Assessing land-use dynamics in a Ghanaian cocoa landscape

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I dedicate this research to the memories of my mum

ABSTRACT

Ghana is one of the two West African nations that produce 60% of the World's annual 4 million tonnes cocoa. The Ghanaian cocoa industry is valued at US$ 2 billion and offers direct jobs to 800,000 farming families. Despite the positive contributions to the Ghanaian economy and livelihoods, cocoa production is a well-known driver of deforestation and forest degradation due to the unsustainable expansion and intensification practices associated with the way it is cultivated. The concept of "zero-deforestation cocoa supply chain" is top on the agenda of the chocolate industry. This, this research seeks to contribute to the works on sustainable sourcing of cocoa beans from developing countries using a case study in Ghana. The aim is to understand land-use dynamics and the ecological implications for the cocoa landscape. Using remote sensing/GIS, statistics, and geostatistics techniques, major land-use types and their historical transitions were mapped. The ecological implications of the observed land-use changes for distribution of soil properties, nutrients and fertility were examined. Furthermore, the effects of cocoa intensification practices on carbon stocks, shade tree characteristics, and species diversity in cocoa plantations were assessed, and the influence of socio-economic factors on farmers' land-use preferences investigated. Using image-fusion of vegetation indices and a digital elevation model derived from multi-temporal Landsat images, areas of six main land-use types were mapped with high accuracy, i.e. cocoa agroforest, cocoa monocrop, forest, open forest, bush/shrub/food crops and settlement. A post-classification change detection was performed on land-use maps of the years 1986 and 2015. The findings from the mapping corroborate that cocoa expansion is a major driver of the historical land-use changes in the cocoa landscape. The historical land-use transitions were dominated by cocoa expansion into open forest and areas categorized as lands-in-transition. The results also show that the spatial distribution of soil nitrogen, organic carbon and phosphorus were neither controlled by topography nor by land-use type. However, forest soils generally contained more organic carbon than soils under cocoa plantations and were strongly associated with the distribution of clay, total nitrogen, and pH. The type of agroforest practices adopted by the farmers also influenced soil fertility. The results conclusively establish that irrespective of the shade tree species composition, number of shade trees and farm age, soil fertility benefits do not depend on whether the farming system is monoculture and simple or complex agroforest. This research corroborates widely documented findings that forest tends to have higher carbon storage and richer tree biodiversity than agroforest or monoculture cocoa plantations. Shade trees contributed more to carbon stocks in the cocoa plantations than the cocoa trees, and the dendrometric characteristics of the shade trees influenced the carbon stocks and diversity levels. This explains the strong statistical relationship between tree parameters and carbon stocks. Significant differences in how farmer ethnicity or gender influenced land-use choices were not identified. Statistically, some socio-economic factors and the farmers' land-use preferences influenced the decision to convert forest to cocoa or to eliminate shade trees. Ethnic origin, farming years and age had a significant influence on farmers' land-use decisions. This research provides good insights into the land-use dynamics in cocoa landscapes and can be useful in designing REDD+ and climate-smart interventions.

Keywords: Cocoa, land-use change, agroforestry, deforestation, soil fertility, carbon stocks, diversity

