Sustainability of traditional cocoa agroforests in Ghana

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Dedication

Dedicated to God for the gift of my life.

"And the Lord brought us out of Egypt with a mighty hand and an outstretched arm and with great terror with signs and wonders" Deuteronomy 26:8.

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English summary

Cocoa (*Theobroma cacao* L.) is an important agricultural commodity that is important to the economies of many countries in the world. Due to cocoa's dependence on fertile forests soils, its production is a major cause of deforestation and soil degradation in producing countries. When grown in agroforestry systems it can conserve biodiversity, sequester carbon (C), and maintain soil fertility. There are many cocoa agroforests which are managed without synthetic agrochemicals. Because organic cocoa certification is now gaining attention in Africa, studies comparing cocoa agroforests under organic management and conventional systems are scarce. To fill knowledge gaps comparing the performance of these management systems, this thesis aimed at comparing the profitability (Study 1), soil fertility (Study 2), and internal nutrient cycling (Study 3) between cocoa agroforests under conventional and organic management. All three studies were conducted in Suhum Municipality in the Eastern Region of Ghana using four villages (two villages per management type).

Study 1 aimed at assessing profitability of the two managements with or without C payments using 100 farmers per management. Net present value of cash flow (NPV), benefit cost ratio (BCR) and modified internal rate of return (MIRR) were used as profitability indicators. Profitability indicators were recalculated under three assumed scenarios: 300% interest rate from 8% to 24%, 20% yield loss, and 10% increase in cost. Results showed conventional management having 13% greater NPV than organic management. Managements were most sensitive to 300% interest rates, but organic farms were more sensitive than conventional farms. Management had no effect on C sequestered. Theoretical C payments at low price (7.5 € t^{-1} CO_2eq^{-1}) made organic management reduce their NPV deficit to conventional management from 13% to 7%. But at a high C price (42 € t^{-1} CO_2eq^{-1}) NPV was similar for both management systems.

Study 2 assessed management effect on soil physico-chemical and microbial properties at depths 0–10 cm and 10–30 cm. Management had no significant effects on soil physico-chemical properties measured. Low chemical properties and microbial biomass C and N observed in Con 2 were due to low clay content. Pairwise comparison in the topsoil showed that organic management had a 35% significantly lower metabolic quotient (qCO_2) than its conventional counterpart, whereas in the subsoil management had no effect on qCO_2. Soil organic C, clay, and pH had a positive effect on microbial biomass C and N.

Study 3 compared litterfall and cocoa leaf decomposition between conventional and organic managements. Monthly litterfall was collected using litterboxes whereby decomposition was studied using a litterbag technique for 12 months. Average annual litterfall was 8 t ha^{-1} yr^{-1}. Management had no effect on annual litterfall, however, during dry season litterfall was 60% significantly greater than in the rainy season. The rate of cocoa leaf decomposition in organic villages was on average 16% greater than in conventional villages.

The results showed that it will be technically easy for conventional cocoa agroforesters to adopt organic management due to major similarities between both systems in Suhum Municipality. On the more general level the results show the feasibility of using traditional cocoa agroforests in REDD+ projects due to their ability to sequester C and provide income for farmers.

Zusammenfassung

Kakao (*Theobroma cacao* L.) ist eine wichtige landwirtschaftliches Kultur, die für die Wirtschaft vieler Länder der Welt von Bedeutung ist. Da der Kakaoanbau auf fruchtbare Waldböden angewiesen ist, ist er eine der Hauptursachen für die Entwaldung und Bodendegradation in den Erzeugerländern. Wenn er jedoch in einem Agroforstsystem angebaut wird, kann er dazu beitragen, die biologische Vielfalt zu erhalten, C zu binden und die Bodenfruchtbarkeit zu bewahren. Es gibt viele Kakao-Agroforstsysteme, dereneren Bewirtschafter auf den Einsatz mineralischer Dünger und anderer Agrochemikalien verzichten. Auch wenn die Zertifizierung von ökologischem Kakao in Afrika zunehmend an Bedeutung gewinnt, gibt es nur wenige Studien, die einen Vergleich zwischen diesem Bewirtschaftungssystem und den konventionellen Pendants durchführen. Ziel dieser Arbeit war es daher, die Wirtschaftlichkeit (Studie 1), die Bodenfruchtbarkeit (Studie 2) und die internen Nährstoffkreisläufe (Studie 3) zwischen konventionell und ökologisch bewirtschafteten Kakaoagroforstsytemen zu vergleichen. Alle drei Studien wurden in vier Dörfern der Gemeinde Suhum in der Eastern Region Ghanas (zwei Dörfer pro Bewirtschaftungsform) durchgeführt.

In Studie 1 wurde die Wirtschaftlichkeit der beiden Bewirtschaftungsformen mit und ohne Kohlenstoff-Ausgleichzahlungen mit 100 Landwirten pro Bewirtschaftungsform untersucht. Als Rentabilitätsindikatoren wurden der Kapitalwert (NPV), das Kosten-Nutzen-Verhältnis (BCR) und der modifizierte interne Zinssatz (MIRR) verwendet. Die Indikatoren wurden unter drei angenommenen Szenarien berechnet: 300% Zinssatz von 8% auf 24%, 20% Ertragsverlust und 10% Kostensteigerung. Die Ergebnisse zeigten, dass die konventionelle Bewirtschaftung einen um 13% höheren Kapitalwert hat als die ökologische Bewirtschaftung. Die Bewirtschaftung reagierte am empfindlichsten auf einen Zinssatz von 300%, wobei die ökologischen Betriebe empfindlicher reagierten als die konventionellen Betriebe. Die Bewirtschaftungsform hat keinen Einfluss auf den gebundenen Kohlenstoff. Theoretische Kohlenstoff-Ausgleichszahlungen bei niedrigem CO_2-Preis (7,5 € t^{-1} $CO2eq^{-1}$) führten dazu, dass die ökologische Bewirtschaftung ihr Kapitalwertdefizit gegenüber der konventionellen Bewirtschaftung von 13% auf 7% reduzierte. Bei einem hohen CO_2-Preis (42 € t^{-1} $CO2eq^{-1}$) war der Kapitalwert unabhängig von der Bewirtschaftungsform jedoch ähnlich.

In Studie 2 wurden die Auswirkungen der Bewirtschaftung auf die physikalisch-chemischen und mikrobiellen Eigenschaften des Bodens in den Tiefen 0 - 10 cm und 10 - 30 cm untersucht. Die Bewirtschaftungsform hatte keinen signifikanten Einfluss auf die gemessenen physikalisch-chemischen Bodeneigenschaften. Die in Con 2 beobachteten niedrigen chemischen Eigenschaften und mikrobiellen Biomassen C und N sind auf den geringen Tongehalt zurückzuführen. Ein paarweiser Vergleich im Oberboden ergab, dass der Stoffwechselquotient (qCO_2) in ökologisch bewirtschafteten Betrieben um 35% niedriger war als in konventionellen Betrieben. Im Unterboden war dieser Effekt jedoch nicht nachweisbar. Der organische Kohlenstoff-Gehalt des Bodens, der Tongehalt und der pH-Wert wirkten sich positiv auf die mikrobielle Biomasse von C und N aus.

Studie 3 verglich den Streufall und die Zersetzung der Kakaoblätter zwischen konventioneller und ökologischer Bewirtschaftung. Der monatliche Streufall wurde mit Hilfe von Streukästen gesammelt, während die Zersetzung mit Hilfe der Streusacktechnik über 12 Monate hinweg untersucht wurde. Der durchschnittliche jährliche Streufall betrug 8 t ha^{-1} $Jahr^{-1}$. Die Bewirtschaftungsform hatte keinen Einfluss auf den jährlichen Streufall, jedoch war der Streufall in der Trockenzeit um 60% signifikant höher als in der Regenzeit. Die Zersetzungsrate der Kakaoblätter war in den ökologisch bewirtschafteten Dörfern 16% höher als in den konventionell bewirtschafteten Dörfern.

Die Ergebnisse zeigen, dass es für konventionelle Kakaobauern grundsätzlich unproblematisch wäre, zur einer ökologischen Bewirtschaftungsform zu welchseln, da die Bewirtschaftungsmethoden in der Gemeinde Suhum ähnlich sind. Allgemein zeigen diese Ergebnisse, dass traditionelle Kakao-Agrarwälder gut in REDD+-Projekte integrierbar sind, da beachtliche Mengen an Kohlenstoff binden und den Bauern Einkommensmöglichkeiten bieten.

Chapter 1

General introduction, objectives, and hypotheses

1.1 Introduction

This thesis is structured in five chapters. Chapter 1 contains a general introduction which provides an overview of cocoa production systems, problem statement of the study, the objectives and hypotheses. Chapter 2 focuses on the financial and economic profitability of cocoa agroforests under conventional and organic management. Chapter 3 details soil fertility properties in traditional cocoa agroforestry systems under conventional and organic management. Chapter 4 comprises a quantification of nutrients stocks in litterfall and the rate of nutrient decomposition in cocoa agroforests. Lastly, Chapter 5 contains a general discussion, conclusions, and recommendations.

1.1.1 The cocoa tree (*Theobroma cacao* L.) and its global importance

Cocoa belongs to the family of Malvaceae and originated from South America (Motamayor et al., 2002). In the wild, the tree grows up to 12 – 15 m (Opoku-Ameyaw et al., 2010), but due to pruning under cultivation its size usually reaches 3 – 5 meters (De Almeida and Valle, 2007). The three main varieties of cocoa are the Criollo, Forastero and Trinitario. Initially, Criollo was cultivated by the Mayas since 1500 years ago (Motamayor et al., 2002). Its pods have a soft texture with green or red colour when unripe (Opoku-Ameyaw et al., 2010). Upon ripening, they turn to yellow or orange. Their processed beans have a fine flavour and pleasant aroma (Marita et al., 2001). However, Criollo cocoa is very susceptible to pests and diseases (Opoku-Ameyaw et al., 2010). Compared to Criollo varieties, Forastero varieties are more disease resistant and higher yielding. Such characteristics make them the favoured variety, contributing 80% of global production (Marita et al., 2001). Forasteros are divided into Upper and Lower (Amelonado) Amazonia types. As the name suggests, the Amazonia varieties were originally cultivated along the wide Amazon River basin (De Almeida and Valle, 2007). They are known for their bitter bean taste and harsh flavour (Opoku-Ameyaw et al., 2010). Their pods have a hard texture, are green when unripe and turn yellow after ripening. Trinitario types are cross-breeds between Criollo and Forastero (Motamayor et al., 2002; Yang et al., 2013). They possess intermediate botanical characteristics of the two-parent materials. Their pods are red or purple when unripe and turn orange upon ripening (Opoku-Ameyaw et al., 2010). These hybrids originated from Trinidad, hence the name "Trinitario" (Yang et al., 2013).

Cocoa is cultivated in the humid tropics of Africa, Southeast Asia, and throughout Latin America. Latin America and Trinidad dominated its production at the beginning of the 19^{th} century (Cunninham and Arnold, 1962). However, currently West Africa dominates in production, with Cote d'Ivoire and Ghana being the largest producers. Cocoa is mainly grown for its beans which is the primary raw material for the chocolate industry. The industry, according to Research and Markets (2020), was worth US$ 137 billion in 2019, and it is projected to grow to US$ 182 billion by 2025. Increasing demand led to a record global cocoa bean production of 5,024 million t in the 2020/21 cropping season

(International Cocoa Organization, 2021). It is estimated that 90% of the world's cocoa is produced on small land sizes ranging from 2 – 5 ha (World Cocoa Foundation, 2012). The crop directly employs 5 – 6 million farmers globally, with 40 – 50 million depending on it for their livelihoods (World Cocoa Foundation, 2012).

1.1.2 Classification of cocoa production systems

Complexity in stand characteristics has been used to classify cocoa production systems worldwide (Rice and Greenberg, 2000). Shade canopies in cocoa systems vary widely between geographical areas, with major inter-farm variation within the same geographic area (Somarriba et al., 2018). Full sun or monoculture cocoa is the simplest production system. Such farms have <10 to >1000 cocoa trees (Siebert, 2002; Ruf, 2011; Tondoh et al., 2015). They usually require high application levels of mineral fertilizers to produce high yields. However, after 25 years declining yields necessitate cocoa tree cuttings and replanting (Obiri et al., 2007; Nunoo and Owusu, 2017). In cocoa producing countries, farmers practicing this system are primarily migrants (Ruf, 2011), have no association with farmer-based organizations, and are less secure in land tenure (Jacobi et al., 2013; Gyau et al., 2015). Hence their interest is to get short term benefits with less focus on long term sustainability. These systems often also have a rather simple, often monospecies shade with just a single stratum above the cocoa canopy, given that cocoa is intercropped with a single tree species. Intercropped trees may be N_2-fixing species like *Gliricidia sepium* (Leuschner et al., 2013), commercial timber species like *Terminalia ivorensis* (Somarriba & Beer, 2011), *Cocos nucifera* (Osei-Bonsu et al., 2002), and fruit trees like *Citrus sinensis* (Koko et al., 2013). The density of cocoa and shade trees range from 1030 – 1115 trees ha^{-1} and 44 – 325 trees ha^{-1}, respectively.

Some systems have remnants of forest trees and mixed planted shade intercropped with cocoa called the “mixed shade system” (Somarriba et al., 2013; Madountsap et al., 2018; Notaro et al., 2020). Typologically, they usually have high tree diversity, C sequestration, and low cocoa tree density (Notaro et al., 2020). Canopy strata are more complex than the monospecies shade. The most complex canopy strata are the rustic cocoa, with more remnant forest trees than in the mixed shade system (Sambuichi et al., 2012; Sonwa et al., 2017; Marconi and Armengot, 2020). Due to their structural complexity, Gama-Rodrigues et al. (2010) reported cocoa systems’ potential to sequester soil C being comparable to Brazilian natural forests. Somarriba & Lachenaud (2013) argued for the addition of successional cocoa agroforests or wild cocoa found along the Amazon River to the cocoa typology. The authors defined it as having a forest-like physiognomy, high species diversity, low cocoa density, and low yield. Jacobi et al. (2014) observed that this cocoa system could store 3-times more C in shade trees than in mixed shade systems.

Apart from the full sun cocoa, all the aforementioned production systems are broadly categorized as cocoa agroforestry systems. Moreover, cocoa production systems can be classified as either conventional or organic (Häger, 2012; Akesse-Ransford et al., 2021). Under the organic production scheme the use of synthetic fertilizers, pesticides and herbicides on cocoa farms are prohibited. Other authors have combined stand complexity and inputs to facilitate a classification of full sun and agroforestry systems under conventional and organic management (Armengot et al., 2016; Niether et al., 2019; Schneidewind et al., 2019).

1.1.3 Organic cocoa management

According to the International Federation of Organic Agriculture Movements - IFOAM (2005), organic agriculture fosters the health of soils, ecosystems and people. It relies on ecological processes, biodiversity, and matter cycles adapted to local conditions rather than inputs with potentially adverse effects. Organic agriculture combines tradition, innovation and process knowledge to the benefit the environment, ideally it may also promote fair relationships and good quality of life for all involved. It revolves around the fundamental principles of health, ecology, fairness, and care (IFOAM, 2005). In the early 20th century, prior to synthetic fertilizer and pesticide use all agricultural production was organic by default (Paarlberg, 2013). The organic movement started in Europe after the two German chemists, Fritz Haber and Carl Bosch, discovered the process of making synthetic N fertilizer in 1909. At the same time Austrian Philosopher Rudolf Steiner was a strong critic of synthetic fertilizer use, hence he championed biodynamic cropping. This approach proposed growing crops with composted manure in addition to other extracts like chamomile blossom (*Matricaria chamomilla* L.) and oak bark (*Quercus spp.)*. At the same time, Sir Albert Howard, a botanist in England, was also skeptical about artificial fertilizer and thus championed composting. According to Paarlberg (2013), in 1942, American Jerome Irving Rodale used the term organic in his published magazine "Organic Garden and Farming" after getting inspired by writings of Sir Albert Howard. At that time, organic farming was restricted to backyard gardening due to high costs and lacking market demand for premium products. In the USA a pivotal moment for organic agriculture was in 1990, when the US Congress mandated the creation of a national standard for organic products certification and labelling (Paarlberg, 2013).

With increasing health-related issues related to negative side effects of conventional agricultural practices and a growing consumer demand for healthy foods, commercialization of organic farming grew globally.

Willer et al. (2021) estimated that in 2019, 72.3 million ha of land was used for organic agriculture, constituting a meagre 1.5% of the world's agricultural land. Of the total land under organic farming 0.4 million ha (8%) were used for cocoa production. Organic cocoa is highly valued and has high demand from premium chocolate brands because of its acidity and bitter taste compared with conventional produce (Market Report, 2017). This is explained by organic cocoa beans high total polyphenol and flavonoid content (Anyidoho et al., 2021). The global organic cocoa market for 2021 amounted to US $ 571 million, and it is projected to reach US $ 943 million in 2028 (Fortune Business Insights, 2021). Organic cocoa bean production is concentrated in South America, with the Dominic Republic alone in 2013 producing 70%, whereas Africa produced only 5% (Potts et al., 2014). The authors associated low organic cocoa production with high fees for organic certification, organic market inaccessibility and, particularly for Africa, high pest infestation of organic production systems.

1.1.4 Importance of cocoa agroforestry systems

Cocoa agroforests are one way for improving farmers' well-being and livelihood, biodiversity conservation, C sequestration, and soil fertility sustenance.

1.1.4.1 Economic benefits

Shade trees incorporated into cocoa farms may provide fruits, timber, medicines, fuelwood and, resins (Gockowski et al., 2010; Osei-Bonsu et al., 2002; Graefe et al., 2017). Although shade trees play essential roles in the livelihood and well-being of smallholder farmers, they have received little attention (Cerda et al., 2014). The timber obtained from shade trees can be used domestically to repair and build houses or it can be sold. A study by Somarriba et al. (2014) in Costa Rica, using *Cordia alliodora* as cocoa shade, highlighted that the shade crop tree yielded 4.43 m^3 ha^{-1} yr^{-1} with an annual market value of US$ 265 ha^{-1}. Also, the authors estimated that after ten years, the harvestable standing timber amounted to US$ 2,633 ha^{-1} in family savings. Because of this, shade trees are referred to as the savings account that small farming families rely on when cocoa prices fall, or environmental conditions like drought, bush fire, or disease negatively affect the yields of cocoa (Beer et al., 1998; Somarriba and Beer, 2011). Some have argued against timber for shade in cocoa as its exploitation may damage cocoa trees (Osei-Bonsu et al., 2002). However, Ryan et al. (2009) argued that the sale of timber trees could quickly compensate for the damage caused to cocoa trees. Fruits trees, such as *Cocos nucifera* L., *Citrus* × *sinensis* L., *Persia americana* Mill., *Mangifera indica* L., ensure that farming families may become self-sufficient and have diversified income (Gockowski et al., 2010; Osei-Bonsu et al., 2002; Graefe et al., 2017). Gockowski et al. (2010) observed that mango (*Mangifera indica* L.), orange (*Citrus* × *sinensis* L.) and African plum (*Dacryodes edulis*) contribute significantly to the daily dietary requirements and financial returns of small-scale cocoa farmers in Cameroun. Domestic consumption is critical for resource-poor farmers as it implies savings for household expenses. Shade trees such as *Alstonia boonei* and *Rauwofia vomitoria* are traditionally used to treat malaria (Gockowski et al., 2010). Such herbal remedies can make farmers save about US$ 27 per attack compared to pharmaceutical drugs (Gockowski et al., 2010). This is important for communities with no native forests and medical centres. However, some trees such as orange and avocado pear (*Persia americana* Mill.) serve as hosts to pests like rodents, mirids (*Sahlbergella singularis*), and mistletoe (*Tapinanthus bangwensis*) (Graefe et al., 2017). Also, some shade trees have been identified as hosts for virus which causes the cocoa swollen shoot and fungi *Phytophthora spp*. causing black pod disease (Akrofi et al., 2015; Ameyaw et al., 2015).

1.1.4.2 Biodiversity conservation

There is often a conflict between cocoa production and biodiversity conservation in the tropics because of the crop's preference for a tropical climate, and its cheap and easy cultivation in tropical forests (Clough et al., 2009). The same tropical forests are also areas of high biodiversity. Cocoa agroforests are important as they deliver agricultural output and foster biodiversity. In comparison to natural forests, they have less species diversity, but their diversity is higher than in monocultures. Maney et al. (2022) found that the biodiversity intactness of cocoa agroforests was 22% lower than in primary forests but 14% higher than in monocultures. Similarly, dung beetle species richness was reduced in the order of forest, cocoa agroforest, plantain agroforest, and plantain monoculture (Harvey et al., 2006). The removal of under forest canopies and forest thinning associated with cocoa agroforest establishment leads to its inferiority in species richness and diversity compared with forests (Sambuichi et al., 2012). Cocoa agroforests' ability to hold more biodiversity than monoculture is due to their structural complexity, which makes them mimic a forest, create niches, and regulate the microclimate (Niether et al., 2020). For this reason, they may also help to connect fragmented forests landscapes (Asare et al., 2014) and act as biological corridors for migratory fauna and flora (Reitsma et al., 2001). Cocoa agroforests' ability to play ecological roles is influenced by the previous land use after which they were established. Vera-Vélez et al. (2019) observed higher tree diversity in cocoa agroforests established from forests than those with fallow and croplands as previous land use. These trees are remnants of the forests, and most trees in cocoa landscapes result from natural regeneration (Graefe et al., 2017). Some authors reported a negative correlation between management intensity and species conservation in cocoa agroforests (Hervé & Vidal, 2008; Wade et al., 2010; Kone et al., 2014). As management intensifies, tree cover is reduced to increase cocoa yield, reducing habitats for various species. Furthermore, the closeness of cocoa agroforests to markets may enhance intensification, causing the replacement of trees with other common and marketable fruit trees (Sonwa et al., 2007, 2017).

