial and temporal effects of drought on soil CO2 efflux in a cacao agroforestry system in Sulawesi, Indonesia. Biogeosciences 7 (4):1223-1235

van Vliet JA, Giller KE (2017) Mineral nutrition of cocoa. Adv Agron (141):185-270. doi:10.1016/bs.agron.2016.10.017

van Vliet JA, Slingerland MA, Waarts YR, Giller KE (2021) A living income for cocoa producers in Côte d'Ivoire and Ghana? Front Sustain Food Syst 5. doi:10.3389/fsufs.2021.732831

Vanlauwe B (2004) Integrated soil fertility management research at TSBF: the framework, the principles, and their application. In: Bationo A (ed) Managing nutrient cycles to sustain soil fertility in sub-Saharan Africa. Academy Science Publishers Nairobi, pp 25-42

Vanlauwe B (2020) Improving integrated soil fertility management (ISFM) by smallholders. The sustainable intensification of smallholder farming systems:175-186

Vanlauwe B, AbdelGadir AH, Adewopo J, Adjei-Nsiah S, Ampadu-Boakye T, Asare R, Baijukya F, Baars E, Bekunda M, Coyne D, Dianda M, Dontsop-Nguezet PM, Ebanyat P, Hauser S, Huising J, Jalloh A, Jassogne L, Kamai N, Kamara A, Kanampiu F, Kehbila A, Kintche K, Kreye C, Larbi A, Masso C, Matungulu P, Mohammed I, Nabahungu L, Nielsen F, Nziguheba G, Pypers P, Roobroeck D, Schut M, Taulya G, Thuita M, Uzokwe VNE, van Asten P, Wairegi L, Yemefack M, Mutsaers HJW (2017) Looking back and moving forward: 50 years of soil and soil fertility management research in sub-Saharan Africa. Int J Agric Sustain 15 (6):613-631. doi:10.1080/14735903.2017.1393038

Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd KD (2010) Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric 39 (1):17-24

Vanlauwe B, Coyne D, Gockowski J, Hauser S, Huising J, Masso C, Nziguheba G, Schut M, Van Asten P (2014) Sustainable intensification and the African smallholder farmer. Curr Opin Environ Sustain 8:15-22. doi:10.1016/j.cosust.2014.06.001

Vanlauwe B, Descheemaeker K, Giller KE, Huising J, Merckx R, Nziguheba G, Wendt J, Zingore S (2015a) Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil 1 (1):491-508. doi:10.5194/soil-1-491-2015

Vanlauwe B, Diels J, Sanginga N, Merckx R (2005) Long-term integrated soil fertility management in south-western Nigeria: crop performance and impact on the soil fertility status. Plant Soil 273 (1-2):337-354

Vanlauwe B, Six J, Sanginga N, Adesina AA (2015b) Soil fertility decline at the base of rural poverty in sub-Saharan Africa. Nature Plants 1:15101. doi:10.1038/nplants.2015.101

Vanlauwe B, Vanlangenhove G, Merckx R, Vlassak K (1995) Impact of rainfall regime on the decomposition of leaf litter with contrasting quality under subhumid tropical conditions. Biol Fertil Soils 20 (1):8-16

Vega CA, Torres-Bazurto J, Barrientos-Fuentes JC, Magnitskiy S, Balaguera-López HE (2021) Efecto de la fertilización orgánica y la poda sobre la producción de cacao en Cundinamarca, Colombia. Revista UDCA Actualidad & Divulgación Científica 24 (2). doi:10.31910/rudca.v24.n2.2021.1818

Veisi H, Carolan MS, Alipour A, Besheh AV (2021) Competing fields in sustainable agriculture: on farmer-expert understandings of good farming, good farmers and organic farming. Int J Agric Sustain 20 (3):289-301. doi:10.1080/14735903.2021.1929740

Vekua K (2013) Analyzing constraints for replanting aged cocoa trees with hybrid cocoa varieties among smallholder farmers in Asamankese District of Eastern Ghana. Van Hall Larenstein University of Applied Science, Leeuwarden