Bewertung der landuse Dynamik in einer ghanaischen Kakao Landschaft

Abstrakt

Ghana ist eine der beiden westafrikanischen Nationen, die 60% des weltweiten jährlichen Kakaos von 4 Millionen Tonnen produzieren. Die ghanaische Kakaoindustrie hat einen Wert von 2 Milliarden US-Dollar und bietet 800.000 Bauernfamilien direkte Arbeitsplätze. Kakao wird in sechs Waldgebieten unter Waldfragmenten angebaut, die eine mehrschichtige Agroforstlandschaft bilden, die sich über 1,6 Millionen Hektar erstreckt. Trotz seines positiven Beitrags zur Wirtschaft und zum Lebensunterhalt ist die Kakaoanbau mit Abholzung und Waldschädigung aufgrund nicht nachhaltiger Expansions- und Intensivierungspraktiken verbunden. Diese landwirtschaftlichen Praktiken bedrohen die zukünftige Versorgung der Kakaobranche mit schwerwiegenden Folgen für die zukünftige Kakaoproduktion, den Lebensunterhalt und die Landschaftsvitalität. In letzter Zeit wurden große Anstrengungen unternommen, um "entwaldungsfreie Kakaoversorgungsketten" zu fördern, um die Abholzung zu bekämpfen und nachhaltige Schokolade zu fördern. Diese Forschungsarbeit soll einen Beitrag zu den Arbeiten zur nachhaltigen Beschaffung von Kakaobohnen aus Entwicklungsländern leisten. Die Forschung zielte darauf ab, die Landnutzungsdynamik und die ökologischen Implikationen für die Kakaolandschaft zu verstehen. Mittels Fernerkundungs- / GIS-, Statistik- und Geostatistiktechniken wurden wichtige Landnutzungsarten und ihre historischen Übergänge abgebildet. Die ökologischen Auswirkungen der beobachteten Landnutzungsänderungen auf die Verteilung von Bodeneigenschaften, Nährstoffen und Fruchtbarkeit wurden untersucht. Darüber hinaus wurden die Auswirkungen von Kakaoverstärkungspraktiken auf Kohlenstoffvorräte, Schattenbaumeigenschaften und Artenvielfalt in Kakaoplantagen untersucht und der Einfluss sozioökonomischer Faktoren auf die Landnutzungspräferenzen der Landwirte untersucht. Unter Verwendung von Bildfusion von Vegetationsindizes und einem digitalen Höhenmodell, abgeleitet von multitemporalen Landsat-Bildern, wurden Bereiche von sechs Hauptlandnutzungstypen mit hoher Genauigkeit kartiert, dh Kakao-Agroforest, Kakaomonocrop, Wald, offener Wald, Busch / Strauch / Nahrungspflanzen und Siedlung. Ein Postklassifizierungsänderungsnachweis wurde auf Landnutzungskarten der Jahre 1986 und 2015 durchgeführt. Die Ergebnisse der Kartierung bestätigen, dass die Kakaoausweitung ein Hauptantrieb für die historischen Landnutzungsänderungen in der Kakaolandschaft ist. Die historischen Landnutzungsübergänge wurden von der Kakaoausweitung in offenen Wald und Gebieten dominiert, die als Land-in-Transition kategorisiert wurden. Die Ergebnisse zeigen auch, dass die räumliche Verteilung von Bodenstickstoff, organischem Kohlenstoff und Phosphor weder von der Topographie noch vom Landnutzungstyp beeinflusst wurde. Jedoch enthielten Waldböden im Allgemeinen mehr organischen Kohlenstoff als Böden unter Kakaoplantagen und waren stark mit der Verteilung von Ton, Gesamtstickstoff und pH assoziiert. Die Art der agroforstlichen Praktiken, die von den Landwirten übernommen wurden, beeinflusste auch die Bodenfruchtbarkeit. Die Ergebnisse legen schlüssig fest, dass ungeachtet der Zusammensetzung der Schattenbaumarten, der Anzahl der Schattenbäume und des Farmalters die Vorteile der Bodenfruchtbarkeit nicht davon abhängen, ob es sich bei dem Bewirtschaftungssystem um Monokultur und einfachen oder komplexen Agroforst handelt. Diese Forschung bestätigt weitreichend dokumentierte Ergebnisse, dass Wald tendenziell eine höhere Kohlenstoffspeicherung und eine reichere Baumbiodiversität aufweist als Agroforst- oder Monokultur-Kakaoplantagen. Schattenbäume trugen mehr zu den Kohlenstoffvorräten in den Kakaoplantagen bei als die

Kakaobäume, und die dendrometrischen Eigenschaften der Schattenbäume beeinflussten die Kohlenstoffvorräte und die Diversitätsniveaus. Dies erklärt die starke statistische Beziehung zwischen Baumparametern und Kohlenstoffvorräten. Große Unterschiede in der Frage, wie die ethnische Herkunft oder das Geschlecht der Landwirte die Landnutzungsentscheidungen beeinflussten, wurden nicht identifiziert. Statistisch gesehen beeinflussten einige sozioökonomische Faktoren und die Landnutzungspräferenzen der Landwirte die Entscheidung, Wald in Kakao umzuwandeln oder Schattenbäume zu beseitigen. Ethnische Herkunft, Landwirtschaftsjahre und Alter hatten einen erheblichen Einfluss auf die Landnutzungsentscheidungen der Landwirte. Diese Forschung liefert gute Einblicke in die Landnutzungsdynamik in Kakaolandschaften und kann bei der Gestaltung von REDD + und klimagerechtem Handeln hilfreich sein.

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ABBREVIATIONS

WCF - World Cocoa Foundation

GDP - Gross Domestic Product

COCOBOD - Ghana Cocoa Board

HFZ - High Forest Zone

HAF - High shade cocoa agroforest

MAF - Medium shade cocoa agroforest

FS - Fullsun cocoa

Mg - Magnesium

EIU - Economic Intelligence Unit

REDD+ - Reducing Emission from Deforestation and Forest Degradation plus

CODAPEC - Cocoa Diseases and Pests Control

Hi-tech - Cocoa high-tech program

ISU - International Sustainability Unit

GSS - Ghana Statistical Services

SOC - Soil Organic Carbon

TN - Total Nitrogen

P - Phosphorous

LSD - Least significant difference

USGS - United States Geological Survey

GPS - Global Positioning System

IDW - Inverse Distance Weight

BD - Bulk Density

DBH - Diameter at Breast Height

CA - Crown Area

CC - Crown Cover

SCS - Social Carbon Stocks

PAST - Paleontological Statistics Software Package for Education and Data Analysis