1.1.4.3 Carbon sequestration

Natural forests serve as important sinks for CO_2, however, their conversion into cocoa cultivation reduces this important ecosystem service. Considerable evidence suggests that the presence of shade trees in cocoa agroforests improves C sequestration than without trees (Asase et al., 2008; Jacobi et al., 2014; Jadan et al., 2015). Asase et al. (2008) recorded substantially higher C stocks in natural forests (224 t C ha^{-1}) than in cocoa agroforests (155 t C ha^{-1}) and cocoa monoculture (71.9 t C ha^{-1}). For cocoa cabruca in Brazil, Gama-Rodrigues et al. (2010) found C stocks comparable to those in natural forests. Hence the ability of cocoa agroforests to sequester C depends on management intensity. Increases in intensity reduce sequestered C. Intensifying traditional agroforests in Cameroun led to a three-fold reduction in their C stocks (Madountsap et al., 2018). The authors noticed that C stocks increased with age of cocoa agroforests irrespective of the management intensity. Annual total C accumulation rate for cocoa agroforests has been reported to range from 5.4 – 7.9 t ha^{-1} yr^{-1} (Somarriba et al., 2013). Under the same management conditions, Nijmeijer et al. (2018) observed that cocoa agroforests established on previously forested land had aboveground C stocks 48% larger than previous savannah lands. According to the authors, this difference was due to natural tree regeneration on the previous forest sites. Furthermore, their results showed that established cocoa agroforests had C stocks 6.3-folds higher than the surrounding savannah control implying that cocoa agroforests could be used as a cost-effective way to reforest savannah and to enhance C storage in soils.

1.1.4.4 Soil fertility sustenance

Cocoa agroforests have high SOC comparable to those in natural forests (Zaia et al., 2012; Dawoe et al., 2014). This is due to their ability to supply high litterfall (10 Mg ha^{-1} yr^{-1}; Dawoe et al., 2010; Fontes et al., 2014), a suitable substrate for soil organisms. Saputra et al. (2020) and Utomo et al. (2016) found higher SOC in cocoa agroforests than in monoculture. Higher litterfall (Schneidewind et al., 2019) and fine root production (Niether et al., 2019) in cocoa agroforest soils than in monocultures was attributed to their higher SOC content. Similarly, Alfaro-Flores et al. (2015) observed lower microbial biomass C and N in cocoa monoculture than their agroforestry counterparts. Niether et al. (2017) reported higher moisture in the topsoil of cocoa agroforests during the dry season than in monoculture. They found lower moisture in lower soil layers of cocoa agroforest and attributed that to shade trees utilizing water beyond cocoa roots. Many shade trees have ability to transfer nutrients from deeper soil layers to reduce the effects of nutrient leaching in cocoa agroforests (Imbach et al., 1989; Hartemink, 2005). Atmospheric N fixation is another source of N supply when N-fixing shade trees are included. Having 124 plants ha^{-1} of *Gliricidia sepium* as cocoa shade trees may lead to a N supply of 31 – 38 kg N ha^{-1} when pruned (Kaba et al., 2019).

1.1.5 Comparisons between cocoa agroforests under conventional and organic management

The current goal of modern agroforestry is to produce more sustainably per unit land area, often referred to as "ecointensification" (Santiago-Freijanes et al., 2021). Critics of organic crop production are concerned about its lower productivity compared with conventional production (Kirchmann et al., 2009). However, cocoa yields under agroforestry are often similar in organic and conventional systems (Armengot et al., 2016; Schneider et al., 2016; Niether et al., 2019). Such conclusions have also been drawn for agroforestry coffee (*Coffea arabica* L.) yields in Costa Rica and Nicaragua (Haggar et al., 2011). However, these results contrast the findings of Lyngbaek et al. (2001) who reported 22% lower coffee yields of organic agroforests than of their conventional counterparts in Costa Rica. But even there Lyngbaek et al. (2001) noted a few groups of organic farmers whose yields were equal or higher than those of conventional farmers. In cost comparison, cocoa agroforests under organic management are often found less costly than conventional farms (Armengot et al., 2016). The authors associated this trend with a higher cost of mineral fertilizers than of compost. In Ecuador, Neira (2016) reported a 49% higher net profit margin for cocoa agroforestry under organic management than under conventional management. Cocoa agroforests under organic management may also be more efficient in water and energy use than under conventional management (Neira, 2016; Armengot et al., 2021), while no system-difference for aboveground biomass was noted (Niether et al., 2019; Schneidewind et al., 2019). Häger (2012) also did not observe any difference between individual C pools, however, total C sequestered in organic farms was 46% higher than in conventional farms. Management has been reported to have little effect on litterfall and decomposition in cocoa agroforests (Fontes et al., 2014; Schneidewind et al., 2019) and Alfaro-Flores et al. (2015) found no management-dependent difference in microbial biomass C and N, which Sánchez-De León et al. (2006) corroborated for coffee. For soil chemical properties, results have been mixed. Niether et al. (2019) found no management effect on phosphorus (P), potassium (K) and pH, however, magnesium (Mg) was higher under conventional management than organic management and N was higher under organic management.

1.1.6 Problem statement and justification of the study

Ghana is the world's second largest cocoa producer, with the crop playing an important role in the country's economy. In 2021 the crop contributed US$ 390 million to the country's GDP and it is projected to reach US$ 489 million by 2024 (Sasu, 2021). The cocoa industry employs 60% of the total labour force of the agricultural sector (Sulaiman and Boachie-Danquah, 2017). It determines the livelihood of 800,000 farmers and indirectly provides income to more than 1 million Ghanaians (Sulaiman and Boachie-Danquah, 2017). Traditionally, cocoa production in Ghana is characterized by intercropped with food crops and fruits trees under thinned forests (Duguma et al., 2001).

During the last decades, research results showing quadruple yields of new hybrid cocoa varieties under little or no shade and high fertilization (Ahenkorah et al., 1987) led to the promotion of full sun cocoa. However, obtained high yields are short-lived as, after 25 years, they drastically decline, whereas in traditional cocoa agroforests no such declines are observed (Ahenkorah et al., 1987; Obiri et al., 2007; Nunoo & Owusu, 2017). Due to high fertilizer costs, small cocoa farmers often are unable to fulfil the requirements for mineral fertilizers of full sun cocoa, which then leads to rapid soil fertility decline. As a result, farmers abandon their farms and encroach forests to establish new ones as this is more cost effective to them than rehabilitating old soils (Clough et al., 2009). Such intensification efforts in Ghana's cocoa sector caused the country to lose 1.9 million ha of its forests cover (FAO, 2020). Current estimates suggest that cocoa is cultivated on 2.2 million ha of land in the country, of which 11.5% are located in forests reserves (Abu et al., 2021). Although both traditional cocoa agroforests and full sun cocoa benefit from forests, the former can self-regulate, prolonging the production cycle. Declining soil fertility threatens sustainable cocoa production in Ghana (Wessel and Quist-Wessel, 2015), especially with declining forest areas and climate change.

Cocoa's susceptibility to drought makes lacking rainfall a major threat to its production (Anim-Kwapong and Frimpong, 2004). Considering much of Ghanaians' livelihood is dependent on the crop, any decline in the sector will increase poverty unless proper policy measures are taken. As a response, policy makers included the cocoa industry into the REDD+ program, naming it Ghana cocoa REDD+ (Ghana Forestry Commission, 2020). The program aims at reducing greenhouse gas emissions from Ghana's cocoa industry by promoting traditional cocoa agroforestry and encouraging farmers to diversify their production as a climate change mitigation strategy. To foster ecosystem services, organic cocoa certification was introduced in Suhum Municipality of Ghana's Eastern Region in 2005 (Glin et al., 2015). Since then, 5000 farmers have adopted organic cocoa production (Yayra Glover Limited, 2021). Since this system change, little research has been conducted to determine how farmers' profitability has changed after adopting organic cocoa production. Such studies are important because profitability is an important factor for the adoption of sustainable land-use systems (Pagiola et al., 2007). Also, most studies about REDD+ only focused on farmers' climate change adaptation and mitigation strategies (Adams et al., 2017; Akrofi-Atitianti et al., 2018). Such studies fail to evaluate the possible impact of C payments on farm profitability as aimed for in the Clean Development Mechanism.

In assessing soil fertility impacts of cocoa agroforests in Ghana, only soil physical and chemical properties are considered, ignoring the microbial properties (Kongor et al., 2019). In other cocoa-producing countries, like Brazil (Zaia et al., 2012), Indonesia (Wartenberg et al., 2017) and Bolivia (Alfaro-Flores et al., 2015), soil microbial properties in cocoa systems have been studied intensively. They are important due to their high sensitivity to soil ecosystem change which may provide an early indication of stress or restoration (Joergensen and Emmerling, 2006). Soil microbial properties respond faster to land use change than physical and chemical properties and soil organic C (SOC) does not only serve as energy source for microorganisms but regulates physical and chemical properties (Joergensen and Emmerling, 2006; Zaia et al., 2012; Wartenberg et al., 2017). However, the amount and quality of SOC depends on litterfall and decomposition, which are the internal nutrient cycling processes (Yao et al., 2021). Although litterfall and decomposition in cocoa have been studied in Ghana (Dawoe et al., 2010), this study was limited to the plot level at a single one location without verification at a larger scale. Generally, studies comparing profitability, soil fertility and litterfall in cocoa agroforests under organic and conventional management are rare, with most of the information originating from Alto Beni, Bolivia (Alfaro-Flores et al., 2015; Armengot et al., 2016; Schneider et al., 2016; Niether et al., 2019; Schneidewind et al., 2019). This is particularly true for Ghana where organic cocoa certification is still in its infancy. Furthermore, the above studies used mineral fertilizers at high applications rates. However, in Ghana and at other locations in West Africa, farmers use no to little fertilizer and the latter often at irregular intervals.

Against this background, this PhD study aimed to explore the economic and ecological functioning of cocoa agroforests under conventional and organic management in Ghana.

The following hypotheses were used to guide the research:

a. Due to lower costs and higher cocoa premium, organic agroforests have higher financial and economic profitability than conventional ones.
b. Because both managements schemes use agroforestry systems, litterfall and its decomposition are similar.
c. Differences in management between conventional and organic systems will not affect soil physico-chemical and microbial properties in cocoa agroforestry.

To test these hypotheses, the following objectives were set:

a. Estimate the financial and economic profitability of organic and conventional cocoa agroforestry systems.
b. Determine the litterfall nutrient stocks and rate of decomposition and nutrient mineralization of cocoa leaves under conventional and organic management.
c. Assess the soil physico-chemical and microbial properties of cocoa agroforests under conventional and organic management.

1.2 Study location and management types

The study was undertaken in Suhum Municipality (6°2'3.84''N and 0°27'8.64''W; mean altitude 450 m a.s.l) in the Eastern Region of Ghana (Figure 1.1), West Africa, 60 kilometres northwest of Accra, the country's capital. The original vegetation is classified as a semi-deciduous forest, but human encroachment has changed it to secondary forests and regrowth thickets (MOFA, 2017). The twelve-year monthly average temperature in Suhum ranges from 20.5 °C to 37.2 °C, with the hottest months being between January and April (World Weather Online, 2021). Annual rainfall ranges from 1270 mm to 1651 mm, with the major rainy season occurring between April and July and a minor rainy season between September and November (MOFA, 2017). Suhum Municipality was chosen for this study as it is among the pioneer cocoa growing areas in Ghana and has the largest number of organic cocoa farmers (Djokoto et al., 2016). The area is predominated by Lixisols (IUSS Working Group , 2015).

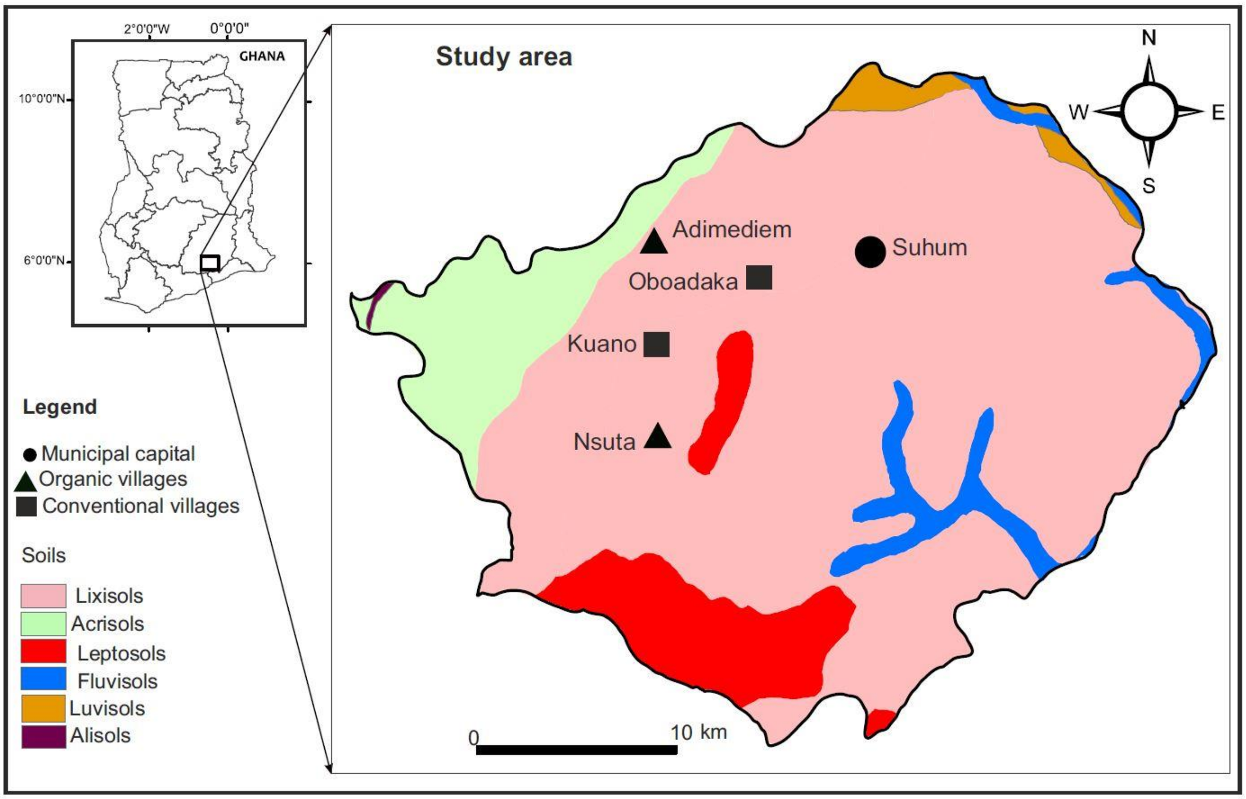

Figure 1.1. Map of Ghana on the left showing the study area in the Eastern Region with the four selected cocoa growing villages and the municipal capital (source for Ghana and Suhum Municipality boundary shapefiles: CERGIS (2012); source for soil classification: IUSS Working Group (2015).

All farmers in the study used a mixture of hybrids (improved cultivars) and Amazonian cocoa varieties (old cultivars). The main dichotomy of the two production systems lies in weed and pest control as well as the use of mineral fertilizers. Organic farmers control weeds strictly by slashing, whereas conventional farmers use both slashing and herbicides with Glyphosate as an active ingredient (Round up™, Sunphosate™, Sarosate™ and Kondem™). Mirids or Capsids, *Distantiella theobroma* (Dist.) are controlled in organic farms using Agropy 5EW™ with pyrethrin, a natural organic insecticide, as the active ingredient. On the other hand, conventional farmers control mirids by using Akate Master™, Confidor™ and Actara™ with the active ingredients being Bifenthrin, Imidacloprid, and Thiamethoxam, respectively. Two years earlier, organic farmers acknowledged that Yayra Glover Limited supplied them with 50 kg Elite Organic Fertilizer™ (NPK 3-4-4 + 9 Ca + 1 Mg + 0.04 B + 0.08 Zn + organic matter), corresponding to fertilizer application rates of 14 to 124 kg ha^{-1} (Agbotui unpublished data) depending on farm size and assuming even distribution across the plantations. The recommended application rate of Elite Organic Fertilizer is 800 kg ha^{-1} yr^{-1} (CHED and WCF, 2016), however, some farmers stated that they did not use this fertilizer at all during this time. Conventional farmers use Asaase Wura™ (Yara, Ghana) inorganic fertilizer (NPK 0-22-8 + 9 CaO + 7 S + 6 MgO, with application rates being 50% of the recommended rate of 300 kg ha^{-1} yr^{-1} (COCOBOD personal communication).

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Chapter 2

Can carbon payments improve profitability of traditional conventional and organic cocoa agroforests? A case study in the Eastern Region of Ghana

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2.1 Abstract

This study investigated the C sequestration of traditional cocoa agroforestry systems in the Eastern Region of Ghana and the theoretical impact of CO_2 emission rights trading on their profitability. The study was conducted in four villages of Suhum Municipality, two each with either conventional or organic cocoa cultivation systems. Profitability was calculated using net present value of net cashflow (NPV), benefit cost ratio (BCR) and modified internal rate of return (MIRR). Allometric equations were used to determine C sequestered in the agroforests. Carbon revenues were calculated using CO_2 emission trading rights prices ranging from 7.5 € t CO_2eq.$^{-1}$ (low price) to 42 € t CO_2eq.$^{-1}$ (high price). We tested the sensitivity of profitability indicators with three scenarios: 300% increase in interest rates, 20% yield reduction and 10% increase in cost. NPV without CO_2 payment for conventional agroforest was 13% higher than that of organic agroforest. Profitability indicators for both systems were most sensitive to 300% interest rate increase. Average C sequestered was 153 ± 13 t ha^{-1} with the soil contributing the largest fraction with an average of 88 ± 11 t ha^{-1}. In contrast to our expectations in this study, organic farms with higher tree density did not sequester more C than conventional ones. Inclusion of CO_2 payments at low price reduced the NPV difference between conventional and organic to 7%. In conclusion, paying CO_2 at high price will make organic system more attractive to farmers.

Keywords: Carbon trading, Climate change, Ecosystem service, Land use systems, Organic agroforestry, Sustainability

2.2 Introduction

Currently, global temperature is 1 °C above pre-industrial levels and is projected to increase to 1.5 °C between 2030 – 2050 (IPCC, 2018). To slow global warming, initiatives such as the Clean Development Mechanism (CDM) in the Kyoto Accord have been developed. The CDM enables companies in developed countries to negate their carbon (C) emissions as a cost-effective mitigation strategy by financing forestry and agroforestry projects in developing countries (Ringius, 2002). In the same vein, C markets were established, where farmers can receive monetary compensation for the C stocks sequestered on their land (Tipper, 2002; Seeberg-Elverfeldt et al., 2009) . This rationale led to the recognition of agroforestry systems as a climate mitigation land use in the Kyoto Accord with the implication that agroforesters can benefit financially from their land use ecosystem services (Takimoto et al., 2008; Walde et al., 2020; Goncalves et al., 2021).

Developing countries like Ghana may utilize this opportunity to reduce poverty and improve the welfare and livelihoods of their small-scale farming communities. One effective strategy to execute this task is by promoting traditional cocoa agroforestry systems (TCAFS) because the country is a leading cocoa (*Theobroma cacao* L.)

producer. In Ghana it is estimated that cocoa is grown on 1.9 million hectares, employing approximately 800,000 farmers (Sulaiman and Boachie-Danquah, 2017). About 9% of the country´s GDP and one third of its export earnings totaling over US $ 1.5 billion are accounted for by cocoa (Sulaiman and Boachie-Danquah, 2017). Traditionally cocoa is grown together with other food crops under sparse forest tree shade resulting in a system mimicking a forest with multi canopy strata (Asase & Tetteh, 2010; Sonwa et al., 2017). TCAFS are more acceptable for C sequestration by the poor rural population than pure forestry, because besides sequestering C, conserving biodiversity and maintaining soil fertility, they also contribute to farmers food security and regular income (Obiri et al., 2007; Asase et al., 2008; Cerda et al., 2014; Asase & Tetteh, 2016; Dawoe et al., 2016; Nunoo & Owusu, 2017). Hence, conflicts originating from ecosystem services on one part and economic interest on the other are reduced yielding a win-win situation.

In recent years many of these complex TCAFS across cocoa growing regions in Ghana are transformed to monocultures (Ruf, 2011). In the Eastern Region of Ghana, intensification of these TCAFS increased cocoa yield by 45% (Wade et al., 2010). In the absence of any economic incentive to keep TCAFS alive, such yield increases serve as economic justification for farmers to intensify their farms. However, these increases may be short lived as observed in the Ashanti (Obiri et al., 2007) and Western (Nunoo and Owusu, 2017) regions of the country where 12 to 16 years after monoculture establishment cocoa yields dropped whilst TCAFS remained productive.

In 2005 organic certification was introduced in the Suhum Municipality, Eastern Region of Ghana (Glin et al., 2015). Prior to this certification, some villages in the Municipality have practiced organic cocoa management for about two decades because they were convinced it sustains their health, plants and soil (Glin et al., 2015). Because organic certification promotes the use of traditional crop varieties, no chemical inputs, complex agroforestry systems and premium payments on sale of cocoa beans (Naturland, 2014), about 5000 TCAFS farmers transitioned from conventional to organic production (Yayra Glover Limited, 2021). Such organic TCAFS have been observed to sequester amounts of soil C similar to forests given high litter deposition (Gama-Rodrigues et al., 2010).

Generally, studies comparing C stocks in organic and conventional traditional agroforests are inconclusive. Whereas Häger (2012) observed that organic coffee agroforests had higher C sequestered than their conventional counterparts, Niether et al. (2019) and Schneidewind et al. (2019) found no difference in cocoa agroforestry systems. Within West Africa such comparisons are scarce because organic certification just started gaining grounds. In addition, data on financial profitability of conventional and organic cocoa production systems are limited and have never been collected under the theoretical implementation of C payments. To fill this knowledge gap, the present study sought to (a) assess the financial profitability and the response of this profitability to adverse production constraints in conventional and organic cocoa agroforestry systems in the Eastern Region of Ghana; (b) estimate the C stocks of organic and conventional traditional cocoa agroforests; and (c) assess the impact of C payment on the economic profitability and its role in reducing the effect of adverse production constraints on profitability in the cocoa agroforestry.