Vervuurt W, Slingerland MA, Pronk AA, Van Bussel LGJ (2022) Modelling greenhouse gas emissions of cacao production in the Republic of Côte d’Ivoire. Agrofor Syst 96 (2):417-434. doi:10.1007/s10457-022-00729-8

von Uexküll H, Cohen A (1980) Potassium requirements of some tropical tree crops (oil palm, coconut palm, rubber, coffee, cocoa). Potassium requirements of crops IPI Research Topic 7:71-104

Vonk WJ, Hijbeek R, Glendining MJ, Powlson DS, Bhogal A, Merbach I, Silva JV, Poffenbarger HJ, Dhillon J, Sieling K, Ten Berge HFM (2022) The legacy effect of synthetic N fertiliser. Eur J Soil Sci 73 (3):e13238. doi:10.1111/ejss.13238

Voora V, Bermúdez S, Larrea C (2019) Global market report: cocoa. In: Voora V, Bermúdez S, Larrea C (eds) Sustainable Commodities Marketplace Series 2019. International Institute for Sustainable Development, Winnipeg, MB, Canada, p 12

Voortman RL (2013) Why the green revolution failed in sub-Saharan Africa. Rural 21 Int J Rural Dev 47:32-33

Vos JGM, Ritchie BJ (eds) (2003) Discovery learning about cocoa: An inspirational guide for training facilitators. CABI Bioscience, Surrey, UK

Wainaina P, Minang PA, Duguma L, Muthee K (2021) A review of the trade-offs across different cocoa production systems in Ghana. Sustainability 13 (19). doi:10.3390/su131910945

Wang N, Jassogne L, van Asten PJA, Mukasa D, Wanyama I, Kagezi G, Giller KE (2015) Evaluating coffee yield gaps and important biotic, abiotic, and management factors limiting coffee production in Uganda. Eur J Agron 63:1-11. doi:10.1016/j.eja.2014.11.003

Waring BG, Powers JS (2017) Overlooking what is underground: root:shoot ratios and coarse root allometric equations for tropical forests. For Ecol Manag 385:10-15. doi:10.1016/j.foreco.2016.11.007

Wartenberg AC, Blaser WJ, Janudianto KN, Roshetko JM, van Noordwijk M, Six J (2018) Farmer perceptions of plant-soil interactions can affect adoption of sustainable management practices in cocoa agroforests: a case study from Southeast Sulawesi. Ecol Soc 23 (1). doi:10.5751/es-09921-230118

Welch BL (1947) The generalization of student's' problem when several different population variances are involved. Biometrika 34 (1/2):28-35

Wessel M (1971) Fertilizer requirements of cacao (Theobroma cacao L.) in south-western Nigeria. Koninklijk Instituut voor de Tropen, Wageningen

Wessel M, Quist-Wessel PMF (2015) Cocoa production in West Africa, a review and analysis of recent developments. NJAS - Wageningen Journal of Life Sciences 74-75:1-7. doi:10.1016/j.njas.2015.09.001

Wilson LRM, Cryer NC, Haughey E (2019) Simulation of the effect of rainfall on farm-level cocoa yield using a delayed differential equation model. Sci Hortic 253:371-375. doi:10.1016/j.scienta.2019.04.016

Woittiez LS (2019) On yield gaps and better management practices in Indonesian smallholder palm plantations. Wageningen University & Research, Wageningen

Woittiez LS, Turhina SRI, Deccy D, Slingerland M, Van Noordwijk M, Giller KE (2019) Fertiliser application practices and nutrient deficiencies in smallholder oil palm plantations in Indonesia. Exp Agric 55 (04):543-559. doi:10.1017/s0014479718000182

Woittiez LS, van Wijk MT, Slingerland M, van Noordwijk M, Giller KE (2017) Yield gaps in oil palm: A quantitative review of contributing factors. Eur J Agron 83:57-77. doi:10.1016/j.eja.2016.11.002

Wu W, Ma B (2015) Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. Sci Total Environ 512-513:415-427. doi:10.1016/j.scitotenv.2014.12.101