AGB - Aboveground biomass

1 INTRODUCTION

1.1 Agriculture and forest landscapes

The intrinsic interrelationships, be it spatial and/or functional, between agriculture, forest and people often drive landscape dynamics in tropical regions (Meyer et al. 2015). Agriculture can immensely drive economic growth, rural livelihoods and landscape vitality (Acharya 2006; Damnyag et al. 2013). Most West African countries have agrarian-based economies (Sarpong & Okyere 2013) that thrive on exports of agricultural commodity crops. Agri-business is even more important to rural development because it is the mainstay of subsistence livelihoods of village households. Most rural households depend on landscapes, markets and government (Villamor et al. 2014) to earn a living from a variety of income-generating ventures (Ruivenkamp et al. 2017) such as productive farming, labor services, market trading and reliance on government entitlements (Acharya 2006) that often undermine landscape integrity (Peprah 2015).

The Agriculture-Forest-People interactions usually lead to unbridled sprawling of cultivated lands into natural forest (Grau & Aide 2008). The process of forest clearing either initiates or adds to the relentless transition of forest frontiers in modifying landscapes and the way they function ecologically (Ojoyi et al. 2017). The resultant effects manifest in soil quality decline (Winowiecki et al. 2016; Ojoyi et al. 2017), biodiversity loss (Gude et al. 2007; Arévalo-Gardini et al. 2015), increased carbon emissions (Meyer et al. 2015) and declining productive capacity of cultivated lands. Managing the forest and agriculture trade-offs to a desirable end give a strong boost to the realization of sustainable development goals (FAO 2016). This is the reason why sustainable agriculture policies are high on the agenda of decision-makers (Gyau et al. 2015) particularly, in developing countries. As Quimby et al. (2002) clearly state, pursuing sustainable agricultural policies can create multiple benefits in the long run without comprising on ecological integrity. Nevertheless, adopting forest conservation and sustainable agriculture principles continues to elude resource managers largely due to short-sighted and incoherent policies (Kovacic & Viteri 2017), technological flaws and wrong conceptualisation of the problem (Scoones 2009).

The evidence of loss of tropical rainforest due to agriculture conversions abounds across developing nations (Margono et al. 2014) and especially in West Africa (Breisinger et al. 2008). In the West Africa Guinean region, the growing expansion of agricultural plantations and the attendant influx of migrants put pressure on the rich rainforest (Bitty et al. 2015). Apart from the fact that the region hosts globally significant biodiversity hotspots (Myers et al. 2000), it has a burgeoning extractive industry (timber, mining and hydrocarbons) and a major production base for agricultural commodities (cocoa, rubber and oil palm). Consequently, forests in the region are highly fragmented and classified among the most severely threatened in the world (USGS, 2017). Cocoa is a leading agricultural crop mostly farmed in forest-rich West Africa nations of Côte D'Ivoire, Ghana, Cameroon, and Nigeria (Wessel & Quist-Wessel 2015). The cocoa industry is sustained by the collective efforts of several millions of smallholder farmers who produce more than 70% of the world's cocoa (WCF 2014) cultivated on over 5 million ha (Ruf & Schroth 2004). The majority of cocoa plantations co-exist with forest patches once dominated by tropical rainforest of global biodiversity importance (Ruf 2007; Gockowski & Sonwa 2007).

1.2 The Cocoa industry in Ghana

Ghana's illustrious icon, Tetteh Quarshie, first introduced Amelonado cocoa beans into the country in 1876 from Fernando Po (now Equatorial Guinea) and established a plantation in the Eastern Region (Gyau et al. 2015). Since then, cocoa plantations have been part of the country's agricultural landscape in the high forest zone. The cocoa industry accounts for 8% of the country's gross domestic product (GDP) via exports and tax revenues as well as the employment of nearly 800,000 farming households (Ghana Cocoa Board, 2017). The foreign exchange from the export of cocoa beans makes up approximately 17% of Ghana's merchandise export earnings (Bank of Ghana 2017). Cocoa revenues also help the government to manage currency exchange fluctuations, inflation and primary balance of the national budget (Kolavalli & Vigneri 2003). On average, each year, 4 million tonnes of cocoa beans are produced for the global market (International Cocoa Organization 2017). Côte D'Ivoire (with an annual production of 1.5 million tonnes) and Ghana (800,000 tonnes) together produce about 60% of the world's cocoa (FAO, 2017). Records show that Ghana's cocoa production has seen a steady rise in the last couple of decades (Gockowski & Sonwa 2007; Vigneri 2007) increasing from 300,000 tonnes in 1995 to 900,000 tonnes in 2014 (Wessel & Quist-Wessel 2015; FAO 2017) (Figure 1.1). However, the average productivity of 400 kg/ha remained low compared to yields of 800 kg/ha in Cote d'Ivoire (Bosompem et al. 2011; Wessel & Quist-Wessel 2015).