2.3 Materials and methods

2.3.1 Site selection and production systems

This study was conducted in Suhum Municipality (6°2`3.84``N and 0°27`8.64``W; mean altitude 450 m a.s.l) in the Eastern Region of Ghana (Figure 1.1), West Africa, 60 kilometers northwest of Accra, the country's capital. The typical natural vegetation is classified as semi deciduous forest, however, human encroachment has reduced it to secondary forests and regrowth thickets (MOFA, 2017). Twelve years monthly average temperature in Suhum ranges from 20.5 °C to 37.2 °C with the hottest months between January and April (World Weather Online, 2021). Annual rainfall ranges from 1270 mm to 1651 mm with the major rainy season occurring between April and July and a minor rainy season between September and November (MOFA, 2017). Suhum Municipality was chosen for this study as it is among the pioneer cocoa growing areas in Ghana and also has the largest number of organic cocoa farmers (Djokoto et al., 2016). The area is predominated by Ferric Lixisols and Haplic Lixisols (IUSS Working Group WRB, 2015). One conventional and one organic village were selected in each of the two soil domains resulting in a total of four villages. In the two organic cocoa villages Nsuta (Haplic Lixisol) and Adimediem (Ferric Lixisol), named as Org 1 and Org 2, respectively, 50 farmers each were randomly selected from a list of organic cocoa farmers provided by Yayra Glover Limited (YGL), the only certified organic cocoa buyer in Ghana. Similarly, in the two conventional cocoa villages Oboadeka (Ferric Lixisol) and Kuano (Haplic Lixisol), named as Con 1 and Con 2, respectively, 50 farmers were randomly selected. Selected organic villages were among the villages having long term organic cocoa agroforesters. All farmers in the study used a mixture of hybrids (improved cultivars) and Amazonian cocoa varieties (old cultivars). The main dichotomy of the two production systems lies in weed and pest control as well as fertilization. Organic farmers control weeds strictly by slashing, whereas conventional farmers use both slashing and herbicides with Glyphosate as active ingredient (Round up™, Sunphosate™, Sarosate™ and Kondem™). Mirids or Capsids, *Distantiella theobroma* (Dist.) are controlled in organic farms using Agropy 5EW™ with pyrethrin, a natural organic insecticide, as the active ingredient. On the other hand, conventional farmers control mirids by using Akate Master™, Confidor™ and Actara™ with the active ingredients Bifenthrin, Imidacloprid and Thiamethoxam, respectively. At the time of this study, organic farmers did not apply any form of fertilizer. However two years earlier farmers acknowledge that YGL supplied them with 50 kg Elite Organic Fertilizer™ (NPK 3-4-4 +

9 Ca + 1 Mg + 0.04 B + 0.08 Zn + organic matter), corresponding to fertilizer application rates of 14 to 124 kg ha^{-1} (Agbotui unpublished data) depending on farm size and assuming even distribution across the plantations. However, some farmers stated that they did not use this fertilizer at all during this time, whereby the recommended application rate of Elite Organic Fertilizer is 800 kg ha^{-1} yr^{-1} (CHED and WCF, 2016). Conventional farmers use Asaase Wura™ (Yara, Ghana) inorganic fertilizer (NPK 0-22-8 + 9 CaO + 7 S + 6 MgO, whereby application rates are 50% of the recommended rate of 300 kg ha^{-1} yr^{-1} by Ghana Cocoa Board (COCOBOD personal communication).

2.3.2 Data collection and analysis

2.3.2.1 Socioeconomic characteristics and financial profitability assessment

In total 200 farmers were interviewed with closed and open-ended questionnaires to obtain data on farmer and farm characteristics such as the age of plantation, size and cash outflows and inflows. In each village all information given by individual farmers was cross checked during focal group meetings to verify any discrepancy given by farmers during the survey process. Furthermore, data was verified with YGL, Cocoa Life coordinators, and COCOBOD district officers. Cost and revenue were estimated on a hectare basis as € ha^{-1} based on farm gate prices of June 2019 (1 € = 6.14 Gh ₵). The cash outflows were differentiated into material and labor costs. Material costs consist of money spent on the purchase of materials necessary for cocoa production such as farm tools, cocoa and shade tree seedlings, edible fruits trees and food crops planting materials as well as chemical inputs. Labor costs comprised labor requirement of cocoa production such for land clearing, cocoa and food crops planting, cultural practices and harvesting. Basic land rent amounted to 16.73 € ha^{-1}, because most farmers were sharecroppers. Cash inflow included revenue from the sale of cocoa beans and food crops as well as a premium. Revenues from cocoa beans were calculated by multiplying the number of harvested bags (64 kg) with the price of 79.46 € per bag as paid by COCOBOD. Revenue from food crops was determined by asking the farmers the amount they accrued from the sale of each food crops from their cocoa farm. This is because food crops in the study area are sold based on bargaining not on set prices per weight. For organic farmers, a premium of 7.53 € bag^{-1} was paid by YGL.

Data from the two villages with the same production system were combined for profitability assessment. Simple net cash flow was determined by subtracting gross cost from gross revenue. Net present value of net cash flow (NPV), benefit cost ratio (BCR) and modified internal rate of return (MIRR) were used as profitability indicators. MIRR was used instead of internal rate of return (IRR) because for agricultural projects where periodic cash flows are generated between the start and end of the project, IRR tend to overestimate profitability (Kierulff, 2008). To determine the present value of future cash streams, a discount rate of 8% was employed, which is the interest given to farmers by the Ghana Export-Import Bank (GEXIM). It was set up by the Ghana Export-Import

Bank Act 2016 (Act 911) to support the Government of Ghana´s quest for a feasible and sustainable export led economy (GEXIM Bank, 2000). Age of plantations were categorized into juvenile (1 – 5 years), young (6 – 15 years), matured (16 – 30 years) and old (31 – 50 years). Average revenue and cost of each age category was then used during the discounting process (Appendix Table 2.1). We assumed a production period of 50 years since this was the age of plantation observed in the study area. At the age of 50 years it is assumed that the cocoa trees are cut and replanted. NPV refers to the net present value of revenue after discounting a stream of revenue and cost to the present year (equation 1). A production system is deemed economically viable, when the NPV is equal or greater than zero. BCR is the ratio of the present worth of revenue stream to the present worth of cost stream (equation 2). It is the rate of return per unit cost, which is considered profitable at BCR greater or equal to one. MIRR is the discount rate, which makes NPV equal to zero (equation 3). The decision criterion is that the land use MIRR is greater than the interest rate.

$$NPV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1 + r)^t} \qquad (1)$$

$$BCR = \sum_{t=1}^{n} \frac{R_t}{(1 + r)^t} \div \sum_{t=1}^{n} \frac{C_t}{(1+ r)^t} \qquad (2)$$

$$MIRR = \sqrt[t]{\frac{(R \times r)}{(C \times f)}} -1 \qquad (3)$$

where R is revenue, C is cost, r is discount rate, f is finance cost and t is time in years, each.

The financial cost comprises only the discount rate because GEXIM does not charge farmers with additional costs as it is a government sponsored bank. To assess the sensitivity of the production systems, where farmers' livelihoods mostly relied on cocoa production, the profitability indices were rerun under three different scenarios:

(a) A 300% increase in interest rate from 8% to 24%, which was the average interest rate in 2016 (Bank of Ghana, 2021).
(b) A 20% reduction in yield due to prolonged drought, which is a realistic scenario for rainfed cocoa cultivation in Ghana.
(c) A 10% increase in cost due to increases in prices for imported agrochemical (currency depreciation) and labor costs (labor scarcity because of migration of young people from villages to urban centers).

2.3.2.2 Estimation of C stocks

Carbon stocks were determined on 40 farms (10 from each village) selected from the 200 interviewed farmers. To estimate C sequestered, a biomass inventory was conducted within a quadrat of 25 m × 25 m in each farm. Within this area, all shade trees were counted, and diameter measured at breast height (DBH; 1.30 m) according to Hairiah et al. (2010). Due to early bifurcation of cocoa trees, diameter was also measured at 30 cm height. Litter on soil surface (standing litter) was collected in a zig-zag manner diagonally through the 25 m × 25 m quadrat at 10 different locations using a 50 cm × 50 cm quadrat. Standing litter was oven dried at 60 °C until constant weight and ground for C determination. At five locations where standing litter was collected, soil samples were taken at depths of 0 - 30 cm. Samples collected from the same farm were bulked, air dried, sieved and ball milled for C and N analysis. Carbon and N in both soil and standing litter were measured using the Vario Max CN analyzer (Elementar GmbH, Hanau, Germany). Soil organic carbon (SOC) was calculated as the difference between total C and carbonate-C. Carbonate concentration was measured by adding 10% HCl to the soil with emanating gas measured volumetrically (Loeppert & Suarez, 1996). Bulk density was measured with metal cylinders with an inner diameter of 3 cm from which contents were oven dried at 105 °C until constant weight was attained. The soil dry weight was then divided by the inner volume of the metal cylinder.

Basal area of shade trees per hectare was estimated using $\frac{(\pi \times d^2)}{4}$, where d is the diameter at 1.30 m height. The density and basal area of fruit and timber trees were summed up to constitute total shade tree density and basal area, respectively. Total biomass was estimated for all trees using general allometric equations developed for similar ecological zones (Table 2.1). Above ground biomass for forest shade trees was estimated using an allometric equation developed for Ghanaian forest trees (Henry et al., 2010) which has been previously used for C estimation in cocoa agroforests in Ghana (Asase and Tetteh, 2016). All belowground biomass was estimated by an equation developed by Cairns et al. (1997) using forest trees from 25 countries across 6 continents. By multiplying both aboveground and belowground biomass with 0.5, C content was estimated in cocoa and shade trees (Albrecht and Kandji, 2003). The potential CO_2 emission prevented by each village was estimated by multiplying total C stocks with 3.64 which is the ratio of molecular weight of CO_2 (44 gmol^{-1}) to C (12 gmol^{-1}) (Pearson et al., 2005).

2.3.2.3 Economic profitability

We made a hypothetical case of how profitability of these traditional cocoa agroforests could be improved using CO_2 sequestered in each production system as a revenue source. To this end we calculated the annual C accumulation rate by dividing the average total C sequestered in each production system with their average age of plantation. Annual C accumulation rate for each production system was multiplied with 3.64 converting them to their CO_2 equivalent. Supposed revenue from CO_2 was determined by multiplying the annual CO_2 accumulation rate with the average prices of 7.5 € t^{-1} (low price; Knopf et al., 2014) and 42 € t^{-1} (high price; United States Government, 2021). The low price is the average price of CO_2 as traded in the EU

Emission Trading System (ETS). This scheme allows industries who emit CO_2 below their allowed cap to sell their extra allowance to large emitters. High price is the average monetary value of net harm to society when a ton of CO_2 is released into the atmosphere estimated by a model of the United States Government (2021) using different discount rates. Assumptions used in the model were global average temperature response to increased atmospheric CO_2, future population, economic and greenhouse gas emissions growth. Profitability indicators of these cocoa production systems and their sensitivity after addition of these assumed CO_2 revenues were recalculated.

Table 2.1. Allometric equation used in estimating C stocks in cocoa agroforestry systems in Suhum Municipality, Eastern Region of Ghana.

Group/Species	Equation	Source
Cocoa	$Y = 10^{(1.625 + 2.63 \times \log (D_{(30)}))}$	Andrade et al. (2008)
Forest	$Y = 0.30 + DBH^{(2.31)}$	Henry et al. (2010)
Fruit trees	$Y = 10^{(-1.11 + 2.64 \times \log (DBH))}$	Andrade et al. (2008)
Musa spp.	$Y = 0.0303 \times DBH^{(2.1345)}$	Hairiah et al. (2010)
Gliricidia sepium	$Y = -70.172 + 11.5353 \times DBH$	Anglaaere (2005)
Citrus spp.	$Y = -6.64 + 0.279 \times BA + 0.000514 \times BA^2$	Schroth et al. (2002)
BGB	$BGB = \exp^{(-1.085 + 0.926 \times \ln(AGB))}$	Cairns et al. (1997)
SOC	SOC × depth × bulk density	
Standing litter	Standing litter C × dry weight	

Y is aboveground biomass in kg $tree^{-1}$, BGB is belowground biomass, $D_{(30)}$ is diameter in cm measured at 30 cm above ground, DBH is stem diameter at breast height (1.3 m) in cm and BA is basal area in cm^2.

2.3.3 Statistical analysis

Kruskal-Wallis test was used to assess the socioeconomic characteristics between the villages. Linear mixed effect model was employed to test village effect on tree density, shade tree basal area and C stocks in the various fractions. Village was used as fixed effects and farms as random effects. At F-test significance, means were separated by the Tukey post hoc test using the lsmeans function in the multicomp package at $p < 0.05$ (Bretz et al., 2011). Correlation analyses were computed between age of plantation and C sequestered by total shade trees. Cash flow from the two production systems were compared using the Mann-Whitney rank sum test. All statistics were undertaken using R 4.0.3 software (R Core Team, 2020).

2.4 Results

2.4.1 Socioeconomic characteristics

Cocoa production in the four investigated villages was dominated by male farmers (Table 2.2). In Con 2 farmers had the lowest average age of plantation, which was two times lower than in the other villages. On the other hand, in Org 1 average farm size was smallest, which was two times lower than in Con 1. The average farmer’s age in the villages is above 50 years with an average household size of 6. In Con 2 farmers had the lowest cocoa farming experience, which was 22% lower than in the other villages. The average cocoa yield in this study was 352 kg ha^{-1}.

2.4.2 Financial profitability

Despite four-fold higher premiums obtained for organic cocoa, the revenue obtained from conventional cocoa production was not different from organic production. Gross revenue did not significantly differ between the two production systems, although conventional farms had a 15% greater revenue from food crops than organic farms (Table 2.3). Gross costs in conventional farms were 2.5 times higher than in organic farms as a result of ten times higher cost for materials and two times higher labor cost.

The NPV of both systems were greater than zero (decision criteria) which indicates that they were profitable (Table 2.4), although conventional NPV was 13% larger than that of organic systems. With an average of 2, there was no difference between the BCR of both systems. This average value is greater than one (decision criteria) denoting system´s profitability. Similarly, MIRR of the two systems was three times greater than the discount rate of 8% denoting their profitability.

Sensitivity analysis showed that both production systems were profitable under all three scenarios but had different profitability indicators (Table 2.4). In the three scenarios, the greatest reduction in profitability was caused by an increase in interest rate from 8% to 24%. In their response to the interest rate increase, conventional systems had a 62% lower NPV, whereas in organic systems such rise in interest reduced NPV by 81% in comparison to current profitability. In scenario b, a reduction of yields by 20% reduced the NPV in both systems by 38% in comparison to current profitability, whereas MIRR reduced by 5% for conventional and 38% for organic system. In scenario c, an increase of costs by 10% lowered NPV by 11% and 10% for conventional and organic systems, respectively.

Table 2.2. Socioeconomic characteristics of cocoa agroforests in four villages in Suhum Municipality, Eastern Region of Ghana, 2019.

Characteristics		Con 1 (Kuano)	Con 2 (Oboadeka)	Org 1 (Nsuta)	Org 2 (Adimediem)	Overall SEM	
Formal education	Years	8.8 a	8.9 a	9.5 a	8.2 a	0.3	$\chi^2 = 3.85$ $p = 0.28$
Farmer age	Years	55 a	51 a	51 a	52 a	0.9	$\chi^2 = 2.59$ $p = 0.46$
Number of cocoa farms		2.9 ab	2.2 a	1.8 b	2.2 a	0.4	$\chi^2 = 9.72$ $p < 0.01$
Experience in cocoa farming	Years	25 a	18 b	23 a	21 ab	0.9	$\chi^2 = 12.2$ $p < 0.01$
Size of household		7.1 a	6.3 a	5.4 a	5.2 a	0.2	$\chi^2 = 7.39$ $p = 0.06$
Age of plantation	Years	31 a	12 b	22 c	21 c	0.8	$\chi^2 = 82.7$ $p < 0.01$
Farm size	ha	3.3 a	2.3 ab	1.7 b	2.2 ab	0.2	$\chi^2 = 11.4$ $p < 0.01$
Cocoa yield	kg ha^{-1}	373 a	331 a	378 a	328 a	13.9	$\chi^2 = 4.18$ $p = 0.24$
Gender							
Male	%	92	91	91	91		
Female	%	8	9	9	9		

Means in the same row with different letters are significantly different at ($p < 0.05$). SEM denotes the overall standard error of the mean.

Table 2.3. Cash flow analysis for cocoa agroforest in Suhum Municipality, Eastern Region of Ghana, 2019.

Items	Conventional	Organic	SEM	
Revenue (€ ha^{-1})				
Cocoa	435	431	103	$p = 0.90$
Food crops	179	156	12	$p = 0.02$
Premium	8	32	152	$p < 0.01$
Gross	623	620	184	$p = 0.78$
Cost (€ ha^{-1})				
Material	32	3	23	$p < 0.01$
Labor	99	50	41	$p < 0.01$
Gross	131	53	56	$p < 0.01$
Net cash flow (€ ha^{-1})				
	492	566	169	$p = 0.09$

Values presented are means and SEM denotes the overall standard error of mean.

Table 2.4. Current financial profitability and sensitivity analysis of cocoa agroforests in Suhum Municipality, Eastern Region of Ghana, 2019: changes in interest rate (scenario a), yield reduction (scenario b) and increased production cost (scenario c).

Profitability indicators and systems	Current financial Profitability	Scenario a: increase of interest rate from 8% to 24%	Scenario b: yield reduction by 20%	Scenario c: increase of production cost by 10%
NPV (€)				
Conventional	5,560	2,129	3,394	4,974
Organic	4,912	911	3,066	4,432
BCR				
Conventional	2.1	1.8	1.6	1.8
Organic	2.1	1.4	1.7	1.9
MIRR (%)				
Conventional	21	21	20	21
Organic	21	21	13	19

NPV is Net Present Value of Net Cash flow, BCR is Benefit Cost Ratio and MIRR is Modified Internal Rate of Return.

2.4.3 Carbon sequestration

Cocoa tree and timber tree density as well as timber tree basal area, did not significantly differ between the four villages (Table 2.5). ANOVA indicated that fruit tree density and fruit tree basal area in Org 1 were more than 3800% higher than in Org 2 and Con 2. Similarly, total shade tree density and basal area in Org 1 was up to 154% greater than in the other villages.

On average, soil, timber trees, cocoa trees, fruit trees, and standing litter stored 54.7%, 29.7%, 10.8 %, 3.2%, and 1.6% of the total C sequestered, respectively. Across the villages, there was no significant difference in C stocks of cocoa trees and standing litter. ANOVA indicated that Con 2 had the lowest soil C sequestered (Table 2.6). Total CO_2 equivalent of total C in Org 2 were two-fold greater than in Con 2. There was a significant positive correlation between age of plantation and total amount of C sequestered by total shade trees (correlation coefficient = 0.51, $p < 0.01$).

2.4.4 Economic profitability

Annual CO_2 accumulation rate was 32.08 t ha^{-1} yr^{-1} and 30.13 t ha^{-1} yr^{-1} for organic and conventional systems, respectively. If only the yearly CO_2 sequestered is valued in Ghana, then at the low CO_2 price, conventional system will yield 232 € ha^{-1} yr^{-1} and 246 € ha^{-1} yr^{-1} for organic system. When the high price of CO_2 is considered, then conventional and organic systems would annually yield 1,392 € ha^{-1} yr^{-1} and 1,482 € ha^{-1} yr^{-1} respectively.

Payment of CO_2 at the low price increased NPV by 52% and 60% for conventional and organic systems respectively. There was an increase in NPV by 283% (conventional) and 339% (organic) when CO_2 was paid at the high price (Table 2.7). Payment of CO_2 using the low price was sufficient to reduce the negative impacts of 20% yield reduction and 10% increase in production cost in both systems. When C payment at the high price is used as revenue source the organic system performs similarly or under certain scenarios outperforms the conventional system. High price CO_2 payment increased BCR of the systems two-folds and MIRR by 19% when compared to current financial profitability.

Table 2.5. Average tree density and tree basal area in two conventional and two organic villages of Suhum Municipality, Eastern Region of Ghana.

Parameters		Con 1 (Kuano)	Con 2 (Oboadeka)	Org 1 (Nsuta)	Org 2 (Adimediem)	Overall SEM	
Cocoa tree density	stems ha^{-1}	1261 a	1176 a	1082 a	1355 a	51.9	$F = 0.29$ $p = 0.30$
Fruit tree density	stems ha^{-1}	122 ab	72 a	365 b	80 a	32.8	$F = 6.00$ $p < 0.01$
Timber tree density	stems ha^{-1}	102 a	130 a	154 a	107 a	13.4	$F = 0.42$ $p = 0.74$
Total shade tree density	stems ha^{-1}	224 a	202 a	518 b	187 a	37.7	$F = 5.83$ $p < 0.01$
Fruit tree basal area	$m^2 ha^{-1}$	2.8 ab	1.2 a	7.2 b	1.4 a	0.6	$F = 5.53$ $p < 0.01$
Timber tree basal area	$m^2 ha^{-1}$	4.6 a	6.2 a	9.5 a	7.1 a	1.2	$F = 2.09$ $p = 0.12$
Total shade tree basal area	$m^2 ha^{-1}$	7.4 a	7.4 a	16.6 b	8.4 a	0.9	$F = 8.62$ $p < 0.01$

Means in the same rows with different letters are significantly different at $p < 0.05$. Overall SEM denotes the standard error of the mean.

Table 2.6. Average C stocks and CO_2 equivalent of C stocks in t ha^{-1} of two conventional and organic villages of Suhum Municipality, Eastern Region of Ghana.

C stocks	Con 1 (Kuano)	Con 2 (Oboadeka)	Org 1 (Nsuta)	Org 2 (Adimediem)	Overall SEM	
Cocoa tree	16.5 a	11.2 a	14.1 a	14.2 a	0.9	F = 2.14 *p* = 0.12
Fruit tree	7.4 ab	1.0 a	11.8 b	2.9 ab	2.2	F = 3.24 *p* = 0.04
Timber tree	30.5 a	39.9 a	52.8 a	50.3 a	5.7	F = 0.65 *p* = 0.59
Standing litter	1.9 a	1.9 a	1.2 a	1.9 a	0.1	F = 2.33 *p* = 0.09
SOC	110.1 b	46.4 a	87.2 b	110.9 b	11.3	F = 4.76 *p* < 0.01
Total C	166.3 ab	100.2 a	167.2 ab	180.2 b	13.9	F = 3.44 *p* = 0.03
CO_2 eq. of total C	609.7 ab	369.6 a	612.9 ab	660.2 b	51.0	F = 3.44 *p* = 0.03

Means along the same rows with different alphabets are significantly different at ($p < 0.05$). Overall SEM is total standard error of mean.