Wu X, Liu H, Li X, Ciais P, Babst F, Guo W, Zhang C, Magliulo V, Pavelka M, Liu S, Huang Y, Wang P, Shi C, Ma Y (2018) Differentiating drought legacy effects on vegetation growth over the temperate Northern Hemisphere. Glob Chang Biol 24 (1):504-516. doi:10.1111/gcb.13920

Xia S-W, Chen J, Schaefer D, Detto M (2015) Scale-dependent soil macronutrient heterogeneity reveals effects of litterfall in a tropical rainforest. Plant Soil 391 (1-2):51-61. doi:10.1007/s11104-015-2402-z

Yaconnelo-Hernandez MJ, de Jesus Cordoba-Gaona O, Redondo-Herrera VM, Hernandez-Arredondo JD, Arenas-Rubio I, Perez-Artiles L (2021) Renovation and rehabilitation practices of unproductive cacao plantations: Strategies to maintain production in Colombia. Rev Fitotec Mex 44 (4):625-633

Yadvinder S, Bijay S, Timsina J (2004) Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Adv Agron 85:270-409

Yahdjian L, Sala OE (2008) Do litter decomposition and nitrogen mineralization show the same trend in the response to dry and wet years in the Patagonian steppe? J Arid Environ 72 (5):687-695. doi:10.1016/j.jaridenv.2007.09.005

Yang HS, Janssen BH (2000) A mono-component model of carbon mineralization with a dynamic rate constant. Eur J Soil Sci 51 (3):517-529

Yang Z, Zhou B, Ge X, Cao Y, Brunner I, Shi J, Li MH (2020) Species-specific responses of root morphology of three co-existing tree species to nutrient patches reflect their root foraging strategies. Front Plant Sci 11:618222. doi:10.3389/fpls.2020.618222

Yao MK, Koné AW, Otinga AN, Kassin EK, Tano Y (2021) Carbon and nutrient cycling in tree plantations vs. natural forests: implication for an efficient cocoa agroforestry system in West Africa. Reg Environ Change 21 (2):44. doi:10.1007/s10113-021-01776-0

Zaia FC, Gama-Rodrigues AC, Gama-Rodrigues EF, Moço MKS, Fontes AG, Machado RCR, Baligar VC (2012) Carbon, nitrogen, organic phosphorus, microbial biomass and N mineralization in soils under cacao agroforestry systems in Bahia, Brazil. Agrofor Syst 86 (2):197-212. doi:10.1007/s10457-012-9550-4

Zhang Y, Li Y, Jiang L, Tian C, Li J, Xiao Z (2011) Potential of perennial crop on environmental sustainability of agriculture. Procedia Environ Sci 10:1141-1147. doi:10.1016/j.proenv.2011.09.182

Zhu AX, Liu J, Du F, Zhang SJ, Qin CZ, Burt J, Behrens T, Scholten T (2015a) Predictive soil mapping with limited sample data. Eur J Soil Sci 66 (3):535-547. doi:10.1111/ejss.12244

Zhu Q, Schmidt JP, Bryant RB (2015b) Maize (Zea mays L.) yield response to nitrogen as influenced by spatio-temporal variations of soil–water-topography dynamics. Soil Tillage Res 146:174-183. doi:10.1016/j.still.2014.10.006

Zuber SM, Villamil MB (2016) Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. Soil Biol Biochem 97:176-187. doi:10.1016/j.soilbio.2016.03.011

Zuidema PA, Leffelaar PA, Gerritsma W, Mommer L, Anten NPR (2005) A physiological production model for cocoa (*Theobroma cacao*): model presentation, validation and application. Agric Syst 84 (2):195-225. doi:10.1016/j.agsy.2004.06.015

Zweifel R, Sterck F (2018) A conceptual tree model explaining legacy effects on stem growth. Front For Glob Change 1. doi:10.3389/ffgc.2018.00009