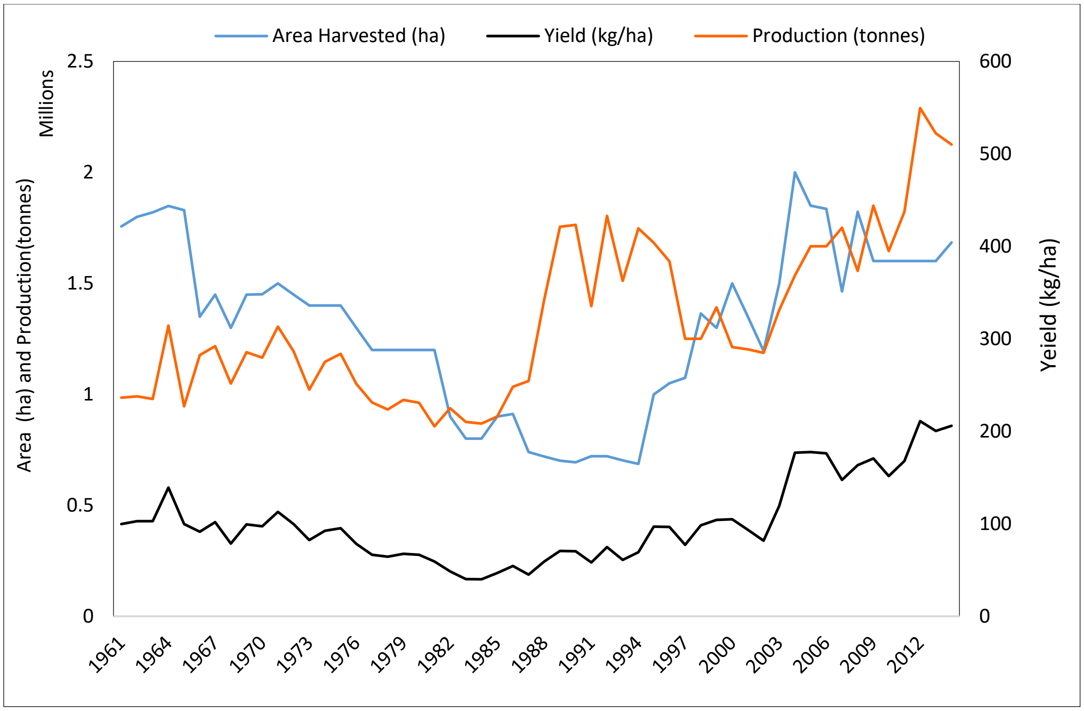


Figure 1.1. Trends of cocoa production (tonnes), area harvested (ha) and yields (kg/ha) in Ghana based on FAOSTAT, 2017

The increases in cocoa production and planted areas have been associated with government fiscal and technical measures on favorable free-on-board (FOB) prices (Vigneri 2007b), free pest and disease control (Gockowski et al. 2013), distribution of hybrid seeds, fertilizers (Bosompem et al. 2011), insecticides and fungicides, improved marketing facilities (Peprah 2015) and the repair of cocoa roads (Wessel & Quist-Wessel 2015). In spite of the recorded production increases, the yield gap per hectare is high (Asare, 2016) due to agronomic and socio-economic barriers. The agronomic and technical barriers include soil fertility exhaustion (Gockowski & Sonwa 2007), pests and diseases (UNDP 2002), sub-standard planting materials (Anglaaere, et al. 2011), tree shade management (Ruf 2011), changing climate pattern (Peprah 2015) and over-age cocoa farms (Asamoah & Owusu-Ansah 2017). The socio-economic factors relate to land tenure (Knudsen 2007), outdated farmer knowledge (Graefe et al. 2017), high labor cost (Sarpong & Okyere 2013), poor incentives for farmer innovation

(Bosompem et al. 2011), migration effects (Knudsen & Agergaard 2016) and slow adoption of farming technologies (Obeng & Weber 2014). As a major player in the industry, the Ghanaian government continues to introduce measures to boost cocoa productivity and to reduce the yield gap. Government programs mainly centre on addressing landscape-wide productivity issues on disease and pest control (i.e. cocoa disease and pest control program introduced by the government in 2001), inputs subsidies, access to credits, rehabilitation of over-age cocoa farms (cocoa high technology programme) (Aneani & Ofori-Frimpong 2013; Bosompem et al. 2011) and research and extension (Dormon et al. 2004). In the same vein, farmers at the farm level deal with the lower yields by weighing the options of either intensification (i.e., adopting fullsun cocoa farming) or expansion (i.e., opening up the forest to plant cocoa plantation) (Ruf 2011).