Table 2.7. Economic profitability at different CO_2 prices and sensitivity analysis of cocoa agroforests in Suhum Municipality, Eastern Region of Ghana, 2019; changes in interest rate (scenario a), yield reduction (scenario b) and increased production cost (scenario c).

Profitability indicators and systems	Potential economic profitability	Scenario a: increase of interest rate from 8% to 24%	Scenario b: yield reduction by 20%	Scenario c: increase of production cost by 10%
Carbon price at 7.5 € t CO_2eq^{-1} (low price)				
NPV (€)				
Conventional	8,433	3,077	5,693	7,848
Organic	7,854	1,913	5,420	7,814
BCR				
Conventional	2.6	2.2	2.1	2.3
Organic	2.8	1.8	2.3	2.8
MIRR (%)				
Conventional	22	22	21	22
Organic	22	22	21	22
Carbon price at 42 € t CO_2eq^{-1} (high price)				
NPV (€)				
Conventional	21,309	7,461	16,004	20,729
Organic	21,573	6,593	16,404	21,529
BCR				
Conventional	5.1	3.8	4.1	4.6
Organic	6.0	3.7	4.8	6.0
MIRR (%)				
Conventional	25	25	24	24
Organic	25	25	24	24

NPV is Net Present Value of Net Cash flow, BCR is Benefit Cost Ratio and MIRR is Modified Internal Rate of Return.

2.5 Discussion

2.5.1 Socioeconomic characteristics

Male domination in cocoa production within this study is in line with studies from other cocoa growing areas in Ghana (Denkyirah et al., 2017; Ameyaw et al., 2018; Kongor et al., 2018). This reflects that men are more endowed with resources such as land than females, which happens through the traditional inheritance system. Another reason may be the recognition of cash crops such as cocoa as a male crop in Africa due to their high labor and capital requirements (Hill & Vigneri, 2011). This perception makes it difficult for landowners to engage the services of female sharecroppers. The average farm size of 2 ha is at the lower end of the range of 2 – 5 ha reported for Ghana (Djokoto et al., 2016; Nunoo & Owusu, 2017; Kongor et al., 2018). Because cocoa production is labor intensive, farmers keep smaller farm sizes to increase productivity (Aneani and Ofori-Frimpong, 2013). Adoption of new agricultural technology is negatively related to farmers age and farming experience (Aneani et al., 2012; Denkyirah et al., 2017; Akrofi-Atitianti et al., 2018). This explains the predominance of traditional cocoa agroforests in the investigated villages, as the age of farmers was above 40 years with average years of experience in cocoa farming of 20. Average cocoa yield of 352 kg ha^{-1} in our study is close to the national average of 400 kg ha^{-1} reported by Aneani & Ofori-Frimpong (2013).

2.5.2 Financial profitability

Both organic and conventional production systems accrued similar revenue from cocoa bean sale because they had similar cocoa yields. Our study confirms earlier reports regarding similarity in cocoa yield in agroforestry under organic and conventional management (Armengot et al., 2016; Schneider et al., 2016). This is because under complex agroforestry systems where light is a limiting factor, fertilizer has little effect on the yield of cocoa (Ahenkorah et al., 1987). With organic systems having higher fruit tree density than conventional ones, higher revenues from fruits sales were expected, which was not the case. One explanation may be lower yields of fruits and food crops in the organic system. Although our study did not measure fruit and food crop yield, data collected by Armengot et al. (2016) and Schneider et al. (2016) suggest higher yields of fruits in conventional agroforests compared with organic agroforests. During fertilization, it is recommended that mineral fertilizers are applied as a circular band 20 – 40 cm around the base of the tree (Opoku-Ameyaw et al., 2010) but due to the tedious nature and high labor requirements of this method most conventional farmers use broadcasting (Bosompem et al., 2010). Therefore, fruit trees and food crops benefit from fertilizer applied to cocoa trees. Also, in the absence of demand and market for organic fruits in the study area, organic farmers are compelled to sell their valued products in the liberalized market as conventional products. Bandanaa et al. (2016) found that cocoa organic farmers consume more of their fruit and food products than their conventional counterparts. This could also be why conventional farms recorded higher revenue from food crops and fruits. But in this study, we did not account for household consumption only revenue for food crops and fruit sales. In comparing the two systems we found that total costs in conventional farms were higher than in organic ones due to high cost of chemical inputs such as mineral fertilizers. Lower labor cost incurred by organic system confirms similar observations made in agroforests with cocoa (Armengot et al., 2016) and coffee (Lyngbaek et al., 2001). However it contradicts data from hazel nut (*Corylus avellana* L.; (Demiryurek and Ceyhan, 2008; Tanrivermis, 2008), rice (*Oryza sativa* L.; (Suwanmaneepong et al., 2020) and maize (*Zea mays* L.; (Adamtey et al., 2016). Contrary to our study, which took place in an agroforestry setting, the above authors' findings came from monocultures which may explain the differences. Although in our study both managements are agroforests the tree density (cocoa and shade trees) is higher in organic farms, which limits the penetration of light to stimulate weeds growth (Pumariño et al., 2015). This probably demonstrates the ability of organic agroforests to suppress weed growth, which reduces labor requirement to control weeds. As conventional cocoa farmers combat weed and pest infestations, they invest in manual weeding in addition to hiring labor to apply herbicides and other chemical inputs, which increases their labor cost. Furthermore, some authors (Denkyirah et al., 2016; Obiri et al., 2021) observed excess utilization of agrochemicals among conventional Ghanaian cocoa farmers, which leads to an increase in their overall cost. As organic cocoa agroforesters are basically independent of fossil fuel, they are thus more energy efficient (Neira, 2016). Following organic principles therefore leads to a reduction in production cost (Tzouvelekas et al., 2001).

Apart from NPV, which showed that the conventional cultivation system was more profitable than the organic one, the other profitability indicators were similar for both systems. The BCR as a profitability indicator demonstrates whether the revenue obtained is worth the cost input of the systems. All systems had a BCR greater than 1 demonstrating their profitability. Three-folds higher MIRR than the 8% interest rate falls within 100% to 300% return to investment for cocoa agroforests in Ghana (Obiri et al., 2007; Asare et al., 2014; Nunoo and Owusu, 2017). Among the profitability indices, NPV is the most suitable because it indicates the amount of money generated from a made investment and is comparatively easy to understand (Thapa and Weber, 1994). Even without accounting for revenue from timber all the systems were profitable confirming a similar assertion made by Duguma et al. (2001). Similarly in the Western and Ashanti Region of Ghana, discounted cash flow techniques have been used to show the profitability of TCAFS (Obiri et al., 2007; Nunoo & Owusu, 2017). Our findings contradict greater NPV for organic than conventional system in orchards of Lemon (*Citrus limon*; Sgroi et al., 2015a) and Olive (*Olea europea* L.; Sgroi et al. 2015b) in Sicily. These contrasting results from plantations may be due to the fact that our study took place in a mixed cropping setting. This reflects the role of crop diversification in cocoa agroforestry systems highlighted by Abdulai et al. (2018) and Cerda et al. (2014) in a changing climate. In Ghana, the major season for cocoa harvesting lasts from October to March and the minor season from May to August (Opoku-Ameyaw et al., 2010). After these purchasing periods, it is food crop consumption and sales that sustains farmers' livelihoods. It is for this reason that 29% and 21% of total revenue resulted from food sales on conventional and organic farms, respectively. In the sensitivity analysis, the NPV reacted more sensitively to a 300% increase in interest rate (Scenario a) in both systems than to a 20% yield loss (scenario b) or a 10% increase in cost (scenario b). The observed reduction was even more severe in organic (81%) than conventional (62%) farming systems. This was because of the negative correlation between NPV and discount rate (Ataniyazova et al., 2014; Do et al., 2020). Also, increased interest rates impact more on present cash streams than future ones (Kalyebara and Islam, 2014). During the earlier years of farm establishment (1 – 5 years), net cash flow of organic farms was 7 times lower than that of conventional farms due to 43% lower revenue in organic farms (Appendix Table 2.1). The lower revenue was due to lower food crop yield. Land clearing prior to cocoa planting is associated with burning plant biomass (Arévalo-Gardini et al., 2015) which leads to nutrient losses through volatilization, leaching and wind erosion (Young, 1990). In organic systems where farmers do not replace these nutrients lower yields for food crops are the consequence. These results also indicate the high financial burden on organic farmers during their farm establishment phase. This adversely affect the adoption of cocoa organic management because of farmers' high preference for present day payoff than long term future profits (Rasul and Thapa, 2006; Do et al., 2020).

2.5.3 Carbon sequestration

The total C sequestered in this study ranges from 100 t ha^{-1} to 180 t ha^{-1} which falls within the range of 92 t ha^{-1} to 172 t ha^{-1} of cocoa agroforests reported from Cameroun (Madountsap et al., 2018) and Central America (Somarriba et al., 2013). There was no clear difference in total C stocks between conventional and organic production systems in this study. The significantly lower C sequestered in Con 2 may be explained by the predominantly young nature of farms in this village (Table 2.2). The average total C sequestration of 153 t ha^{-1} in this study is in accordance with average C sequestrations of 140 t ha^{-1} to 155 t ha^{-1} found in Ghana, Bolivia, and Ecuador (Asase et al., 2008; Jacobi et al., 2014; Jadan et al., 2015). Higher C sequestration of up to 266 t ha^{-1} were found in cocoa agroforests of Ghana with larger shade trees, storing more than 50% of the total C stocks (Dawoe et al., 2014; Asase & Tetteh, 2016). Comparing the time lapse between their study and ours could imply that with deceasing timber resources in Ghana, these traditional cocoa agroforests are now becoming the new frontier for timber harvesting (Ruf, 2011). However, this assertion needs further investigation to quantify the disappearance rates of shade trees in these traditional cocoa agroforestry landscapes. Another reason for the lower C estimates of our study in comparison to those of the authors above may be older farms than those in our study. We observed a significant positive correlation between farm age and C stocks in shade trees, which supports findings of higher C stocks in shade trees as cocoa farm ages reported by Madountsap et al. (2018) and Saj et al. (2017).

Forests are major sinks for CO_2 in terrestrial ecosystems (Jadan et al., 2015; Asase and Tetteh, 2016). Hence transforming forests into cocoa agroforests leads to losses of biomass and CO_2 into the atmosphere (Obeng and Aguilar, 2015). The Atewa forest, which is a primary forest close to the study area is reported to hold C stocks of 304 t ha^{-1} (Asase and Tetteh, 2016). The implication is that 50% of the C stocks in primary forests are lost when they are converted to traditional agroforests (Duguma et al., 2001). However, this loss is still lower than in primary forests that have been converted to simple cocoa- *Gliricidia sepium* shade agroforests (Sari et al., 2020) and cocoa monoculture (Asase et al., 2008) loosing up to 80% of C stocks. Though traditional cocoa agroforests cannot replace the C sequestration function of natural forests, converting cocoa monocultures and simple agroforests into multi-strata complex agroforests will play a crucial role in reducing C losses.

The average soil C (88 t ha^{-1}) of this study is comparable to studies in Ghana (Mohammed et al., 2015), Bolivia (Jadan et al., 2015), and Brazil (Gama-Rodrigues et al., 2010), which ranges from 62 t ha^{-1} to 127 t ha^{-1} for a soil depth of 0-30 cm. As the greatest fraction of total C sequestered, soil played an important role in cocoa C sequestration. It should be noted that two farms in Con 1 and Org 2, had soil C stocks above 300 t ha^{-1} demonstrating the high heterogeneity of the soils under these cocoa agroforestry systems. Standing litter is primarily regulated by the rate of litterfall and its subsequent decomposition (Briggs, 2004). Similarity in the standing litter of villages suggests that rate of litterfall and decomposition are similar across villages, hence not affected by the application of chemical inputs. This observation confirms findings of Fontes et al. (2014), who observed no difference in standing litter, litterfall, and decomposition between fertilized and unfertilized traditional cocoa agroforests established on both Latosols and Cambisols.

2.5.4 Economic profitability

Inclusion of theoretical C payments impacted both production systems profitability positively. Similarly, theoretical C payments as a source of revenue have been reported to increase profitability in agroforests in Ghana (cocoa, Asare et al. 2014), Brazil (coffee, Goncalves et al. 2021) and Ethiopia (homegardens, Walde et al. 2020). This revenue source increased NPV between 55% to 311% using the low price and high price, respectively, which is comparable to profitability increase range of 60% to 300% reported by Walde et al. (2020) and Asare et al. (2014). However, findings of this study contradict Goncalves et al. (2021), who reported less than 1% and 1.4% increases in NPV with current and social CO_2 payments, respectively, were used as revenue sources. The disparity likely reflects less revenue from CO_2 payments reported by the above authors because their average C sequestered was 61 t ha^{-1}, which was 2.5-fold lower than the average we report. With the inclusion of low CO_2 payment, the organic system still lagged marginally behind the conventional system. This was mainly caused by high initial investment costs (1 – 5 years) in organic farming systems. However with high CO_2 payment, organic cocoa agroforests became similarly profitable in terms of NPV as conventional cocoa agroforests. Suggesting in the consideration of C payment as an incentive for adoption of organic farming, the value must not be less than the high price. Our results show the importance of C payments on farm profitability, when interest rates increase, yields decline, or production cost increase. For example, the addition of low C payments increased conventional (45%) and organic (110%) systems' resilience to three folds increase in interest rate (scenario a). This resilience was further increased by 250% and 624% for conventional and organic systems, respectively, when high C payments were assumed. It is important to mention that our study only addressed C sequestration as one of many environmental benefits of TCAFS. If other ecosystem benefits such as biodiversity conservation are valued, then organic production might become even more profitable. Organic production systems have been observed to harbor more biodiversity than their conventional counterparts (Fuller et al., 2005; Asigbaase et al., 2019; Stein-Bachinger et al., 2020). Cocoa premium alone may not be sufficient to induce conventional agroforesters to transform to organic cultivation. However, additional premiums from other fruits and crops in addition to C payments may add to the arguments for certified organic cocoa agroforestry. Although cocoa monoculture has been reported to be more profitable than traditional cocoa agroforests (Obiri et al., 2007), such environmental payments will have the potential to make monocultures transition to a more sustainable land use (Asare et al., 2014).

Short term C payments have been shown to be successful in transforming degraded pastures to simple to complex silvopastoral systems in Nicaragua (Pagiola et al., 2007). However, the authors noted a high likelihood of farmers reverting to their unsustainable land use when funding ends. For C payments to be reality there needs to be a long-term funding source. Helping farmers to trade C sequestered in voluntary C markets, which has been successful for agroforesters in Mexico in Scolel Te´ project (Tipper, 2002), may be a sustainable funding source. Clean Development Mechanism (CDM) also offers a funding source especially for African cocoa producing countries considering the fact that African countries have underexploited this mechanism (Röttgers & Grote, 2014; Kreibich et al., 2016). Another issue that needs addressing is the standardization of methodologies for C accounting (Perez et al., 2007; Smith et al., 2007). This is due to the aggregation of C sequestered in small plots to a scale large enough to trade in C markets which requires rapid, cost effective and feasible way for estimating C stocks (Perez et al., 2007). Capacity building is therefore needed in cocoa producing countries on the use of GIS, remote sensing and machine learning tools to validate C sequestration in this agroecosystem (Perez et al., 2007). Furthermore, there is a high possibility of abuse and conflicts if farmers are not adequately educated in addition to their accessibility of information regarding C trading contracts. For example farmers must understand that they will not receive market prices for sequestered C due to operational cost accrued in the process of selling C (Smith et al., 2007; Tipper, 2002). Absence of land and tree ownership rights by cocoa sharecroppers and land title certificates by land owners will greatly affect C payments implementation if not addressed (Smith et al., 2007; Jaza Folefack and Darr, 2021). Because of such hurdles that need to be overcome, C payments for African cocoa agroforesters in the short term may not be feasible (Jaza Folefack and Darr, 2021).

2.6 Conclusions

Conventional and organic production systems exhibited similar revenues gained from the sales of cocoa beans, however, conventional systems accrued more revenue from the sale of food crops. Cash flow analysis showed that there was no difference in net cash flow between the two systems. Financially both systems were profitable, but conventional NPV was 13% greater than organic under the current situation. Three times increase in interest rate was the production constraint that had the most negative effect on both production systems. In addition, increased interest rate negatively affected organic system more than conventional system, which resulted from a longer time for organic farmers to receive returns from their initial investments. Carbon sequestration payments using low price and high price on average increased NPV of systems by 55% and 311%, respectively. Our study showed that in case of considering C payments as an incentive to motivate cocoa agroforests in the Suhum Municipality to switch from conventional management to organic, the amount must be at least around 40 € t CO_2 eq^{-1}.

2.7 References

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2.8 Appendix

Appendix 2.1. Cash flow analysis of traditional cocoa agroforests in Suhum Municipality, Eastern Region of Ghana, 2019. Number of farms for each plantation age category was 12 (1 – 5 years), 20 (6 – 15 years), 43 (16 – 30 years) and 25 (31 – 50 years).

	1 – 5 years	6 – 15 years	16 – 30 years	31 – 50 years
Conventional				
Revenue (€ ha^{-1})				
Cocoa	198	354	535	470
Premium	11	14	14	9
Food crops	1,213	218	164	81
Gross	1,422	686	713	560
Cost (€ ha^{-1})				
Material	441	64	68	126
Labor	407	183	142	131
Gross	848	247	210	257
Net cash flow (€ ha^{-1})	574	439	503	303
Organic				
Revenue (€ ha^{-1})				
Cocoa	433	369	489	339
Premium	31	28	38	32
Food crops	430	172	413	169
Gross	894	569	940	540
Cost (€ ha^{-1})				
Material	184	6	13	0
Labor	626	123	151	51
Gross	810	129	164	51
Net cash flow (€ ha^{-1})	84	440	776	489

Chapter 3

Soil fertility parameters in cocoa agroforests under organic and conventional management in Suhum, Eastern Region of Ghana.

3.1 Abstract

Our study aimed at investigating differences in soil physico-chemical and microbial properties of traditional cocoa agroforests under organic *versus* conventional management in Suhum Municipality, Eastern Region of Ghana. To this end two villages each was selected for organic and conventional management, resulting in a total of four study locations. The soil physico-chemical and microbial properties were analysed in three fields per village at soil depths of 0-10 cm and 10-30 cm. Management had no effect on the measured soil physico-chemical properties and microbial biomass. Rather than management, soil properties such as the clay content explained differences in chemical properties and lower microbial biomass in one of the conventional villages, whereby the other three villages showed similar values. Conventional management significantly increased the metabolic quotient (qCO_2) in topsoil compared with organic management, indicating a higher demand of soil micro-organisms for maintenance energy, probably due to the use of herbicides and pesticides.

Keywords: Soil quality, Sustainability, Land use, Microbial indicators, Nutrient cycling

3.2 Introduction

Cocoa (*Theobroma cacao* L.) is an important global agricultural commodity cultivated in many parts of the humid tropics throughout Africa, Southeast Asia and South America (Somarriba et al., 2013; Wessel and Quist-Wessel, 2015; Wartenberg et al., 2020). Increasing demand for cocoa beans motivated farmers to cultivate the crop in monoculture to increase yield (Andres et al., 2016), which has often enhanced deforestation and soil degradation. After decades of cultivation, soil fertility declines, which forces farmers to abandon their farm and establish new farms in existing forests (Arévalo-Gardini et al., 2015; Fountain and Hütz-Adams, 2018). Such shifting cultivation systems considerably contribute to forest degradation in cocoa producing countries (Gockowski and Sonwa, 2011; Arévalo-Gardini et al., 2015; Fountain and Hütz-Adams, 2018). Declining soil fertility is among the most limiting factors in cocoa production in Africa (Wessel and Quist-Wessel, 2015).

In Ghana, attempts to prevent declining soil fertility and to boost yields by enhancing farmers´ adoption of chemical inputs have been largely unsuccessful (Gockowski and Sonwa, 2011). This is due to the high cost of mineral fertilizers and pesticides in addition to lack of knowledge about their efficient utilization (Wessel and Quist-Wessel, 2015; Kongor et al., 2018; Obiri et al., 2021). Many soils under cocoa cultivation in Ghana are highly vulnerable to degradation given rapid mineralization of organic matter as well as nutrient losses from leaching and erosion. Soil degradation is a major threat to farmers' livelihoods in a country whose economy heavily relies on cocoa (Kolavalli and Vigneri, 2011).

Agroforestry technologies have been proposed to counter these problems (Dawoe et al., 2014; Alfaro-Flores et al., 2015). Cocoa can be easily cultivated under the shade of forest trees and be intercropped with other perennials (Amoah et al., 1995; Snoeck et al., 2013) and food crops (Obiri et al., 2007). Such traditional agroforests mimic the forest ecosystem and provide ecosystem functions such as soil fertility restoration (Dawoe et al., 2014; Suárez et al., 2021). Increased plant diversity within such traditional cocoa agroecosystems provides a diversification of litter quantity and quality, root architecture, and other physiological traits, which may improve substrate quality for soil microorganisms (da Silva Moço et al., 2009). Furthermore, nutrient losses from erosion and leaching can be reduced by litter covering the soil surface and nutrient pumping capacity of trees with deep roots (Imbach et al., 1989; Hartemink, 2005).