Summary

Chocolate consumers, through the downstream industry, put pressure on supply chain actors to improve global sustainability of cocoa. West Africa, the heartland of cocoa production, is confronted with low crop productivity and poverty of farmers who, having no control over fluctuating prices, are forced to open new plantations in remaining forest patches to sustain their families, thus causing deforestation. Expanding cocoa land in this manner, without adequate nutrient supply, exhausts soil fertility and results in rapid yield decline and yield stagnation on established fields. A major initiative to address these challenges was launched with the CocoaSoils programme, which aims to achieve sustainable intensification of cocoa production through the development and dissemination of Integrated Soil Fertility Management (ISFM) knowledge. Despite being long-established in arable farming, never before was the ISFM paradigm applied at scale to a tropical tree crop system. The overarching objective of this thesis was to explore how ISFM could be operationalized in West African cocoa farms and to better understand nutrient cycling as a first step towards improved nutrient management. Four individual studies presented in this thesis comprised a discussion of the paradigm, seeking meaningful adaptation to cocoa, followed by assessments of two selected components of nutrient cycles, and a field test of fertilizer application.

The guiding principles of ISFM are: (a) the use of improved germplasm; (b) management according to sound agronomic principles; (c) alleviating local site and soil constraints; (d) efficient use of mineral fertilizer; and (e) the use of organic inputs, all with the aim of maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. Are these principles aligned with the characteristics and functioning of mature smallholder cocoa production systems? A literature review quantified major stocks and flows of carbon (C), nitrogen (N), phosphorus (P) and potassium (K), and insights were given into practical implementation of ISFM in cocoa. A large amount of C and plant nutrients circulate within a mature cocoa crop, which enables maintenance of soil organic matter and preserves other soil properties. This questions the common interpretation of the core principle of ISFM: (e) the use of (external) organic inputs. Large knowledge gaps make an accurate estimation of crop

nutrient requirements impossible and fertilizer recommendations inaccurate. Meanwhile, other crop-specific management practices such as pruning and pod husk disposal strongly affect internal nutrient circulation and biomass allocation to tree organs, and must be central to ISFM in cocoa. Managing an existing plantation resembles to a situation whereby the farmer is limited by the legacy effects of previous management, environmental conditions and unchangeable poor-quality genetic materials. In addition, on-farm organic resource availability is limited beyond the cocoa field, hampering the production of sufficient quantities of compost or biochar. Therefore, there is little scope to implement radical changes, unless through replanting.

The farmer is further limited in that he/she has no control over large nutrient flows. A production of 10 ton ha^{-1} year^{-1} of litter was estimated in three farms located in south-western Nigeria, corresponding to an annual transfer of approximately 101 kg N ha^{-1}, 5 kg P ha^{-1}, and 89 kg K ha^{-1} from vegetation to soil through litterfall. Apart from K, these nutrients are not immediately available for uptake by cocoa trees: after a year of decomposition, 90% K, but only 33% N, and virtually no P was lost from the litter layer. Macrofauna significantly increased relative litter decomposition rates and N and P flows from the litter layer, but these effects were previously not estimated in cocoa.

Unlike litter, cocoa pod husks are subjected to a more flexible management by farmer. The husks are rich in K, but are often abandoned to rot in heaps after cocoa beans are extracted, resulting in nutrients concentrating in a few spots within or outside the field. Short-term nutrient release patterns during cocoa pod husk decomposition were analysed in a laboratory leaching experiment whereby chunks were submitted to two rainfall amounts and three rainfall frequencies in a full-factorial design. Potassium losses recorded within 25 days were large and strongly affected by rainfall frequency. When fresh cocoa pod husks were water-saturated, 11% of K was lost within 2 days; but such losses amounted to 92% for partially-decayed chunks. This study showed that initial decomposition of cocoa pod husks was required to expose K to rapid leaching losses; but considerable losses occurred thereafter, especially under higher rainfall event frequencies.