1.3 Expanding cocoa frontiers

In Ghana, cocoa is mostly cultivated in the forest regions. The six regions (Ashanti, Western, Eastern, Central, Volta and Brong Ahafo) are all found in the high-forest ecological zone (HFZ), of which the Western Region is the highest producer (Ghana Cocoa Board 2017) (Figure 1.2). These regions form a cocoa belt that spans nationwide over about 1,683,765 ha (FAO 2017) in middle part of the country close to a number of protected forests and active mining areas. The cocoa production frontier has moved since its introduction in the 1880's (Figure 1.3). According to Knudsen & Agergaard (2016) and Ruf (2011), the oldest cocoa frontier in the Eastern Region was established in the 1880's before moving to Ashanti Region in the 1910's (Figure 1.3). In the 1940's, the center of cocoa production shifted to the Brong Ahafo and Central Region until the 1960's when production shifted to the Western Region.

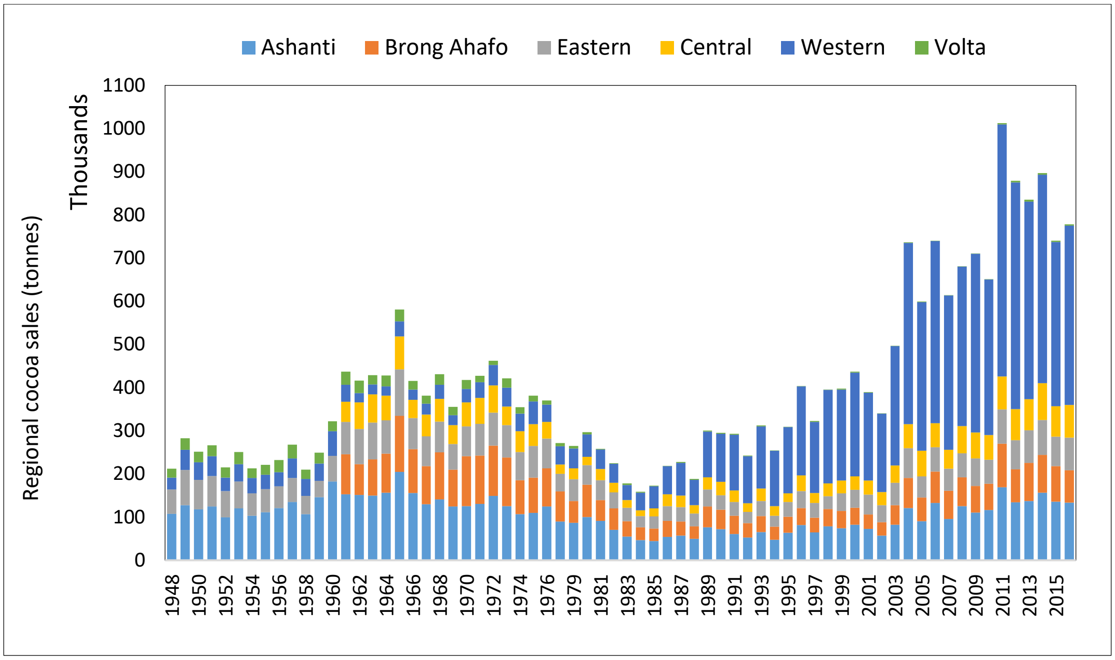


Figure 1.2. Cocoa sales in the six cocoa growing regions with the Western Region (deep blue) as the latest major cocoa producing region followed by Ashanti Region (light blue)

The movement of the cocoa frontier from one region to another in search for fertile lands, high yields and incomes has led to the continued opening-up of intact forest for cocoa cultivation (Knudsen & Agergaard 2016). The transitioning in the cocoa frontier across the regions (Figure 1.3) was usually associated with deforestation and migrant influx. At present, the Western Region is considered to be the only remaining cocoa frontier in the Ghanaian landscape because it is known to have the last intact forest in the country (Knudsen & Agergaard 2016) and favorable climate for cocoa growing. Since the 1880's, the establishment of cocoa plantations has led to the clearing of an estimated 1.6 million ha intact forest (FAO 2017), which makes cocoa cultivation one of the top drivers of deforestation in Ghana (Forestry Commission 2015).