To increase the sustainability and profitability of traditional cocoa agroforests, organic certification was introduced in Suhum Municipality, Eastern Region of Ghana in 2005 (Glin et al., 2015). By certification, agroforesters benefit from premium prices for their cocoa beans devoid of mineral fertilizers and pesticides. There have been several studies comparing soil fertility of traditional agroforestry systems under conventional and organic managements (Haggar et al., 2011; Alfaro-Flores et al., 2015; Sauvadet et al., 2019). However, results have been inconclusive. For example, Haggar et al. (2011) reported higher soil fertility under organic management than under conventional management in coffee agroforests of Costa Rica. In contrast, within traditional agroforests under cocoa in Bolivia (Alfaro-Flores et al., 2015) and coffee in Costa Rica (Sauvadet et al., 2019), no difference in soil fertility was observed between organic and conventional management. The disparity between the results of Haggar et al. (2011) and those of Sauvadet et al. (2019) was likely due to the high amount of organic fertilizers used by Haggar et al. (2011). All these studies were conducted in systems with moderate to high fertilizer inputs ranging from 46-300 kg N ha^{-1}, 2-205 kg P ha^{-1} and 44-326 kg K ha^{-1}. In West Africa, where most of the world´s cocoa is produced (Wessel and Quist-Wessel, 2015), input levels of farmers are much lower due to their poor investment capacities. Furthermore, due to organic certification being in its developmental stages, studies comparing soil fertility in traditional cocoa agroforests under conventional and organic systems are rare. Hence this study (a) compares the soil physical, chemical and microbial properties under conventional and organic cocoa agroforests in Ghana, (b) compares the rate of nitrogen (N) mineralization and potential N mineralized under conventional and organic cocoa agroforests, and (c) determines the physical and chemical properties regulating microbial properties in these cocoa agroforests.

3.3 Materials and methods

3.3.1 Study sites

Our study was conducted in Suhum Municipality, covering an area of 359 km^2 (6°2`3.84``N and longitude 0°27`8.64``W) in the Eastern Region of Ghana, West Africa (Figure 1.1). Human activities have changed the vegetation of Suhum from natural semi-deciduous forests to secondary forests and regrowth thickets (MOFA, 2017). The area has a bi-modal rainfall pattern, whereby between 2009 – 2020 annual mean rainfall ranged from 1270 mm to 1651 mm and annual mean temperature from 23 °C to 32 °C (World Weather Online, 2021). The predominating soils in the study region are Lixisols (IUSS Working Group WRB, 2015). In Suhum, cocoa agroforestry has a long tradition. In 2005, some cocoa agroforests shifted from conventional to organic management, resulting in closely located villages in Suhum being either cultivated under conventional or organic management. Two villages for each management system were selected within 6 km distance on Lixisols (Figure 1.1). The organic villages were Nsuta (Org 1) and Adimediem (Org 2) whereas conventional villages were Kuano (Con 1) and Oboadeka (Con 2). Stand characteristics for the villages can be found in Table 3.1.

Table 3.1. Stand characteristics of cocoa agroforests in villages under organic and conventional management in Suhum Municipality, Eastern Region of Ghana.

	Org 1	Org 2	Con 1	Con 2	CV (± %)
Cocoa trees density (stems ha^{-1})	1296	1301	1472	1317	20
Fruit trees density (stems ha^{-1})	480	96	202	37	93
Timber trees density (stems ha^{-1})	96	107	107	219	70
Fruit trees basal area (m^2 ha^{-1})	9.4	1.4	5.0	1.0	100
Timber trees basal area (m^2 ha^{-1})	6.2	6.9	3.3	7.8	77
Standing litter (Mg ha^{-1})	0.87	0.79	0.91	0.89	15

Org 1 and Org 2 refer to villages with organic management, Nsuta and Adimediem respectively, Con 1 and Con 2 denote villages with conventional management, Kuano and Oboadeka, respectively, CV = mean coefficient of variation between replicates within a village (n = 4).

3.3.2 Soil sampling

Within each village three cocoa fields from three different farmers were selected. The ages of cocoa trees ranged from 8 to 25 years, the most productive age range of cocoa trees (Obiri et al., 2007), with trees of different ages present in all fields. Each field was divided into 3 to 5 sub-plots for sample collection to account for heterogenity of the topography. Criteria for sub-plot delineation was based on natural occurring slopes based on the farmers' knowledge of their field topography. Within each sub-plot, ten soil samples were taken diagonally in a zig-zag manner at depths of 0-10 and 10-30 cm.

Soil samples from one sub-plot and depth were pooled and air dried for determination of physico-chemical and microbiological properties.

3.3.3 Soil physico-chemical properties

Bulk density (BD) was measured using metal cylinders with an inner diameter of 3 cm and a length of 10 cm at a point randomly selected in each field. Soils sampled with the metal cylinders were oven dried at 105 °C until constant weight and soil dry weight was divided by the inner volume of the metal cylinder. After adding 10% H_2O_2 and 2 M HCl to destroy organic matter and carbonate, respectively, soil texture was determined by wet sieving for sand and gravitational sedimentation for silt and clay (Glendon and Dani, 2017). Air-dry soil samples were sieved to 2 mm mesh prior to further analysis. Total C and N were determined by a Vario Max CN analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany) after soil was grinded with a ball mill and oven dried at 60 °C for 24 h. Soil pH was assessed at a soil to water ratio of 1:2.5 using a glass electrode (pH 3110, Xylem Analytics Germany Sales GmbH & Co. KG, Weilheim, Germany). Electrical conductivity (EC) was measured at soil to water ratio of 1:5 with a digital conductivity meter (GMH3430, GHM Messtechnik GmbH, Regenstauf, Germany). Carbonate concentration was determined gas volumetrically by adding 10% HCl to the soil according to the Scheibler method (Loeppert and Suarez, 1996). Soil organic carbon (SOC) was calculated as the difference between total C and carbonate C. Using 0.0125 M $CaCl_2$, K was extracted followed by its measurement by flame photometry (BWB Technologies, BWB Technologies UK Ltd., Newbury, United Kingdom). Bray P2 (Bray and Kurtz, 1945) extractable soil P was measured colorimetrically by the use of a spectrophotometer (Hitachi U-2000, Hitachi Ltd. Corp., Tokyo, Japan). For N mineralization, 20 g air dried soil was incubated at 25 °C at 60% water holding capacity in the dark for 28 days. Nitrogen mineralization was determined at time intervals of 1, 7, 14 and 28 days after distilled water addition. Soils were extracted by 0.0125 M $CaCl_2$ followed by measurement of mineralized N with continuous flow analysis (Evolution II, Alliance Instruments GmbH, Freilassing, Germany).

3.3.4 Soil microbial properties

Prior to analysis of microbial properties, soil moisture was adjusted to 60% field capacity and incubated at 25 °C for 7 days in the dark. Microbial biomass C (MBC) and N (MBN) were determined by the chloroform fumigation method (Brookes et al., 1985; Vance et al., 1987) with 0.5 M K_2SO_4 as an extractant. Organic C and total N in the fumigated and non-fumigated soil extracts were recorded with a CN analyzer (Multi N/C 2100s, Analytic Jena GmbH, Jena, Germany). MBC was calculated as E_C/k_{EC}, whereby E_C = (extracted organic C from fumigated soil samples) – (extracted organic C from non-fumigated soil samples) and k_{EC} = 0.45 (Wu et al., 1990). MBN was calculated as E_N/k_{EN}, whereby E_N = (extracted organic N from fumigated soil samples) – (extracted organic N from non-fumigated soil samples) and k_{EN} = 0.54 (Brookes et al., 1985).

Microbial quotient (MQ) was MBC in % SOC. Basal respiration was measured using a LGR 915-0011 (Los Gatos Research, Los Gatos, CA, USA) ultra-portable greenhouse gas analyzer. Briefly, 20 g of pre-incubated moist soil was placed into a 100 ml PET bottle. The bottle was placed into a 1.6 l Mason jar connected to the gas analyzer via inlet and outlet tube of 0.6 m length in a closed chamber system. The gas analyzer recorded through-flowing air continuously at an accumulation period of 5 min. The measured gas concentrations were used to calculate the basal respiration determined as CO_2 flux rate using the “gasfluxes” package in R software (Fuss et al., 2020). The metabolic quotient (qCO_2) was estimated as the ratio of basal respiration and MBC.

3.3.5 Statistical analysis

Data were analyzed using one way analysis of variance. When Shapiro-Wilk normality tests and Levene´s test for homogeneity of variance failed, data were analyzed using Kruskal-Wallis one-way analysis of variance. Pearson correlation was used to analyze the relationship between physico-chemical and microbial properties. Using a first order equation ($N_{min} = N_0 (1 - e^{-kt})$), the potential nitrogen mineralization (N_0) and nitrogen mineralization rate constant (K) were estimated (Stanford and Smith, 1972). Multiple regression was used to determine the relationships between soil physico-chemical and microbial properties. All statistical analyses were done using R 4.0.3 software (R Core Team, 2020).

3.4 Results

In the topsoil, no significant differences were observed in sand, silt, and bulk density between the four villages (Table 3.2). The physical soil properties of the subsoil followed a similar trend as in the topsoil. In contrast, the chemical soil properties of Con 2 were significantly lower than in the other three villages for all measured parameters.

Table 3.2. Soil physical properties at different depths of cocoa agroforests in villages under organic and conventional management in Suhum Municipality, Eastern Region of Ghana.

Soil physical properties	Depth (cm)	Management villages				*P* value	CV (± %)
		Org 1	Org 2	Con 1	Con 2		
Sand (%)	0-10	46	52	43	73	0.15	28
	10-30	46	55	43	75	0.13	28
Silt (%)	0-10	24	18	30	14	0.20	32
	10-30	26	17	23	12	0.08	31
Clay (%)	0-10	25	28	24	10	0.08	24
	10-30	25	25	31	10	0.12	33
Bulk density ($g\ cm^{-3}$)	0-10	0.62	1.12	1.17	1.00	0.15	26
	10-30	0.90	1.30	1.34	1.30	0.38	25

Org 1 and Org 2 refer to villages with organic management, Nsuta and Adimediem respectively, Con 1 and Con 2 denote villages with conventional management, Kuano and Oboadeka, respectively, CV = mean coefficient of variation between replicates within a village (n = 4).

The average SOC of the other villages in the top and subsoils were twice and thrice, respectively, higher than in Con 2 (Table 3.3). Similarly, total N in both top and subsoils in Con 2 was two-fold lower than in the other villages. For both top and subsoils, extractable P was the only parameter, where Con 1 significantly exceeded Org 1.

Table 3.3. Soil chemical properties at different depths of cocoa agroforests in villages under organic and conventional management in Suhum Municipality, Eastern Region of Ghana.

Soil chemical	Depth	Management villages				*P* value	CV
properties	(cm)	Org 1	Org 2	Con 1	Con 2		(± %)
EC (μS cm^{-1})	0-10	61 a	71 a	74 a	35 b	< 0.01	37
	10-30	44 a	37 a	53 a	24 b	< 0.01	24
pH	0-10	6.83 a	6.84 a	6.78 a	6.10 b	< 0.01	8
	10-30	6.27ab	6.68 a	6.61 a	5.85 b	< 0.01	8
SOC (mg g^{-1})	0-10	18.2 a	20.9 a	17.7 a	8.0 b	< 0.01	40
	10-30	8.0 a	9.8 a	10.8 a	3.3 b	0.01	44
Total N (mg g^{-1})	0-10	1.92 a	2.29 a	1.95 a	1.00 b	< 0.01	34
	10-30	0.97 a	1.17 a	1.23 a	0.55 b	< 0.01	31
SOC/total N	0-10	9.4 a	9.1 a	9.0 a	7.7 b	< 0.01	10
	10-30	8.1 a	8.0 a	8.7 a	5.3 b	< 0.01	19
Extractable P (μg g^{-1})	0-10	10 bc	61 a	35 ab	6 c	< 0.01	107
	10-30	5 bc	25 a	28 ab	2 c	< 0.01	113
Extractable K (μg g^{-1})	0-10	84 a	43 ab	39 ab	26 b	< 0.01	70
	10-30	31 a	30 a	30 a	21 b	0.03	85

Org 1 and Org 2 refer to villages with organic management, Nsuta and Adimediem respectively, Con 1 and Con 2 denote villages with conventional management, Kuano and Oboadeka, respectively, CV = mean coefficient of variation between replicates within a village (n = 4).

Before incubation, ammonium concentration was highest in Con 1, which was 87% greater than the average of Org 1 and Con 2 (Figure 3.1A). Day 7 showed peak and similar ammonium concentrations for all villages. There was a drop in ammonium for all villages on day 14 with Org 1, being 11-fold lower than Org 2, which had the highest concentration. Con 1 was 166% greater than the average of other villages after 28 days of incubation. Initially, nitrate in Con 1 was 50% greater than the average of Org 2 and

Con 2, which recorded the lowest (Figure 3.1B). On day 7, Org 2 was two-fold larger than the average nitrate concentration in the other villages. Nitrate concentration on day 14 was highest in Org 1 and Org 2 whose average was 125% higher than in Con 2, which recorded lowest. Soils of all villages had their highest nitrate levels at 28 days of incubation with Con 2, being two-fold lower than average values of the other villages.

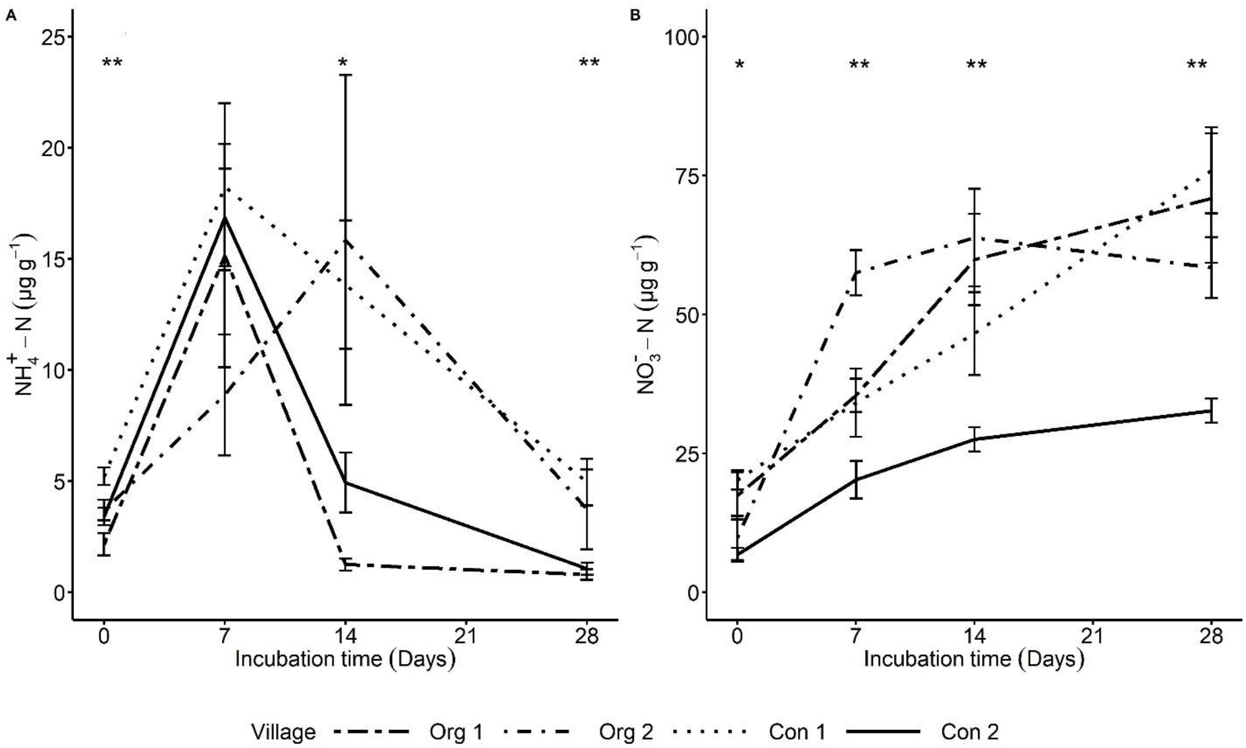

Figure 3.1. Ammonium (A) and nitrate (B) dynamics of topsoil in cocoa agroforests of villages under organic and conventional management in Suhum Municipality, Eastern Region of Ghana. Soils were incubated under laboratory conditions for 28 days at 25 °C and 60% WHC. Org 1 and Org 2 refer to villages with organic management, Nsuta and Adimediem respectively, Con 1 and Con 2 denote villages with conventional management, Kuano and Oboadeka, respectively. Error bars show +/- one standard error of the mean. * and ** indicate P values of 0.05 and 0.01, respectively.

Con 1 soils had the highest N mineralization potential, which significantly differed from Con 2 soils (Table 3.4). Con 2 soils had the lowest N mineralization potential in both top- and subsoil samples, which were 51 to 55% lower than in the other three villages. Even though the N mineralization rate constant in Org 1 and Con 2 soils were up to two times greater than in the other two villages, this difference was not significant.

Average MBC in the top- and subsoils of the villages Org 1, Con 1 and Org 2 were 149% and 83% respectively, greater than in Con 2 soils (Table 3.5). The MBN in the topsoils of Con 2 soils were three-fold lower than in the other villages. Con 1 soils had the highest MBN in the subsoils of all villages and were 200% higher than in Con 2 soils. No difference was found between villages for MB-C/N in topsoils but in subsoils, it was 58% greater in Org 1 than Con 1 samples. There was no difference between MBC/SOC in the topsoil of villages, but in the subsoil Org 1 and Org 2 were up to 38% lower than in Con 2 soils.

Table 3.4. Nitrogen mineralization of soils at different depths from cocoa agroforests in villages under organic and conventional management in Suhum Municipality, Eastern Region of Ghana incubated for 28 days. Nmin = N_0 (1 - e^{-kt}); Nmin refers to nitrogen (N) mineralized, N_0 to N mineralization potential, K to the N mineralization rate constant and t to time.

	Depth	Management villages				*P* value	CV
	cm	Org 1	Org 2	Con 1	Con 2		(± %)
N_0	0 - 10	86.6 ab	89.5 a	111.2 a	43.1 b	< 0.01	55
(µg g^{-1})	10 - 30	32.5 a	36.1 a	37.5 a	17.3 b	< 0.01	37
K	0 - 10	0.32	0.19	0.16	0.32	0.07	70
(day^{-1})	10 - 30	0.44	0.30	0.34	0.52	0.29	51
R^2	0 - 10	0.88	0.80	0.81	0.91		
	10 - 30	0.80	0.81	0.83	0.80		

Org 1 and Org 2 refer to villages with organic management, Nsuta and Adimediem respectively, Con 1 and Con 2 denote villages with conventional management, Kuano and Oboadeka, respectively, CV = mean coefficient of variation between replicates within a village (n = 4).

Table 3.5. Soil microbial properties at different depths of cocoa agroforests in villages under organic and conventional management in Suhum Municipality, Eastern Region of Ghana.

Soil microbial properties	Depth (cm)	Management villages				*P value*	CV
		Org 1	Org 2	Con 1	Con 2		(±%)
MBC (µg g^{-1})	0-10	97 a	110 a	98 a	43 b	< 0.01	40
	10-30	47 a	51 a	67 a	30 b	< 0.01	29
MBN (µg g^{-1})	0-10	19.1 a	23.1 a	20.2 a	6.9 b	< 0.01	40
	10-30	5.7 bc	7.9 b	11.8 a	3.9 c	< 0.01	38
MB-C/N	0-10	5.0	5.4	5.2	6.2	0.08	25
	10-30	9.0 a	6.7 ab	5.7 b	7.8 ab	0.01	29
Basal respiration	0-10	35 b	48 ab	70 a	30 b	< 0.01	59
(mg CO_2-C g^{-1} d^{-1})	10-30	12	19	16	7	0.07	68
MBC/SOC (%)	0-10	0.52	0.54	0.57	0.58	0.67	22
	10-30	0.61 b	0.57 b	0.64ab	0.95 a	< 0.01	28

Org 1 and Org 2 refer to villages with organic management, Nsuta and Adimediem respectively, Con 1 and Con 2 denote villages with conventional management, Kuano and Oboadeka, respectively, CV = mean coefficient of variation between replicates within a village (n = 4).

Pairwise comparison of qCO_2 between organic and conventional management in topsoil showed that it was 35% lower under organic than under conventional management ($P < 0.01$; Figure 3.2). However, this difference was not observed in the subsoil.

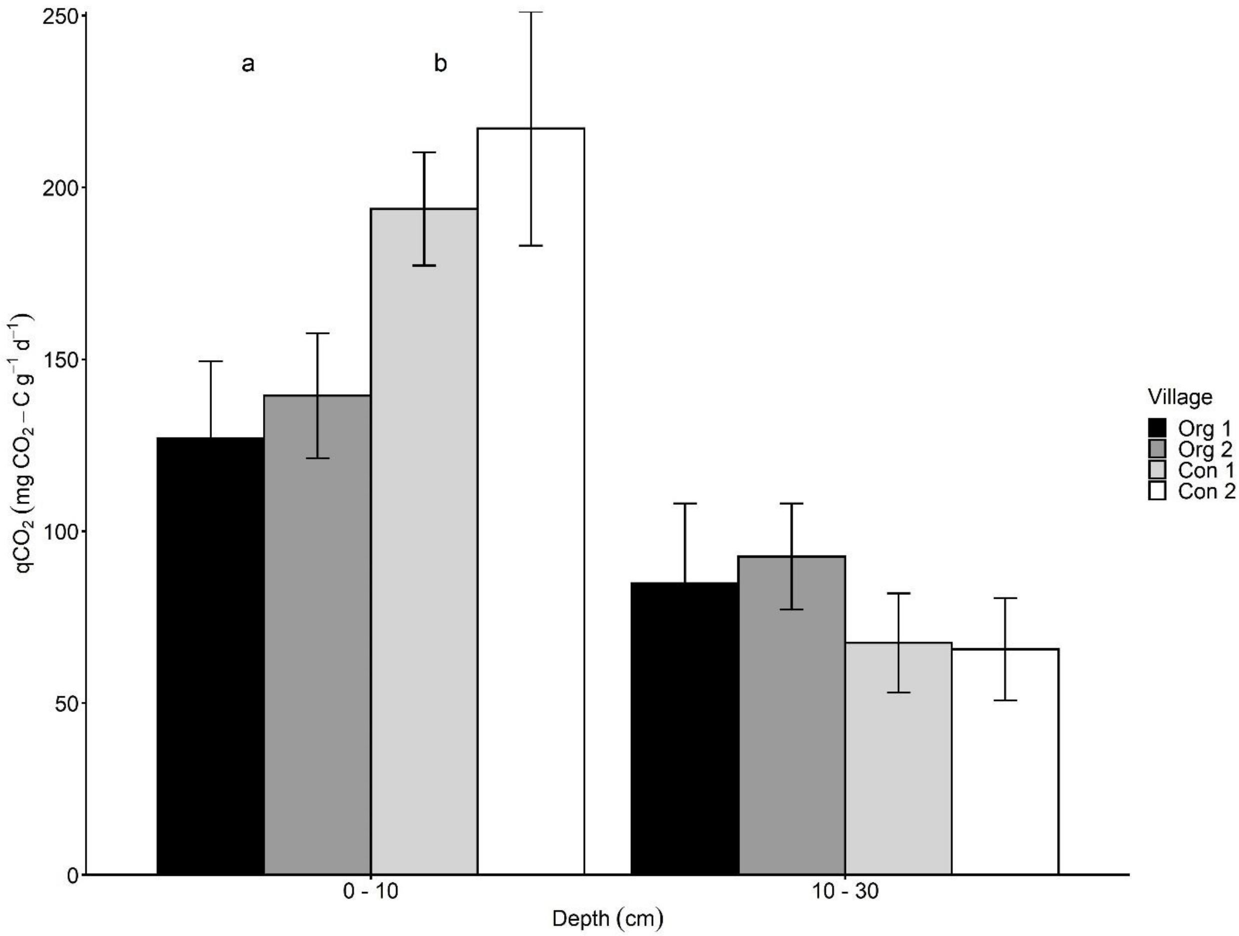

Figure 3.2. Metabolic quotient (qCO_2) at two soil depths in cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana. Error bars indicate +/- one standard error of the mean. Means with different letters indicate significant differences in organic versus conventional management.