Among the panoply of ISFM practices, only fertilizer application was tested because it had *a priori* the greatest potential to combat nutrient mining and rapidly increase cocoa yields. The objective was to measure fertilizer yield response and yield response variability under farmer management. Three fertilizer schemes, only differing in the N rates applied, were tested in ten nearby smallholder farms in fields with cocoa trees of 15-20 years. Large field-to-field and tree-to-tree variability combined with limited treatment effects highlighted the challenges related to measuring yield responses on-farm. Moreover, the overall lack of cocoa yield response indicates that we should question whether applying fertilizers is the most logical entry-point to sustainable intensification of current smallholder cocoa farms.

This thesis thus invites the research community to engage in a deeper reflection of how to sustainably intensify the current cocoa production systems in West Africa. It recognizes that our current knowledge of the systems is too limited to address the yield increase challenge adequately. To answer the many remaining questions, further tests are needed on younger cocoa stands and methodological constraints of field experiments should be leveraged by embracing complementary research methods and alternative options to ISFM.

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PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review/project proposal (10.5 ECTS)

- Integrated soil fertility management in cocoa: assessment of current options
- Carbon dynamics, nutrient use efficiency, and productivity of cocoa plantations

Post-graduate courses (5.6 ECTS)

- Farming systems and rural livelihoods: pathways to sustainability; PPS (2018)
- Meta-analysis; PE&RC (2018)
- Crop physiology and climate change; PE&RC (2022)

Invited review of journal manuscripts (1 ECTS)

- Agroforestry Systems: nutrient cycling (2021)

Competence strengthening/skills courses (2.8 ECTS)

- Webinar: career opportunities after your PhD; AcademicTransfer.nl (2022)
- Essentials of scientific writing; WGS (2022)
- Career exploration; WUR (2022)

Scientific integrity ethics in science activities (0.3 ECTS)

- Ethics in plant science; PE&RC (2022)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

- PE&RC First years weekend (2018)

Discussion groups / local seminars or scientific meetings (5.6 ECTS)

- 1st CocoaSoils annual meetings; Ghana (2019)
- 2nd CocoaSoils annual meetings; Cameroon (2020)
- 3rd CocoaSoils annual meetings; online (2021)
- 4th CocoaSoils annual meetings; online (2022)

International symposia, workshops and conferences (6 ECTS)

- 1st Farmer centric on farm experimentation; online (2021)
- 5th World congress on agroforestry; online (2022)
- International symposium on cocoa research; Montpellier (2022)

BSc/MSc thesis supervision (5 ECTS)

- Litterfall, litter decomposition, and nutrient release in low-shade cocoa agroforestry systems in South-West Nigeria
- Biomass accumulation and partitioning in cocoa: effect of age, fertilizer application, and shade

About the author

Deo-Gratias was born and grew up in Cotonou (Benin). He was rather an average student who followed an ordinary curriculum. His rare encounters with actual food production were realized when he would go on holidays to his father's farm then located at some 30 km in the outskirt of the city. In 2000, he enrolled at the Faculty of Agronomic Sciences of the University of Abomey-Calavi (FSA-UAC) and earned a degree of Agronomist Engineer in 2005. He started his career in the northside of the country as an agricultural extension officer first for the cotton crop only, and a year later for all major crops in smallholder farms. An extensive contact with the rural world spurred questions about methods of agricultural research and validity of the recommendations passed onto the extension service. The impossible dialogue with key actors pushed him to search more knowledge. In 2012, he registered for a short course at UNESCO-Institute of Water Education in Delft, and discovered another passion: travelling. He also understood that his contribution as extensionist would not have the same impact as researcher. After earning a MSc in Sustainable Agricultural Development at University of Copenhagen (KU) and Montpellier SupAgro (IRC) in 2016 under the auspices of AgrisMundus, he joined the national centre of cotton research (CRA-CF). His thirst of knowledge could not be quenched by the stiff-necked methodologies then employed in the research centre. Thanks to a friend of his, Marius Assogba, he successfully applied to the PhD position which made up the last five years he joyfully spent at the Plant Production System Group (PPS). Deo-Gratias is convinced that everyone has the right to be a pilgrim. Inquisitive and open-minded, his preferred pilgrimage sites are located near the mountain cols of sustainability and tropical crop system analysis. He can be contacted at shadowhgni@yahoo.fr.

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