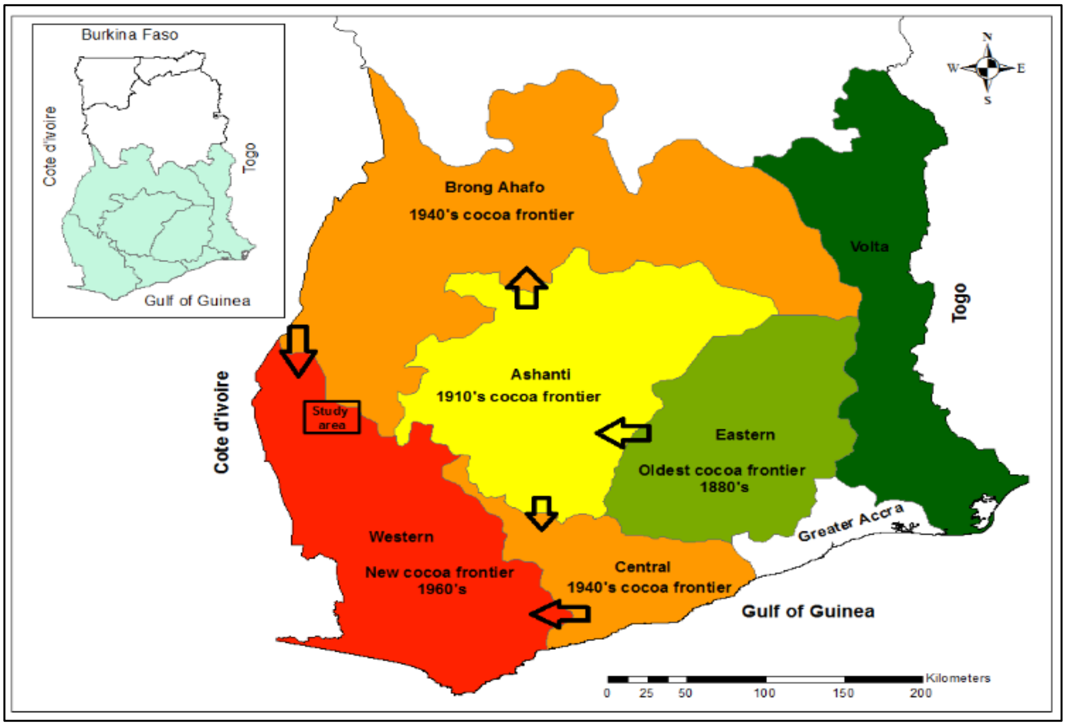


Figure 1.3. Modified map showing moving cocoa frontier in Ghana from the 1880's to 1960's based on Knudsen & Agrergaard, 2016. Arrows are direction of movement.

1.4 Cocoa production systems

The cocoa production system in Ghana is traditionally simple, labor-intensive, and small-scale, and a certain amount of shade is provided by indigenous timber trees. Cocoa is cultivated in the forest regions in forest fragments (Mohammed et al. 2016), which form a multi-story agroforestry plantation (Asare & Anders 2016). The remaining natural forest is cleared during farm establishment in a new cocoa frontier (Knudsen & Agrergaard 2016) or the agroforestry converted to monoculture plantations by removing tree remnants. This gives rise to an emergent cocoa landscape characterized by a sprawling mosaic of small (less than 3 ha), structurally diverse complex-to-simple agroforest or monoculture cocoa plantations intermixed with natural forest (Ruf 2011; Norris et al. 2010; Asare & Ræbild 2016) (Plate 1).

1.4.1 Agroforestry cocoa plantations

Cocoa is under-planted in a selectively thinned forest, forming a complex agroforestry system where naturally established and planted trees share the same space (UNDP 2002; Ruf 2011; Gockowski & Sonwa 2007; Acheampong et al. 2014; Vaast & Somarriba 2014). The cocoa trees require a unique microclimate provided by the tropical forest canopy. This practice is known as shaded cocoa agroforestry (Plate 1) similar to other agroforestry systems elsewhere (Ordonez et al. 2014). Often, maintaining higher proportions of non-cocoa trees in a diverse structure is viewed as a sustainable land-use practice that complements the conservation of biodiversity (Duguma 1998; Parrish et al. 1998; Power & Flecker 1998; Rice & Greenberg 2000; Leakey 2001; Schroth et al., 2004). This form two levels of canopy storage in some parts of the cocoa farm, which can then be interpreted as a "simple agroforestry system" or "light agroforestry" (Ruf 2011). However, biodiversity is poor and there is no real canopy above the cocoa (Ruf 2011; Acheampong et al., 2014; Dawoe et al. 2015).

Plate 1: Simple agroforest cocoa plantation and adjoining natural forest showing cocoa interspersed with shade trees. (A) natural forest. (B) Cocoa monocrop and (C) agroforest cocoa

The representation of complex, i.e. high shade agroforest and simple agroforestry, (medium shade agroforest), as well as fullsun cocoa plantations in the cocoa landscape of Ghana is widely acknowledged, but the relative proportion of the areas under these systems is not well documented, though observations by Acheampong et al. (2014) indicate that fullsun and medium agroforest systems dominate the Ghanaian cocoa landscape. Furthermore, there is evidence in Ghana that cocoa farmers are increasingly making a deliberate choice in favor of fullsun or medium shade agroforest (Ruf 2011).