Pairwise correlation showed a strong positive relationship for SOC and N with MBC and MBN in topsoils regardless of the management system (Figure 3.3). Basal respiration was positively related to MBC and bulk density (Table 3.6). In addition to SOC, pH and clay positively affected MBC and MBN, respectively.

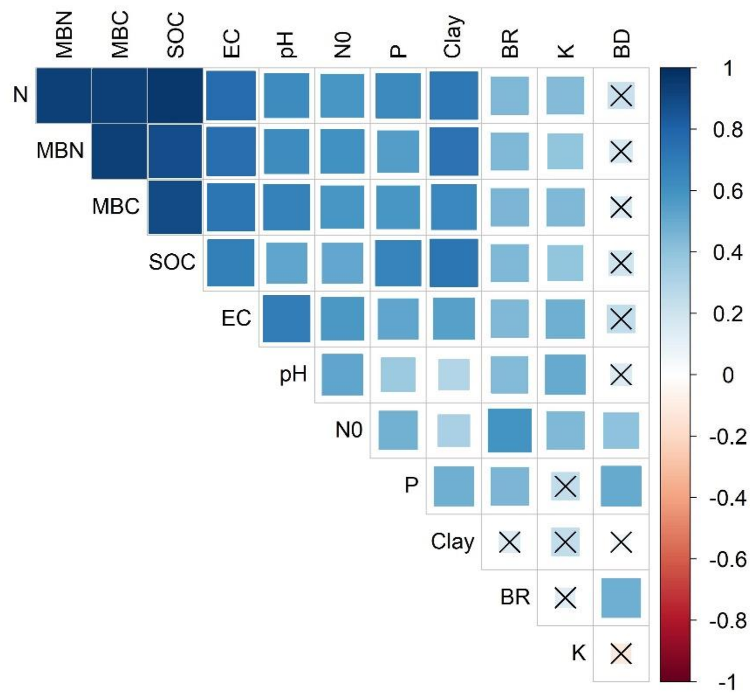

Figure 3.3. Pearson correlation of soil physico-chemical and microbial properties in the topsoils of cocoa agroforest from Suhum Municipality, Eastern Region of Ghana. × shows no significant difference at p > 0.05. N0 refers to the nitrogen mineralization potential, BD = bulk density, and BR = basal respiration.

Table 3.6. Multiple linear regression in the topsoil of cocoa agroforests in Suhum Municipality, Eastern Region of Ghana.

	Constant	Variable 1	Variable 2	R^2
BR	- 16.76	0.26 MBC**	41.02 BD**	0.38
MBC	- 50.55	4.72 SOC**	9.23 pH*	0.90
MBN	- 3.42	0.93 SOC**	0.27 Clay**	0.87

** indicates significant relationship at $P < 0.01$, BR = basal respiration and BD = bulk density.

3.5 Discussion

Cocoa agroforests are known to have high SOC due to high continuous supply of organic material *via* litterfall and turnover of fine roots (Dawoe et al., 2010; Niether et al., 2019). The average SOC of the investigated soil was similar to values reported for cocoa agroforests in the Ashanti Region of Ghana (Dawoe et al., 2014) and in Cameroon (Sauvadet et al., 2020) ranging from 0.7 to 2.6%. The SOC levels in our topsoils were four-folds larger than averages reported by Suárez et al. (2021) from a young cocoa agroforest established on abandoned pasture lands in Columbia. In cocoa agroforests in Brazil two-fold higher SOC concentrations were reported for top and subsoils (Zaia et al. 2012), which may be explained by the high clay content in their soils and a higher quality and quantity of litterfall from leguminous shade trees. Clay is known to stabilize SOC by adsorption and by occluding organic materials within aggregates, protecting it from fast decomposition (Plaza et al., 2013; Singh et al., 2018). Among the villages, Con 2 soils had the lowest SOC, correlating with lower pH, total N, extractable P and K. SOC is an important regulator of these chemical properties because of its ability to increase cation exchange capacity and nutrient buffering (Crasweu and Lefroy, 2001; Oorts et al., 2003). The lower SOC in Con 2 in comparison with the other three villages was not caused by reduced litterfall rates (Agbotui, unpublished data), but rather resulted from fast decomposition of organic matter in the soil lowest in clay content. Similarity in chemical properties between agroforests under organic and conventional management has also been reported for cocoa in Bolivia (Niether et al., 2019) and coffee in Costa Rica (Sauvadet et al., 2019).

Low ammonium compared with nitrate concentration in the soils of the current study are typical for cocoa agroforests and are due to the rapid conversion of ammonium into nitrates (Santana and Cabala-Rosand, 1982; de Souza et al., 2018;). Confirming the findings in a forest soil in Canada (Stratton and Stewart, 1991), we observed that herbicide and occasional usage of mineral fertilizers in conventional cocoa production systems did not affect ammonification and nitrification. Again, soil properties led to lower ammonification and nitrification in Con 2. The average N mineralization rate constant reported for the topsoil in our study was ten-fold higher than that reported for cocoa agroforests in Brazil (Zaia et al., 2012). This may be explained by a high clay content in the latter study. Soils with high clay content generally have low N mineralization rates (Bechtold and Naiman, 2006; Soinne et al., 2021). Most likely the soils in our study mineralized organic N more rapidly to inorganic forms than those reported by Zaia et al. (2012). However, it is important to mention that the net N mineralization in our incubation study demonstrates the soils N mineralization potential. This, however, cannot be directly applied to field conditions because sieving of soil prior to incubation disrupts the natural soil structure, which increases mineralization rates (Hassink, 1992).

Current average MBC and MBN contents were close to the 125 µg C g^{-1} and 22 µg N g^{-1} soil reported for rice (*Oryza sativa*) based agroforestry in India (Kaur et al., 2000). However, it was 79% for MBC and 84% for MBN lower than reported for cocoa agroforests in Bolivia (Alfaro-Flores et al., 2015) and in Brazil (Zaia et al., 2012). Differing SOC levels were the main reason for these differences, which is supported by our observation of strong relationships between SOC and microbial biomass (Figure 3.3 and Table 3.6). In our study, SOC was 51% lower than the values reported by Zaia et al. (2012). Also in the case of Alfaro-Flores et al.(2015), the constant use of compost and inorganic fertilizer led to an increase of soil MBC. Another reason for these disparities may be the high clay content, protecting not only microorganisms from herbivory, but also protecting them from desiccation effects during dry spells (van Gestel et al., 1991; Sugihara et al., 2010), which occurred in the study sites of the above authors and in ours. Our results confirm earlier findings of similarity in soil MBC under organic and conventional management previously found in cocoa and coffee agroforests (Sánchez-De León et al., 2006; Alfaro-Flores et al., 2015). The main distinction between organic and conventional in our study villages is the use of herbicides by the latter. In our study villages herbicide usage by conventional farmers is the main distinguishing factor between them and organic farmers. Herbicides usage did not affect MBC in an incubated soil planted to *Sorghum bicolor* L. Moench. (Haney et al., 2000) and on an arable field (Harden et al., 1993), confirming the similarity in MBC between conventionally and organically managed villages.

In our study, the qCO_2 were four times greater than those reported for natural forest (32 to 53 mg CO_2-C g^{-1} d^{-1}) in Brazil (Bini et al., 2013) and India (Dinesh et al., 2003). These high qCO_2 could be also associated to high availability of organic matter, reducing the average age of soil microorganisms and increasing the demand for maintenance (Anderson and Domsch, 1990, 2010; Joergensen and Wichern, 2018). In general, qCO_2 found in the investigated cocoa agroforests are within the range of 60 to 218 mg CO_2-C g^{-1} d^{-1} reported for agroforests in India (Kaur et al., 2000) and Brazil (Notaro et al., 2014). Pairwise comparison between management showed higher qCO_2 in conventional topsoil than organic, which confirms the claims of other authors (Fließbach and Mäder, 2000; Araújo et al., 2008; Santos et al., 2012). Pesticides and herbicides may lead to physiological stresses of soil microorganisms, increasing the demand for maintenance energy as indicated by high qCO_2 (Duah-Yentumi and Johnson, 1986; Gaupp-Berghausen et al., 2015; García-Pérez et al., 2016).

3.6 Conclusions

Our study showed that organic management of cocoa agroforests had no effect on soil physico-chemical properties and microbial biomass compared to conventionally managed agroforests. Differences found between Con 2 and the other three villages' soils was mainly due to the low clay content. Nitrate was the dominant N form in cocoa agroforests due to the rapid conversion of ammonium into nitrates. Again, management had no significant effect on the N mineralization rate. Lastly, the topsoil of conventionally managed soils had higher qCO_2 than of organically managed ones, which indicates higher demand for maintenance energy, probably due to the use of herbicides and pesticides.

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Chapter 4

Role of internal carbon and nutrient cycling in sustaining traditional cocoa agroforests under organic and conventional management in the Eastern Region of Ghana.

4.1 Abstract

In cocoa agroforestry systems, nutrient cycling acts as energy and nutrient input-output system for organic matter sustenance. We investigated annual litterfall and cocoa leaf decomposition rate in cocoa agroforestry systems under conventional and organic managements. The study was conducted in four villages in the Suhum Municipality in the Eastern Region of Ghana with two villages either under organic or conventional management. Annual litterfall was collected on a monthly basis using litterboxes. Litterbag technique was employed to study the rate of decomposition and nutrient release of cocoa leaf for 12 months. Average annual total litterfall was 8 t ha^{-1} yr^{-1} in this study. Litterfall was 60% higher in the dry season than the rainy season. In the rainy season nitrogen (N) concentration of shed leaves were 17% higher than in the dry season and double (38%) for potassium (K). Management had no effect on total annual nutrient stocks in litterfall. Villages with organic management recorded 16% greater rates of decomposition than villages with conventional management. On the other hand, calcium (Ca) release rate was 28% greater in conventional villages than in their organic counterparts. Annual K and Ca stocks in cocoa pod husk were 4 and 9-folds, respectively, greater than in cocoa beans. In conclusion, spreading cocoa pod husk in farms after harvest will improve internal nutrient cycling.

4.2 Introduction

In terrestrial ecosystems, soils have been recognized as an important carbon (C) sink (Lal et al., 2018). The ability of soils to sequester C depends on highly dependent on type of land use system and its management (Lal et al., 2018). In a global meta-analysis tree based croplands known as agroforestry systems were observed to sequester 41% more soil C than monocultures (Chatterjee et al., 2018). Cocoa (*Theobroma cacao* L.) is an important agricultural commodity whose cultivation is currently largely being converted from agroforestry to monoculture systems (Niether et al., 2020). Because of its dependence on fertile forest soil, cocoa production causes deforestation and CO_2 emissions (Gockowski & Sonwa, 2011). Although traditionally grown in agroforests, higher yields under monoculture (Armengot et al., 2016) motivated farmers to adopt this unsustainable practice. Nonetheless, cocoa agroforests are known to conserve biodiversity and sequester C (Asase & Tetteh, 2010). In some regions cocoa agroforests sequester C comparable to natural forests which is associated to higher litterfall (Gama-Rodrigues et al., 2010). Litterfall in cocoa agroforests is estimated to amount to 10 t ha^{-1} yr^{-1} (Dawoe et al., 2010). Litterfall quantity and chemistry in cocoa agroforestry systems is influenced greatly by climate and shade tree diversity (Saj et al., 2021; Sari et al., 2022). Litterfall is generally higher in the dry season (Saj et al., 2021), however, thunderstorms and high wind speeds in the rainy season causes it to peak occasionally (Becker et al., 2015). In addition, climate affects the nutrient concentration of litterfall. While magnesium (Mg) concentrations were higher in litterfall during rainy season, phosphorus (P) and calcium (Ca) concentrations were higher in dry season litterfall (Pérez-Flores et al., 2018).

The decomposition of litter biomass leads to the release of nutrients into the soil. Decomposition is greatly influenced by climate, soil organisms, and litter chemistry (Aerts, 1997). In cocoa agroforests, initial N, P, lignin, cellulose, and polyphenol are important regulators of litter decomposition (Dawoe et al., 2010; Fontes et al., 2014). Decomposition begins with the physical breakdown of litter by soil macro-organisms such as ants and earthworms (Li et al., 2015). Then the fragmented litter is colonized by soil microbes which alter the litter chemistry through enzymatic activities further breaking down the litter into simple forms (Hobara et al., 2014). However, usage of chemical herbicides and pesticides in agriculture can have adverse effects on soil organisms which alters the decomposition process (Afolabi & Muoghalu, 2018).

There are cocoa agroforestry systems which are managed without synthetic agrochemicals. Under organic management, cocoa agroforestry systems are more diversified in terms of shade trees (Asigbaase et al., 2019) and arthropods (Akesse-Ransford et al., 2021) than those under conventional management. Such differences imply that litterfall and decomposition process in cocoa agroforests under organic management are higher than those under conventional management. However, studies comparing litterfall and decomposition of cocoa agroforests under conventional and organic managements are scarce. The few studies which exist are from South America (Fontes et al., 2014; Schneidewind et al., 2019). For West Africa such studies are unavailable due to the only recent developmental of organic cocoa certification. In Ghana, the first certified organic cocoa production system was established in Suhum Municipality in 2005 (Glin et al., 2015). Globally organic cocoa is produced on 363,000 ha, which constitute 3.1% of total area under cocoa production (Willer et al., 2021). In 2011, West Africa produced 70% of the world’s conventional cocoa, but only 3.3% of organic cocoa (Potts et al., 2014).

In cocoa agroforestry systems, the nutrient cycling process of litterfall and decomposition acts as an input-output system for organic matter sustenance (Fontes et al., 2014). Nutrient cycling is reduced when forests are converted into cocoa agroforests (Saj et al., 2021) due to a reduction in biodiversity and annual nutrient exports in the harvest. Especially in West Africa where nutrients removed annually through harvest are not replaced by fertilizer, it is nutrient cycling which sustains these agroforestry systems. This process can be improved if the cocoa pod husks after separation from beans are spread instead of heaping them to rot (Fontes et al., 2014). Understanding of nutrient cycling will improve our knowledge on how to effectively manage soil fertility in cocoa agroforestry systems in Ghana.

Against this background, we aimed at filling this knowledge gap by studying litterfall and decomposition in Suhum Municipality in Eastern Region of Ghana. The objectives for this study were to (a) determine the influence of seasonality on litterfall and its nutrient concentrations in cocoa agroforests under organic and conventional management, (b) estimate annual litterfall and nutrient recycling in cocoa agroforests under the two management systems, (c) compare the rate of cocoa leaf decomposition and nutrient release over 12 months in organic and conventional cocoa agroforests, and (d) assess nutrient stocks in cocoa beans and pod husk.

To achieve these objectives, we used wooden litter boxes to collect monthly litterfall. For decomposition of cocoa leaves, we used the litterbag method (Anderson & Ingram, 1993).

4.3 Materials and Methods

4.3.1 Study site

The study was conducted in Suhum Municipality (latitude 6°2´3.84´´N, longitude 0°27´8.64´´W) in the Eastern Region of Ghana (Fig. 1.1). The natural vegetation in the Municipality is classified as a semi-deciduous forest, however, human encroachment has reduced it to secondary forests, thickets and grassland (MOFA, 2017). The area has a bi-modal rainfall distribution with the major rainy season lasting from March to July and the minor rainy season from September to November (MOFA, 2017). For 10 years Suhum Municipality had an average yearly rainfall of 222 mm with monthly rainfall ranging from 41 mm in January to 462 mm in September (World Weather Online, 2021). Average monthly temperatures for the past decade range from 20 °C to 35 °C with the hottest months in January and February (World Weather Online, 2021). Suhum was selected as a study area because both conventional and organic cocoa agroforestry systems exist in close vicinity. Local soils are classified as Lixisols (IUSS Working Group WRB, 2015) with an average pH of 6 and a texture made up of 54% sand, 22% silt, and 24% clay (Table 3.2). Within a distance of 6 km we chose four villages, two for each cocoa management system. The villages Kuano (Con 1) and Oboadeka (Con 2) were selected for conventional management, whereas Nsuta (Org 1) and Adimediem (Org 2) villages were selected for organic management. Within each village, three farms were randomly used for litterfall collection and two for cocoa leaf decomposition studies. The 12 farms selected for the study had an average cocoa tree density of 1,347 trees ha^{-1} and average shade tree density of 335 trees ha^{-1} (Table 2.5).

4.3.2 Sampling and laboratory analyses

Litterfall was collected in 50 cm × 50 cm × 30 cm open wooden boxes raised 30 cm above the ground. Nylon netting with mesh size of 2 mm was used to cover the bottom of the boxes to allow aeration and draining of rainwater. Five boxes were placed randomly in each of the 12 farms. Litterbox positions were changed every two months to improve litterfall representativeness of each farm. Litter trapped within the boxes was collected fortnightly and sorted into leaves, reproductive parts, and twigs. Monthly litterfall samples were pooled per farm for laboratory analyses. Reproductive parts and twigs were pooled annually for nutrient determination, due to small quantities of monthly collections.

Litter decomposition was studied in two fields per village. To this end freshly fallen cocoa leaves on the ground were collected in each farm, thoroughly mixed and air dried. Of these 50 g DM were filled into litterbags of 30 cm × 30 cm size and 2 mm mesh. In each farm 36 litterbags were placed on the soil surface and pinned with nails to assure close contact with the soil. A set of six bags were randomly placed in six different locations per farm. The bags were sampled after 1, 2, 4, 6, 8, and 12 months of decomposition. At each sampling time, one bag from each location was randomly picked amounting to 6 bags per farm. Upon bags retrieval, litter was cleaned from soil and other debris, dried, and stored until analysis.

For biomass estimation of dry cocoa pod husks (CPH), twenty fruits from each farm were harvested and cocoa beans were separated from CPH. Beans and CPH were dried at 60 C until constant weight and DM was determined for calculation of bean/CPH ratio. Cocoa bean yield was estimated as the three-year average of r the whole farm as documented in the farmers' Cocoa Passbook and recorded on hectare basis. In Ghana the Cocoa Passbook is the official document, where the weight of dried cocoa beans is recorded at the time of sale by the purchasing clerk (Asare et al., 2019).

Prior to chemical analysis, all collected samples were oven dried at 60 C for 72 hours, weighed, and milled. The C and N concentration of milled samples were determined using a Vario Max CN analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). For major and trace nutrient analyses, milled samples were dry-ashed at 550 C overnight, followed by generating an ash solution (Motsara & Roy, 2008). Major and trace nutrient concentrations in ashing solution were measured using a Spectrogreen ICP-OES (SPECTRO Analytical Instruments GmbH, Kleve, Germany). Acid detergent fiber (ADF) and acid detergent lignin (ADL) were analysed as described by Van Soest (1963) to determine lignin and cellulose, which was estimated as the difference between ADF and ADL. Polyphenols were examined by using the Folin-Ciocalteau method with aqueous acetone (70% v/v) as extractant (FAO & IAEA, 2000). After addition of polyvinyl polypyrrolidone (PVPP) to bind the total tannins in the extract, the supernatant was used to determine the non-tannin phenols with the above-mentioned method. Total tannins were calculated as the difference between polyphenols and non-tannin phenols. Condensed tannins were measured using the butanol-HCl method (butanol-HCl 95:5 v/v; FAO & IAEA, 2000). The initial chemical characteristics of cocoa leaves used in 12 months decompositions are found in Appendix 4.1.

4.3.3 Data analysis

Two-way ANOVA was used to test the interaction between village and season on quantity and nutrient concentrations of fallen leaves. Months with rainfall below 60 mm (December, January, February and August) were considered as part of the dry season. One-way ANOVA was used to test the differences of quantities and nutrient concentrations of annual litterfall differences between villages. Data violating the assumptions of ANOVA were transformed.

For the decomposition study, we used dry ashing to correct for mineral soil contamination of bagged cocoa leaf. The difference between the dry weight of cocoa leaf and their ash dry weight were taken as ash free dry weight. The amount of nutrient remaining (%) was calculated as $\frac{(C_t \times M_t)}{(C_0 \times M_0)} \times 100$ where C_t is the ash free concentration of nutrient at sampling time t, M_t is the ash free dry weight of decomposed leaf litter at sampling time t, C_0 is the ash free initial nutrient concentration, and M_0 is the ash free initial dry weight of the litter. Constants of decomposition and nutrient release rates were estimated using the three parameter exponential model according of Olson (1963): $Y_t = A + Be^{-kt}$

where Y_t is the mass or nutrient remaining at time t in months, A is the recalcitrant pool fraction, B is the labile fraction and K is the decay or nutrient release rate.

The three parameter exponential model was fitted using Sigmaplot 14.0 (Systat Software, Inc., San Jose California USA). Decomposition and nutrient release rate between villages were compared numerically. Time taken for 50% of the litter to decompose (half-life) was calculated as $\frac{\mathrm{In}\,(2)}{K}$ (Olson, 1963). Pearson correlation coefficients were calculated for initial chemical properties of the cocoa leaves used in the litterbags, their decomposition and nutrient release rates. All statistics were performed with R (R Core Team, 2020).