1.4.1.1 Ecological functions of shade trees

Cocoa agroforestry as practiced by most cocoa farmers goes beyond shade provision and the incorporation of shade trees in cocoa systems. It includes many other species in different densities that provide varied services and benefits to the cocoa farm. Given also that various stages of cocoa maturity (young, matured and old), as observed by Tondoh (2015) and Isaac (2007), could influence the microclimate of the cocoa system, including the amount of litter-fall and decomposition (Hartemink & Donald 2005; Isaac & Quashie-Sam 2010). In addition to fixing carbon, non-cocoa trees are known to offer direct ecological and financial benefits to the farmers (Kessler et al. 2012) and biodiversity conservation (Norris et al. 2010). Multi-strata cocoa agroforestry systems provide shade effects that increase the humidity of the microclimate (Beer et al. 1998). Although Boyer (1973) found this to have little effect on decomposition rates, and Ahenkorah et al. (1974) also did not find shading to affect decomposition rates. A relatively recent observation by Ofori-Frimpong et al. (2007) found decomposition rates and nutrient release to be faster in cocoa agroforestry with shade trees than in fullsun cocoa farms.

Cocoa trees lose fewer leaves under multi-strata agroforestry systems (Evans & Murray 1953; Boyer 1973; Ofori-Frimpong et al. 2007). Thus, agroforestry systems, be they complex, simple or fullsun could influence litter incorporation into soils and hence mineralization and nutrient release. The amount of litter produced also depends on the age of the plantation, as older systems have higher litter fall (Hartemink & Donald, 2005; Dawoe et al. 2010). Considerable amounts of carbon and nutrients are returned to the soil through litter production of both cocoa and non-cocoa trees (Hartemink & Donald 2005; Dawoe et al. 2010; Fontes et al. 2014). The density of these trees and the type of trees (species composition of non-cocoa trees) are important, as more trees will produce more litter and different tree species produce different amounts of litter (Hartemink & Donald 2005; Fontes et al. 2014). According to Fontes et al. (2014), shade tree leaves in agroforestry systems (Cabruca & Erythrina sps.) function predominantly as a source of nutrients, while cocoa tree leaves function as a sink except for magnesium (Mg). Hence, shade trees and other non-cocoa trees may increase both the quantity and the quality of the litter (Dawoe et al. 2010), thus increasing nutrient availability.

Agroforestry may also reduce soil degradation and increase nutrient availability through litter cycling and nitrogen fixation (Evans & Murray 1953; Cunningham & Arnold 1962; Ahenkorah et al 1974; Beer et al. 1998; Isaac, Timmer & Quashie- Sam 2007; Ofori-Frimpong et al. 2007). Thus, non-cocoa trees in cocoa farms serve as a major source of organic material inputs to the soil and aid in improving soil fertility. Though Blaser et al. (2017) observed that shade trees have limited benefits for soil fertility in cocoa agroforestry, their study focused on individual upper-story trees within the cocoa farms as solitary trees at the plot level without considering the influence of other lower canopy tree species that are commonly grown in tandem with cocoa and dominate most cocoa systems (Acheampong et al. 2014; Dawoe et al. 2015) and other larger numbers of non-cocoa trees, which more closely represent the scale at which farmers implement and manage their agroforestry (Blaser et al. 2017).

1.4.2 Monoculture cocoa plantations

Most cocoa systems are established as agroforestry systems, but in recent times, so-called fullsun systems or monocrop cocoa plantations have been introduced and advocated (Cunningham & Arnold 1962; Boyer 1973; Gockowski & Sonwa 2011). A number of factors have been noted to influence farmers' decisions to incorporate trees in cocoa systems as agroforestry or fullsun systems. These include tree tenure and legislation (Amano 2005), land tenure (Acheampong et al. 2014), and uncertainty of farmers about the ecological services of non-cocoa trees to cocoa systems (Ruf 2011). It is also known that the choice of incorporating trees in cocoa systems or opting for fullsun systems is also driven by migration status (Ruf 2011). Migrants often opt for fullsun, while native farmers mostly incorporate shade in their farms, as observed in the western cocoa landscape of Ghana (Ruf 2011). In the fullsun system, the cocoa trees alone often define only one level of canopy storage. Almost all the large natural forest trees have been felled or burned. The practice of removing shade trees to make room for high-yielding fullsun cocoa systems (Plate 2) has gained popularity because of the adoption of hybrid cocoa varieties. This is evident in Ghana and Cote D'Ivoire where 28.1% and 27.9% of smallholder cocoa farms are without shade trees leading to loss of carbon stocks and tree diversity (Gockowski & Sonwa 2011; Gbala et al. 2017).