4.4 Results

4.4.1 Quantification of litterfall

Seasonality influenced litterfall quantity in all villages with highest litterfall being recorded in December on the onset of the dry season and lowest in June and July at the end of the major rainy season (Fig. 4.1).

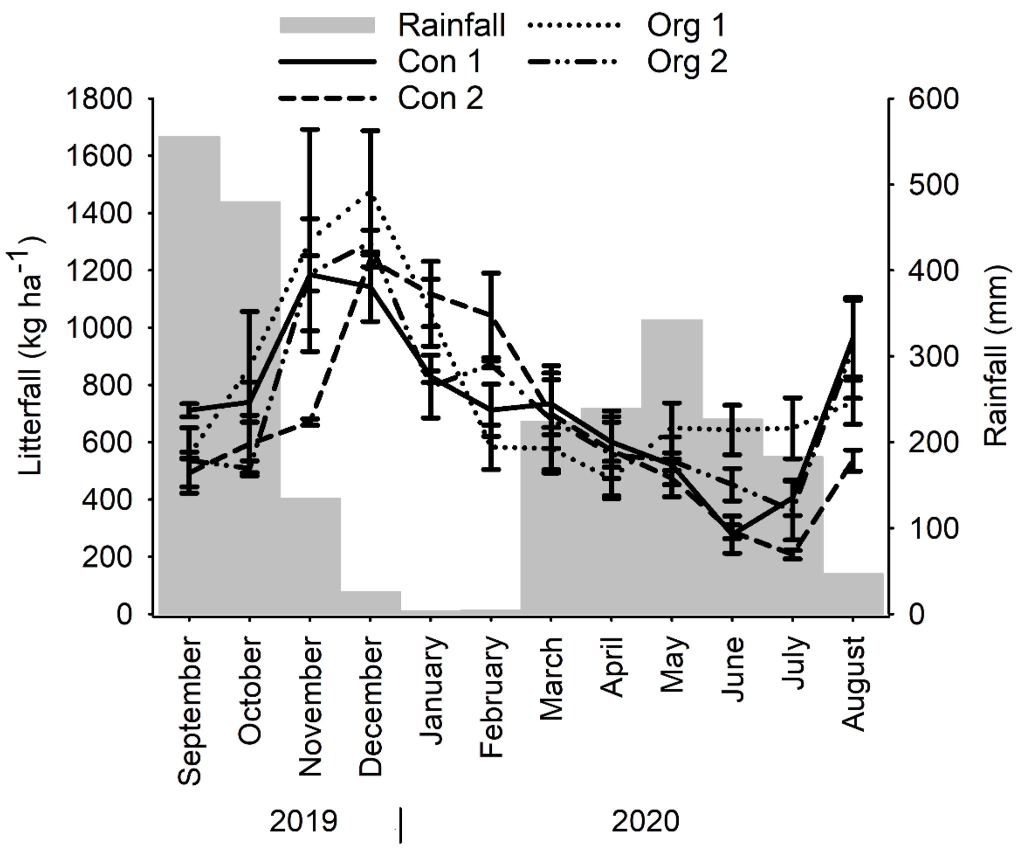

Figure 4.1. Monthly total litterfall (mean ± standard error of the mean) for cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana. 2019 – 2020 average monthly rainfall (World Weather Online, 2021) indicated in bars. Con 1 (Kuano) and Con 2 (Oboadeka) represent villages under conventional management. Org 1 (Nsuta) and Org 2 (Adimediem) represent villages with organic management.

Annual litterfall ranged from 7.9 – 9.6 t ha^{-1} yr^{-1} in the four villages. There was no significant difference in annual litterfall between the villages (Fig. 4.2b). The dry season triggered 60% higher leaves shedding than the rainy season (Fig. 4.2a).

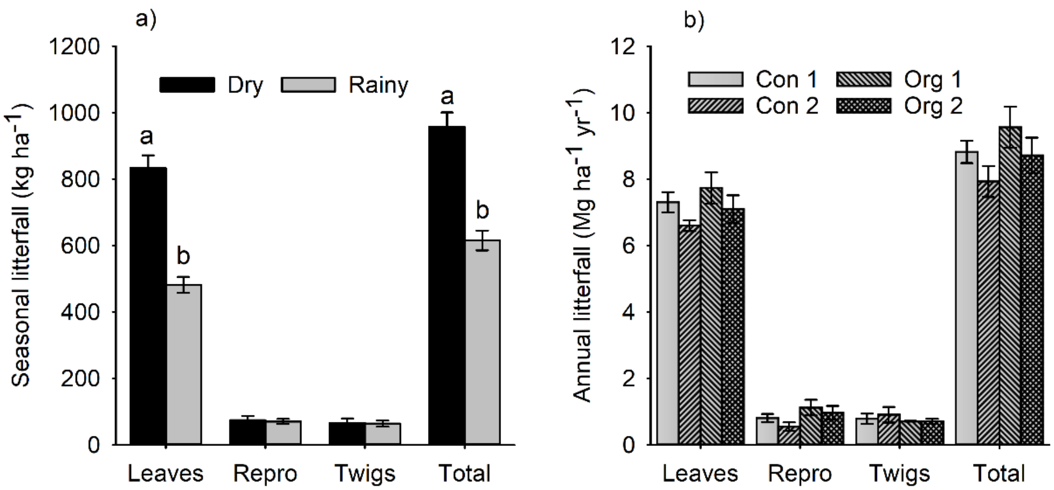

Figure 4.2. Seasonal litterfall separated into leaves, reproductive parts, and twigs (dry and rainy seasons) (a) and annual litterfall in four villages (b) in Suhum Municipality, Eastern Region of Ghana. December to February and August represent the dry season whereas March to July and September to November were considered as part of the rainy season based on monthly precipitation. Repro stands for reproductive parts. Error bars indicate +/- one standard error of the mean. Lower case letters in Fig. (a) indicate significant differences of means between seasons. Con 1 (Kuano) and Con 2 (Oboadeka) represent villages with conventional management and Org 1 (Nsuta) and Org 2 (Adimediem) villages with organic management.

There was no village by season interaction for all nutrient concentrations. Average N and K concentrations were by 10% and 29%, respectively, lower in Con 2 compared with the other three villages (Table 4.1). Phosphorus concentration in Org 2 was 2-fold greater than average for Org 1 and Con 2. In comparison to the other villages, Ca concentration in Org 2 was 13% greater. Magnesium concentration in Con 2 was 8% and 23%, respectively, higher than Con 1 ($P < 0.05$) and Org 1 ($P < 0.05$). During the rainy season leaves recorded a 17% higher N concentration than during the dry season. In contrast, K concentration in the dry season was 38% greater than in the rainy season.

Table 4.1. Nutrient concentrations of litterfall averaged per village across seasons, averaged per season across villages for cocoa agroforests under conventional and organic management in Suhum Municipality, Eastern Region of Ghana.

	C	N	P	K	Ca	Mg
			g kg^{-1}			
Village						
Con 1	441	13.8 a	1.3 b	6.5 a	26 b	7.5 b
Con 2	434	12.1 b	0.8 c	4.4 b	25 b	8.1 a
Org 1	434	13.3 a	0.9 c	6.4 a	26 b	6.6 c
Org 2	435	13.2 a	1.8 a	5.7 ab	29 a	7.6 ab
CV (% ±)	3	14	48	13	13	11
Season						
Dry	432 b	11.8 b	1.3	7.2 a	27	7.6
Rainy	437 a	13.6 a	1.1	5.2 b	26	7.4
CV (% ±)	4	13	84	45	13	11

Con 1 (Kuano) and Con 2 (Oboadeka) represent villages with conventional management. Org 1 (Nsuta) and Org 2 (Adimediem) represent villages with organic management. Lowercase letters indicate significant differences between means at $P < 0.05$. CV is the mean coefficient of variation of village (n = 4) and season (n = 2).

Except for K in leaves, no statistical differences were observed between villages annual nutrient stocks in litterfall (Appendix 4.2). The average annual quantity of K in litterfall leaves for all villages was 1.5 times greater than in Con 2. To annual nutrient stocks in litterfall, leaves alone contributed 71% of N, 65% of P, 61% of K, 82% of Ca, and 85% of Mg. Annual N and P stocks in cocoa beans were 2 and 3-folds greater, than N and P in cocoa pod husks (Appendix 4.3). Annual K and Ca stocks in cocoa pod husk were 4 and 9-folds respectively, greater than those in cocoa beans.

4.4.2 Decomposition of cocoa leaf

Villages with the same management had similar decay rates, whereby mass loss in organic villages was 16% greater than in their conventional counterparts. In all villages within the first two months, 50% of the initial litter disappeared (Fig. 4.3a). At the end of the 12 months only 20% of initial litter remained in litterbags. Con 1 had the highest N release rate which was 59% greater than in Org 1, which was the lowest (Table 4.2). After four months of decomposition, on average 50% of N was released in all villages (Fig. 4.3c). The P release rate in Con 2 was 28% higher than the average release rate in the other three villages. In all villages except for month 2 in Con 1 where there was immobilization P was released (Fig. 4.3d). In all villages a rapid release of K, Mg, and Ca was observed (Fig. 4.3e, f, g). After four months 90% of these nutrients were released from litter biomass. Release rates of Ca were similar for villages with same management, whereby conventional villages' Ca release rate was 28% greater than that of organic villages.

Initial C concentrations of Cocoa leaves correlated positively with C and negatively with Ca release rates (Table 4.3). Cocoa leaf N concentration was positively related to rates of decay (r = 0.91) and C release but was negative again for Ca release rate (r = 0.92). Both cellulose and lignin were statistically negatively correlated with N release rate.

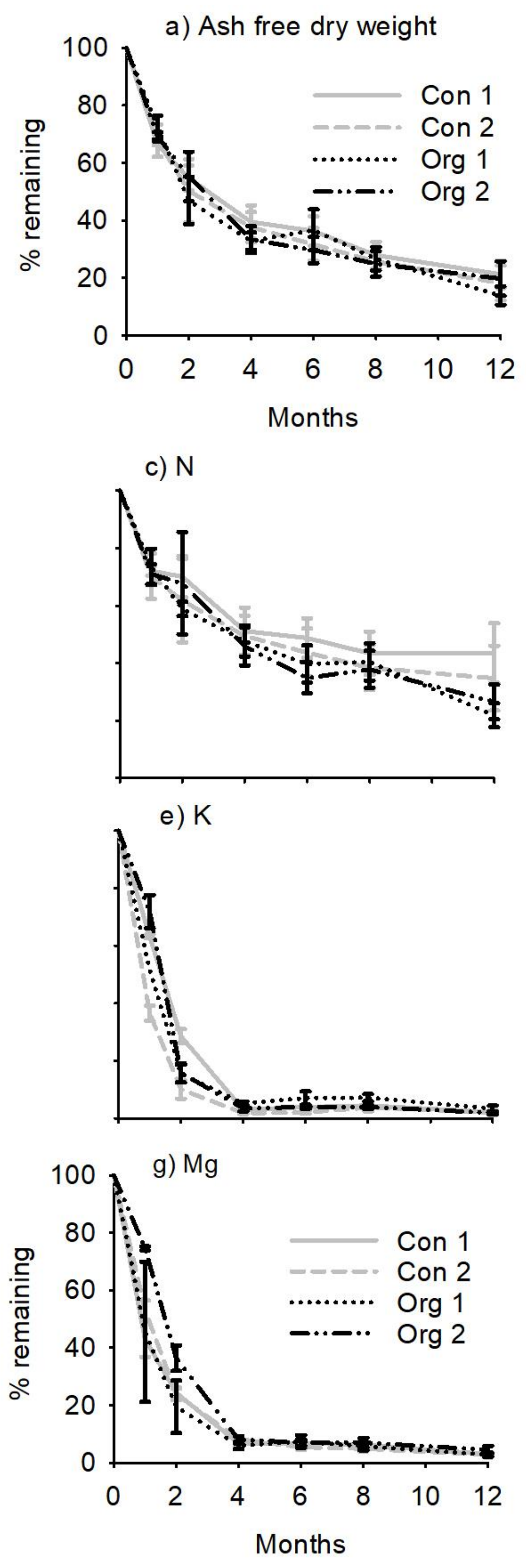

Figure 4.3. Decay and nutrient release patterns of cocoa leaf during 12 months in cocoa agroforests under conventional and organic management in Suhum Municipality, Eastern Region of Ghana.

Table 4.2. Nonlinear regression model for 100% (50g) cocoa leaf dry weight and nutrient losses (A + Be^{-kt}) after 12 months in litterbags placed on the soil surface in cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana.

	A	B	K	t_{50}	R^2	P value
Dry matter						
Con 1	24.32	70.46	0.37	1.87	0.53	< 0.01
Con 2	21.09	74.29	0.37	1.87	0.51	< 0.01
Org 1	22.02	74.83	0.41	1.69	0.53	< 0.01
Org 2	21.95	76.87	0.44	1.58	0.58	< 0.01
C						
Con 1	22.40	73.44	0.40	1.73	0.53	< 0.01
Con 2	20.65	75.17	0.42	1.65	0.54	< 0.01
Org 1	19.18	78.25	0.44	1.58	0.61	< 0.01
Org 2	19.42	79.85	0.46	1.51	0.63	< 0.01
N						
Con 1	43.27	54.83	0.46	1.51	0.24	0.11
Con 2	35.73	59.97	0.38	1.82	0.24	0.09
Org 1	28.08	65.79	0.29	2.39	0.41	< 0.01
Org 2	29.32	68.15	0.35	1.98	0.40	0.02
P						
Con 1	8.39	93.89	0.55	1.26	0.84	< 0.01
Con 2	6.76	94.67	0.69	1.00	0.93	< 0.01
Org 1	19.75	77.39	0.51	1.36	0.40	0.01
Org 2	6.13	102.63	0.55	1.26	0.86	< 0.01
K						
Con 1	1.63	102.49	0.70	0.99	0.96	< 0.01
Con 2	2.12	98.39	1.13	0.61	0.98	0.01
Org 1	5.33	95.82	0.97	0.71	0.94	< 0.01
Org 2	1.50	104.31	0.72	0.96	0.94	< 0.01
Ca						
Con 1	8.86	91.92	0.69	1.00	0.92	< 0.01
Con 2	6.84	94.40	0.69	1.00	0.93	< 0.01
Org 1	8.41	97.10	0.54	1.28	0.89	< 0.01
Org 2	8.50	98.29	0.53	1.31	0.84	< 0.01
Mg						
Con 1	5.26	94.66	0.89	0.78	0.96	< 0.01
Con 2	3.83	96.99	0.74	0.94	0.98	< 0.01
Org 1	4.87	95.70	0.91	0.76	0.89	< 0.01
Org 2	3.84	102.36	0.60	1.16	0.93	< 0.01

A is the recalcitrant pool fraction, B is the labile fraction and K is the decay or nutrient release rate and t_{50} is half-life in months. Con 1 (Kuano) and Con 2 (Oboadeka) represent villages with conventional management. Org 1 (Nsuta) and Org 2 (Adimediem) represent villages with organic management.

Table 4.3. Pearson correlation coefficient (r) between initial chemical properties of cocoa leaf and decay and nutrient release rates in cocoa agroforests under conventional and organic management Suhum Municipality, Eastern Region of Ghana.

	K_D	K_C	K_N	K_P	K_K	K_{Ca}	K_{Mg}
C	0.87	0.96*	-0.74	0.16	-0.00	-0.92*	0.20
N	0.91*	0.99**	0.67	0.14	-0.00	-0.90*	0.28
P	0.36	0.67	-0.71	0.03	0.26	-0.38	-0.29
Lignin	0.71	0.86	-0.90*	0.12	0.03	-0.85	0.11
Cellulose	0.59	0.79	-0.95*	-0.06	0.09	0.75	0.09
Polyphenols	0.53	0.75	-0.26	0.03	0.01	0.33	0.81
Total tannins	0.53	0.75	-0.26	0.03	0.01	0.34	0.81
Lignin/N	-0.75	0.67	0.07	0.05	0.23	0.44	0.71
Cellulose/N	0.48	0.70	0.98*	0.04	0.16	0.66	0.06
Polyphenols/N	0.45	0.69	-0.26	0.07	0.03	-0.26	-0.81

where * represents $p < 0.05$ and ** $p < 0.01$.

4.5 Discussion

4.5.1 Litterfall quantity and quality

We found no effect of management type on total annual litterfall, confirming findings for other cocoa agroforests under organic and conventional management in Bolivia (Schneidewind et al., 2019). Average litterfall of our study (8 t ha^{-1} yr^{-1}) falls within the upper limit for the range of 5 – 10 t ha^{-1} yr^{-1} reported for other cocoa agroforests in Ghana (Dawoe et al., 2010), Cameroun (Saj et al., 2021) and Indonesia (Sari et al., 2022). Contribution of leaves to total annual litterfall (82%) in our study is within the range of 60 – 92% reported for cocoa agroforests (Dawoe et al., 2010; Fontes et al., 2014; Sari et al., 2022) and homegardens in Tanzania (Becker et al., 2015). High litterfall caused by dry seasons is well documented in cocoa agroforests (Saj et al., 2021) and was also observed in our study. This phenomenon is explained by tree adaptation to reduce foliage transpiration during the dry season, which is triggered by stimulation of abscisic acid in plant foliage (Yang et al., 2003). Another reason might be due to rapid leaf ageing during this period, which can be caused by photoinhibition, leaf overheating and stomatal closure (Wright & Cornejo, 1990).

Higher concentrations of N in the rainy season compared with those of the dry season confirms findings of Teklay (2004). Green fresh leaves have higher N concentrations than senescent leaves (Teklay, 2004). Therefore, it is likely that litterfall during the rainy season is more composed of fresh leaves rather than senescent leaves than during the dry season. This might be caused by thunderstorms in the rainy months mechanically forcing N rich fresh and young leaves to drop (Paudel et al., 2015). Additionally, the availability of N in the soil during the rainy season could have increased N uptake by trees (Teklay, 2004). Potassium concentrations in litterfall were lower during rainy seasons compared with dry seasons. On one hand, K is an important osmotic agent, accumulated by plants in reaction to drought. On the other hand, growth rates of leaves are reduced during dry periods, generally leading to an increase in mineral leaf components due to a concentration effect. Moreover, because K is not bonded to any known organic compound, it likely (partly) leaches from leaves in litter traps during rainfall events (Wood et al., 2005). Low N, P and K concentrations found in Con 2 was due to low availability of these nutrients in the soil. In comparison to soils in the other villages, earlier soil analyses showed that soils in Con 2 had lower clay content and organic C (Table 3.2 and 3.3) implying low nutrient retention.

4.5.2 Decomposition of cocoa leaf

Initial rapid decomposition, as observed in all villages, was caused by leaching and break down of soluble compounds like sugar, starch, and amino acids (Wieder & Lang, 1982). The disappearance of 50% of the initial material in the first two months is a common occurrence in tropical agroforestry system (Yao et al., 2021). Particularly cocoa agroforests with high litter diversity on the soil surface host a diverse community of soil and litter macro and microfauna (da Silva Moço et al., 2009) accelerating litter fragmentation. Latter stages of decomposition were more gradual because of accumulation of more recalcitrant compounds like cellulose, lignin, and tannins (Wieder & Lang, 1982). Our average decomposition rate of 0.40 falls within the range of 0.30 – 0.58 reported for cocoa leaves in Nigeria (Afolabi & Muoghalu, 2018) and Cote d´Ivoire (Yao et al., 2021). However, Dawoe et al. (2010) reported a decomposition rate of 0.23 cocoa agroforests in the Ashanti Region of Ghana, which was 43% lower than ours. Considering that both studies worked under similar soil fertility and a cocoa leaf C to N ratio of around 37, litter quality and soil fertility were unlikely the reason for this variation. Instead differences in climate may account for this difference (Aerts, 1997), because the study site of Dawoe experiences longer dry seasons (5 months) compared to four months in Suhum Municipality. Another reason could be an inhibition of decomposition processes due to the use of herbicides (Hendrix and Parmelee, 1985) and pesticides (Afolabi & Muoghalu, 2018). The higher decomposition rate of cocoa leaves in organic villages compared to conventional villages may be due to the prohibition of the use of herbicides and pesticides in certified organic agriculture. Agrochemicals have been found to have adverse effects on the growth and population of macro decomposers such as ants and earthworms (García-Pérez et al., 2016; Masoni et al., 2017) as well as on bacteria and fungi population (Afolabi & Muoghalu, 2018). An indirect effect of agrochemicals on litter is their ability to alter the chemical composition of the litter or microclimate of the decomposition subsystem (Hendrix & Parmelee, 1985). The initial N concentration was found to be a good predictor of cocoa leaf degradability, which was also observed for cocoa leaves mixed with shade leaves (Dawoe et al., 2010). Because microorganisms need N to grow and accelerate decomposition, the more N the better C rich compounds are decomposed (Talbot & Treseder, 2012). Lignin and cellulose are recalcitrant to microbial degradation resulting in slow mineralization of N bound to these complex compounds (Tian et al., 1992). This was indicated by the negative correlation of N release with lignin and cellulose (Partey et al., 2013). One limitation of our study was that the decomposition and nutrient release rates were determined for cocoa leaves alone without accounting for leaves from surrounding shade trees. A mixture of leaves from different species alters litter chemistry, which could be synergistic or antagonistic to decomposition processes and nutrient release (Cuchietti et al., 2014).

4.5.3 Nutrient stocks in cocoa beans and pod husks

The nutrient stocks in cocoa beans and pod husk were determined by estimating the proportion of beans to CPH of cocoa fruits and multiplying it by the three year average yield recorded in the farmers' passbooks (Abdulai et al., 2020). The recorded cocoa yields of 559 kg $ha^{-1}yr^{-1}$ were higher than the 477 kg $ha^{-1}yr^{-1}$ reported for the mid zone of Ghana (Abdulai et al., 2020), which has similar climatic conditions as Suhum. Farmers could reduce nutrient export from harvest by 33% for N and 25% for P if they spread the cocoa pod husks in their farms after harvest. This is particularly important for nutrients such as K, Ca, and Mg, which were 300%, 800% and 28%, respectively, higher in cocoa pod husks than in cocoa beans. Nutrients to be retained after harvest if cocoa pod husk were spread would be 81% for K, 90% for Ca, and 56% for Mg. The traditional practice of spreading cocoa pod husk is often avoided to prevent the spread of diseases such as cocoa black pod disease which is caused by *Phytophthora spp*. (Opoku-Ameyaw et al., 2010). Composting of cocoa pod husk could be an option to control disease pathogens (Opoku-Ameyaw et al., 2010) and return nutrients to the cocoa trees. Cocoa farmers in the study area will therefore require adequate training on composting to be able to use cocoa pod husk for improvement of their internal nutrient cycling.

4.6 Conclusions

Our findings show that litterfall followed a seasonal pattern with peaks at the onset of the dry season. Seasonality had effect on litterfall K and N concentrations and management had no effect on annual litterfall. Cocoa leaf decomposition rate in organic management was greater than in conventional management. But for Ca, conventional management release rate was higher than in organic management. Cocoa leaf initial N, cellulose and lignin are important regulators for cocoa leaf decomposition and nutrient release. We also conclude that spreading of cocoa pods husks in farms after harvest can improve the internal nutrient cycle of cocoa agroforestry systems.

4.7 References

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4.8 Appendices

Appendix 4.1. Initial chemical properties of cocoa leaf used in decomposition in Suhum Municipality, Eastern Region of Ghana.

	C	N	P	Lignin	Cellulose	Polyphenol	Total tannin	Lignin/N	Cellulose/N	Polyphenol/N
Con 1	413	10.9	3.0	492	220	108	105	45	20	9.9
Con 2	422	11.3	3.2	489	205	121	207	43	18	18.8
Org 1	354	9.8	1.7	440	108	100	95	45	11	10.4
Org 2	375	10.3	3.0	463	166	142	140	45	16	13.9
CV (% ±)	1	3	22	3	18	28	27	6	21	31

Con 1 (Kuano) and Con 2 (Oboadeka) represent villages with conventional management. Org 1 (Nsuta) and Org 2 (Adimediem) represent villages with organic management. CV is the mean coefficient of variation of village (n = 4).

Appendix 4.2. Annual nutrient stocks in litterfall, cocoa beans and pod husk of cocoa agroforests under conventional and organic management in Suhum Municipality, Eastern Region of Ghana.

	C	N	P	K	Ca	Mg
				$kg\ ha^{-1}\ yr^{-1}$		
Leaves						
Con 1	3200	99	9	47 a	187	55
Con 2	2854	78	5	28 b	167	53
Org 1	3331	104	7	47 a	191	50
Org 2	3081	72	13	41ab	202	54
CV (% ±)	8	12	30	14	12	12
Repro						
Con 1	351	21	3.0	12	18	5.4
Con 2	241	13	2.3	8	10	3.2
Org 1	470	31	3.7	22	27	7.3
Org 2	412	23	3.4	12	23	6.5
CV (% ±)	36	39	56	61	43	37
Twigs						
Con 1	361	11	1.5	9.8	22	5
Con 2	425	10	1.3	6.2	19	5
Org 1	326	9	1.1	5.3	20	3
Org 2	329	8	1.5	3.4	17	3
CV (% ±)	25	31	39	56	37	41
Total						
Con 1	3912	131	13	70	227	65
Con 2	3519	102	9	42	197	61
Org 1	4127	143	12	75	238	60
Org 2	3824	123	18	56	245	63
CV (% ±)	9	14	32	24	12	10

Con 1 (Kuano) and Con 2 (Oboadeka) represent villages with conventional management. Org 1 (Nsuta) and Org 2 (Adimediem) represent villages with organic management. Lowercase letters indicate significant differences between means. The CV is the mean coefficient of variation in a village (n = 4).

Appendix 4.3. Annual nutrient stocks in cocoa beans and pod husks of cocoa agroforests under conventional and organic management in Suhum Municipality, Eastern Region of Ghana.

	C	N	P	K	Ca	Mg
			kg ha^{-1} yr^{-1}			
Cocoa beans						
Con 1	382	14.4	2.96	6.7	0.48	2.10
Con 2	345	12.9	2.57	5.9	0.40	1.86
Org 1	273	10.3	2.12	4.5	0.39	1.48
Org 2	330	13.1	2.69	5.5	0.43	1.88
CV (% ±)	29	30	33	33	33	31
Cocoa pod husk						
Con 1	256	7.3	0.93	26.0	3.61	2.40
Con 2	283	6.0	1.00	24.0	3.59	2.49
Org 1	200	4.7	0.66	20.0	3.14	1.89
Org 2	277	6.8	1.17	27.0	3.89	2.45
CV (% ±)	32	28	34	36	31	31

Con 1 (Kuano) and Con 2 (Oboadeka) represent villages with conventional management. Org 1 (Nsuta) and Org 2 (Adimediem) represent villages with organic management. Lowercase letters indicate significant differences between means. CV is the mean coefficient of variation of village (n = 4).

Chapter 5

General discussion, conclusions, and recommendations

5.1 Discussion

In this final chapter, I will return to the original research objectives and hypotheses and assess the strengths and limitations of the methods used to address the objectives and test the initial hypotheses. I will also assess alternative methods which could have reduced the limitations of the study. The latter part of this chapter will be used to make some conclusions as well as management and policy recommendations for the various stakeholders involved.

5.1.1 Review of methods used to assess profitability and C sequestration (Study 1)

Although important for agricultural systems profitability calculations, opportunity costs were not considered in our study as compared to a study from Bangladesh where opportunity cost reduced agroforestry systems' profitability by 72% (Rasul and Thapa, 2006). This was because agriculture is the predominant source of employment in our study area, employing about 50% of the population in Suhum Municipality (MOFA, 2017). Also, within the agriculture sector, cocoa production receives a lot of governmental support in terms of extension services and subsidies making it an attractive agriculture venture for farmers. Additionally, state regulation and standardization of annual cocoa beans' prices (Kolavalli and Vigneri, 2011) ensures guaranteed yearly revenues to farmers. Lastly, growing cocoa in agroforestry systems offer farmers the opportunity to benefit from the yields of other crops thus cocoa agroforests offer ample employment opportunities. These reasons made us to assume that opportunity costs are de facto zero.

Due to the absence of well-kept farm records, we had to interview farmers to obtain food crop revenue information – a common practice to obtain cost and revenue for cocoa agroforestry systems (Obiri et al., 2007; Nunoo and Owusu, 2017). Hence the food crop revenue reported in Study 1 remain estimations influenced by farmers perceptions. Furthermore, the food crop revenue reported in this study did not account for the monetary value of other crop yields from cocoa agroforestry systems which farmers usually consume as food. This, however, matters as Bandanaa et al. (2016) reported that organic cocoa farmers consume more harvested food products than conventional cocoa farmers in Ghana which has a substantial effect on food security.

To obtain an accurate revenue from food crops, we could have weighed all harvested food crops and determined their farm gate price as done by Armengot et al. (2016) on an experimental station with plots designed for different cocoa production systems. However, this approach was not adopted because our study took place in a comparatively large area (approximately 840 km^2) involving 200 farmers. Alternatively, farmers could have recorded their revenue from annual food crops, but due to their often low literacy rate (Table 2.2) this was hardly possible.

In estimating C sequestered in cocoa agroforestry systems, we assumed that 50% of the tree biomass was C (Albrecht and Kandji, 2003), although C content in tree biomass is species-dependent (Arias et al., 2011; Nair, 2012). In assessing C sequestered, we divided the tree biomass into above ground biomass (AGB) and below ground biomass (BGB). Direct (destructive) and indirect (non-destructive) methods are the two approaches used in estimating AGB of trees (Nair, 2012).

The direct method involves excavating the whole tree, followed by cutting it into different components before determining the dry matter of each fraction (Zaro et al., 2020). Although this method is accurate, it is time- and labour-intensive especially for large trees (Nair, 2012). It is for this reason that the indirect, less costly and non-destructive approach was used in this study. This method uses allometric equations based on biophysical tree properties validated by destructive methods for specific forest ecology and climatic zones (Chave et al., 2005; Brown et al., 2020). In estimating AGB, it is desirable to use species specific equations. However, given the high tree species diversity in tropical ecosystems, this would be a daunting task. As a result, shade trees AGB in this study were measured using allometric equation developed for forest trees within the wet and moist climatic zones in Ghana (Henry et al., 2010). According to the authors, a combination of stem diameter (measured at 1.5 m), crown diameter, and wood density is the best predictive model to estimate AGB. But because of the complexity in obtaining accurate crown diameter and wood density, the use of stem diameter, which is easy to measure in the field, provides the best practical model to estimate AGB. This guided our decision to use only stem diameter (Table 2.1). As these allometric equations were developed based on trees growing either in closed plantations or in natural forests (Nair, 2012), they do not give accurate AGB in open spaced agroforests. However, considering the variations in agroforestry systems, getting specific allometric equation for each of them is nearly impossible.

Our approach to calculate economic profitability by monetizing C sequestered in the agroforestry systems is simple but using this approach, generally called payment for environmental services (PES) to promote C sequestration and biodiversity conservation, has its shortfalls. The most important limitation is the issue of permanence (Swart, 2003; Engel et al., 2008) which is the achievement of long term environmental service even beyond the payment period (Engel et al., 2008). Swart (2003) critiques PES by doubting the continuation of sustainable land use when payment stops taunting it as “no pay no care”. Swart (2003) further argues that the monetarization of environmental services implies that non-nature alternatives that deliver the same service can be used as substitutes. Also according to Engel et al. (2008) the success of PES is highly dependent on the paid amount, and low payment will rather hamper the adoption of sustainable land use. Implying that payment of C at low price as shown in this study will impede the adoption of organically managed cocoa agroforestry system. The last PES limitation worth noting is the issue of leakage which refers to PES promoting the damage of environmental services outside the geographic boundaries of where it is been implemented (Le Velly et al., 2017). In view of these challenges with PES, Swart (2003) proposes non-monetary nature conservation strategies fostered by ethical, aesthetic, cultural, and religious beliefs. Such cultural and traditional methods have been effective in conserving tree species like iroko (*Milicia excelsa*) in Benin (Ouinsavi et al., 2005) and colobus monkeys (*Colobus vellerous*) in Ghana (Saj et al., 2006), both are frequent components of cocoa agroforestry systems.

5.1.2 Review of methods used to assess soil fertility (Study 2)

Generally, traditional farmers have adequate knowledge on soil properties making them often valuable agents during soil sampling procedures (Pennock et al., 2008; Dawoe et al., 2012). As a result, together with farm owners we delineated each farm into sub-plots according to slopes followed by sampling 10 soil samples in a zig-zag manner along the slope. Using this method made us obtain a representative sample for each farm.

We used the laboratory incubation method to estimate N mineralization in the soils. However, there are other field methods which include incubations in plastic bags, PVC or metal cylinders and resin ion cartridges (Eno, 1960; Hanselman et al., 2004; Isaac et al., 2005). The plastic bag method involves burying plastic bags filled with soil at the depth of 10 cm in the field for several days or weeks. This method is easy and has the potential to capture field temperature variability effect on N mineralization but physical damage of plastic bags and penetrating roots leads to mineralized N losses (Eno, 1960). A durable and robust alternative to the buried bag method is incubating intact soil cores by inserting PVC or metal pipes covered at the top into soils (Isaac et al., 2005). But the limitation of this approach is the denitrification of mineralized N due to anaerobic conditions in tubes after heavy rainfall (Isaac et al., 2005). Secondly, through the open bottom end, plant roots are able to penetrate and utilize mineralized N (Hanselman et al., 2004). A more advance field method is to capture mineralized leached N through the soil with resin-sand mix enclosed in a PVC container known as cartridges. This method is able to eliminate the temperature, moisture and aeration variation between incubated and surrounding soils (Hanselman et al., 2004). However, care must be taken during installation that the soil layer above the cartridges is not disturbed to disrupt downward water infiltration. Also, drying out of resins can affect the adsorption capacity of mineralized N (Kjonaas, 1999). In general, all field methods described above permit longer studies but they require more replicates to capture spatial field variabilities (Jarvis et al., 1996). We used laboratory incubation because it is flexible, allowing to define and hold environmental conditions constant (Piccolo et al., 1994). In addition, the method's ability to accommodate air-dried soils, their rewetting, and incubation eliminates the complications associated with transporting fresh frozen samples. Hence sampled soils can be analyzed far from the field of sampling. However the sieving process associated with laboratory incubation disrupts natural soil structure which hastens N mineralization (Hassink, 1992).

The soil parameters we analyzed in Chapter 2 have been used in comparing fertility between cocoa agroforests under conventional and organic management (Alfaro-Flores et al., 2015; Niether et al., 2019). In a recent review on cocoa production systems in Ghana, Amponsah-Doku et al. (2022) highlights the neglect of soil microbial properties in the assessment of soil fertility. According to Joergensen & Emmerling (2006) because soil microbial properties respond quickly to land use change than soil physico-chemical properties, they give early indication to soil ecosystem restoration or degradation. This formed the basis for their inclusion in our study.

We used the chloroform fumigation extraction (CFE) method to analyze soil microbial biomass C and N. This method is an adaptation of the chloroform fumigation incubation method (CFI). Both methods estimate microbial biomass based on the principle of increased biochemical activity after chloroform ($CHCl_3$) fumigation of moist soil leading to decomposition of dead microbes by recolonizing microbial population in aerobic conditions (Jenkinson, 1966). The difference between CFE and CFI is that the former corrects the increased amounts of C extractable with 0.5 M K_2SO_4 in $CHCl_3$ fumigated soils with a correction factor (Vance et al., 1987). The advantage of CFE over its predecessor is it effectiveness in soils with low pH (Chen & He, 2004) and flooded soils (Witt et al., 2000). Success of these two methods rely on two assumptions (Jenkinson, 1966). Firstly, the amount of CO_2 produced in killed microbes in fumigated soil must be greater than those that die in unfumigated soils. Secondly, the amount of CO_2 breakdown in non-living soil organic matter must be similar for fumigated and unfumigated soils. The second requirement is particularly challenging for soils amended with organic materials which leads to low or negative biomass values (Martens, 1995). According to Martens (1985) this underestimation of microbial biomass in amended soils is due to lower degradation of added C in fumigated soils. Aside this weakness, critics such as Ingham and Horton (1987) argue that $CHCl_3$ does not kill all soil microbes after observing soil bacteria and fungi reduction range of 37% to 79% in $CHCl_3$ fumigated soils. On the contrary, there is numerous evidence suggesting that $CHCl_3$ fumigation kills 80 - 90% of soil microbes (e.g. Chen et al., 2015). Fungi are more sensitive to $CHCl_3$ fumigation than bacteria which according to Toyota et al. (1996) is due to the secretion of exopolysaccharides by bacteria which shield them from the fumigant. Fresh soil samples are desired for CFE, but rewetting incubated air-dried soil samples also give results comparable to those in fresh soils (Zornoza et al., 2007).

One important limitation in our study is the use of two villages per management. At least four villages per management would have improved the statistical efficiency by reducing variability (Blainey et al., 2014). This also holds for the number of cocoa fields per village, which at least should have been four.

5.1.3 Review of methods used to assess internal nutrient cycling (Study 3)

Wooden litter boxes used in this study are an effective way of studying litterfall. But wind turbulence around the box can move litter in and out of the box (Kumar, 2007), whereby the probability of this occurring is higher in shallow boxes than deeper ones (Kumar, 2007; Saj et al., 2021). Taking this into account, litterboxes used in this study were 30 cm deep. Another issue to consider is the *in situ* decomposition of litter in the boxes, which underestimates litter and their nutrient concentration. In our case, we addressed this issue by using suspended boxes raised 30 cm aboveground with 2 mm mesh size nylon netting underneath, allowing easy draining of rainwater and adequate aeration. Also, our adoption of two weeks litter collection schedule prevented *in situ* decay. Our deployment of 5 litter boxes per farm and constant changing of boxes position (every two months) made us improve litterfall representativeness for each farm. Litterfall studies should exceed 12 months duration, especially when studying inter-year variations (Wood et al., 2005; Kumar, 2007; Tang et al., 2010). However, according to Kumar (2007), 12 months duration also give reasonable accounts provided the climatic parameters represent the period and agroecosystems are in a steady-state condition. Many authors have used the duration of 12 months to study litterfall in agroforestry systems (Becker et al., 2015; Pérez-Flores et al., 2018; Saj et al., 2021). However, one limitation of our study was having pooled all leaves rather than separating them into cocoa and shade tree leaves. As a result, we could not estimate the relative contribution of shade trees to litterfall.

The litterbag technique used in this study is an easy and reliable method for litter decomposition studies (Potthoff & Loftfield, 1998; Idol et al., 2002). When using this method, it is imperative to separate soil particles and exogenous materials from the enclosed litter after periodic litterbag removal. This can be done by washing external materials with water before oven drying and weighing (Anderson & Ingram, 1993; Hartemink & O´Sullivan, 2001). The demerit of this process is the loss of material and the leaching of soluble carbohydrate and K resulting in the overestimation of decay and nutrient release rate (Potthoff and Loftfield, 1998; Kumar, 2007). Because of this, we used a brush to thoroughly clean cocoa leaf prior to dry matter determination. We then corrected for soil contamination by ashing. Potthoff & Loftfield (1998) reported a high correlation (r = 0.99) between measured ash content and straw with predefined soil contamination when the samples are homogenized by grinding before subsampling for ashing. To reduce errors we followed the Potthoff & Loftfield (1998) procedure to homogenize cocoa leaf by grinding before subsampling for ashing. The ashing process has the disadvantage of not correcting for soil organic matter contamination (Rustad, 1994; Cortez & Bouche, 1998). Besides the assumption that all ash is from the mineral soil, the method ignores the ash from minerals in the litter (Kurzatkowski et al., 2004).

The above-mentioned shortcomings lead to an underestimation of the decomposition and nutrient release rate. Therefore, Potthoff & Loftfield (1998) proposed using Al as an alternative marker because it is 100-times higher in soils than in straw. However, measuring Al is more expensive and complicated than using simple ash. Similar to the ash method, the above authors assume that the ash or Al in the litter or straw remain constant before and after decomposition. Rustad (1994) proposed enclosing inert undecomposable material into the litterbag. A change in the mass of the inert material is used to indicate total litterbag contamination by both soil mineral and organic matter. Idol et al. (2002) used the inert control bag method and they report higher decomposition rates for inert control bag correction than for ash-free correction. However, the above authors also named two drawbacks associated with the inert method. One is differences in the surface area and characteristics (e.g. chemical reactivity and texture) between inert material and litter may vary their ability to hold organic material falling in the litterbags. Additionally, the interaction between macro and microfauna with inert material and litter may differ.

We only studied cocoa leaf decomposition because the litterbag technique restricts the number of leaf types. Our decomposition results do not reflect the litter decomposition in cocoa agroforestry systems at the field scale due to mixing of cocoa leaves with those of shade trees in the field. Cuchietti et al. (2014) reported changes in decomposition and nutrient release rates when leaves with different qualities are mixed. Hence depending on quality of shade tree leaves, decomposition and nutrient release will be higher or lower than what we reported. Other authors have overcome this shortfall of the litterbag approach by sampling accumulated litter on soil surface at regular intervals to estimate litter mean residence time which has the advantage of considering all available litter in a study site (Martius et al., 2004; Dawoe et al., 2010). However the limitation of this method is the assumption that the whole system is in a steady state (Kurz-Besson et al., 2005). Having observed seasonal effect on N and K concentration in litterfall, it would have been interesting to study how dry and wet seasons influence decomposition and nutrient release rates to better predict decomposition and nutrient release in cocoa agroforestry systems.

Our results showed annual cocoa pod husks to be rich in Ca, K, and Mg. Despite their high nutrient concentrations, farmers in the study area leave the cocoa pod husks for mineralisation in heaps after taking out the beans. To improve the internal nutrient cycling we propose to compost cocoa pod husks with poultry manure followed by its use as an organic fertilizer.

5.2 Conclusions

The profitability analysis of different cocoa agroforestry systems demonstrates the feasibility of using traditional cocoa agroforests in REDD+ projects. Such systems create a win-win situation for both conservationists and farmers. Conventional management was more profitable than organic management because of low food crop revenue during the establishment phase (1 – 5 years). The production constraint with the most adverse effects on profitability in the study area was a 300% increase in interest rates. Assumed payments for C trapping improves the profitability of cocoa agroforestry systems, however at high C payment (42 € t CO_2eq.$^{-1}$), organic management profitability is only marginally higher than conventional management. Paying C at a high price will be a good incentive to hasten the adoption of organic cocoa management. Under agroforestry systems, management had no effect on soil physico-chemical and microbial properties. Contrarily, the metabolic quotient (qCO_2) in conventional management topsoil was higher indicating stress for microbial communities because of herbicide and pesticide use. Considering the similarities between cocoa agroforests under organic and conventional management, it should be easy for conventional management to adopt organic management in the study area.

5.3 Recommendations

Sustainable cocoa production is hinged on farmers adopting regenerative agriculture practices like cocoa agroforestry systems under organic management. To ensure farmers adopt these practices, it will be helpful to make them profitable through improving soil fertility and internal nutrient cycling.

For the Government of Ghana and all cocoa stakeholders in Suhum Municipality, it will be important to foster the development of an organic market for cocoa organic farmers to benefit from premium from sale of other food crops from their organic cocoa farms. There should also be training of farmers on the composting of cocoa pod husks as a cheap organic fertilizer to improve nutrient cycling. Conventional farmers should be informed about the adverse effect of herbicide and pesticide on soil microbial communities which will have long term effect on soil fertility, biodiversity, and human health.

In future studies the number of villages per management and farms per village should be raised to at least four. This will improve statistical power. In assessing profitability between the two management types, other ecosystem services such as biodiversity conservation should be considered in addition to C sequestration. Efforts must be made to collect reliable data on revenue obtained from the sale of food crops associated to cocoa agroforestry systems. Inclusion of such data will yield more accurate information on the economic and ecological functions of such systems. To fully understand the nutrient requirements of these systems, complete nutrient balance should be calculated whereby all nutrient inputs and outputs are evaluated. Understanding of herbicide and pesticide effects on soil microbes will require studies comparing microbial functional diversity and C use efficiency in the soils of different cocoa management systems. Successful promotion of cocoa pod husk composting will require on-farm experiments assessing the effect of cocoa pod husk compost on cocoa yield and soil fertility.

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