Plate 2: Mosaic of monocrop cocoa plantation (a – red arrowed) and shade tree removal in cocoa farm (b – red arrowed).

Even with the perceived quick return on yield per hectare, the practice is susceptible to pests, disease attack and soil deterioration leading to low yields in the long run (Tondoh et al. 2015) finally burdening the already poor farmers who are not able to afford the cost of additional labor, fertilizer, weeding, and disease and pest control (UNDP 2002; Ruf 2011). The farmer's decision to replace forest with cocoa or shift from agroforestry to no shade cocoa is not made in isolation. It is rather a reflection of careful and rationale consideration of how farmers seek to make optimal use of available resources for the realization of their production objective of attaining high yields and incomes in the shortest possible time (Schroth & Sinclair 2013).

1.5 Factors affecting cocoa production in Ghana

Despite the often-stated benefits cocoa provides to the country and communities that depend on the industry, there are negative ecological effects from the unsustainable cocoa practices (UNDP 2002). These negative ecological impacts include deforestation (Ruf & Schroth 2004), biodiversity loss (Kessler et al. 2012) and soil nutrient depletion (UNDP 2002). On the other hand, the long-term sustainability of cocoa production has been a source of concern to policymakers due to the threats from illegal mining (Snapir et al. 2017), climate change (Schroth et al. 2016), timber logging (Solidaridad West Africa 2013), ageing cocoa farms (Anglaaere et al. 2011) and intensification (shade removal) (Gockowski & Sonwa 2011).

1.5.1 Impacts of illegal mining on cocoa production

Cocoa and gold are the two top mechanised export commodities that annually fetch the country US$ 1,923.3 million and US$ 4919.5 million, respectively, making up 61% of the total export earnings in 2016 (Bank of Ghana 2017). Cocoa cultivation and mining are both land-based activities which are predominant in the high forest ecological zone (Boateng et al. 2014) and compete for land and labor based on their financial returns. Typically, cocoa farms get converted to mining sites, and even more, farmers may abandon cocoa farming to engage in galamsey (illegal mining) because of the perceived high profits (Snapir et al. 2017). In addition, through the galamsey operations, parts of or whole cocoa farms are destroyed to the point where illegal miners take over the farm (Boateng et al. 2014). During the cocoa off-season, some cocoa farmers take up jobs in gold mines to earn additional income to invest in their cocoa farms (Okoh & Hilson 2011).

1.5.2 Cocoa as a driver of deforestation

The rapid sprawling of the cocoa frontier at the expense of forest makes it the key driver of deforestation in Ghana (Forestry Commission 2015) and the West Africa sub-region (Asare & Anders 2016). The rationale behind cocoa-driven deforestation is clearly connected to the “boom-bust” cocoa cultivation cycle (Ruf & Zadi 1998). Other studies have associated the cycle of establishing and decommissioning cocoa farms as a key driver of deforestation (Koranteng et al. 2016; FC 2015; Asare et al. 2014; Obiri et al. 2007; Gockowski et al. 2011; Tondoh et al. 2015) due to its expansive nature and the accompanying influx of migrants (Ruf and Zadi 1998). A study by Ruf (2011) in three cocoa growing districts in Ghana pointed out that the type of farming method of migrant farmers induces deforestation in contrast to that of the native farmers who largely prefer the traditional agroforestry.

The Governments in cocoa-producing nations continue to formulate new domestic policies to boost production and global supply of cocoa beans, which is projected to rise to 3.8% in the coming years (EIU 2017). Many of such new policy initiatives target at hiking farm-gate prices, subsidizing inputs, aiding access to credit, promoting adoption of hybrid seedlings, and introducing cocoa rehabilitation programs (Wessel 2015). These government-initiated fiscal and management incentives aim to create enabling conditions to boost cocoa production. However, they also have the potential to fuel deforestation. The notion of cocoa-driven deforestation has gained wide acceptance among policymakers and the cocoa industry and has led to cocoa landscape governance programs (FC 2016). This is because cocoa deforestation is notably prominent in the sustainable cocoa policy discourse due to the implications for greenhouse gas emissions and biodiversity loss (Alo et al. 2005).

1.5.3 Unsustainable intensification practices

Apart from clearing forest to make room for cocoa plantations, the kind of intensification practices cocoa farmers adopt can also contribute to changing the landscape. The recent popularization of monoculture cocoa plantations has been identified as a major cause of forest degradation (Dawoe et al. 2016). In the early years of cocoa establishment in forest frontiers, productivity is usually high because soils are then still fertile, thus requiring less labor and lower input costs (Wessel 2015). As the cocoa farm ages, labor and input costs start to outweigh the declining yields and incomes, so farmers find the practice unprofitable and begin to evaluate their options. They usually abandon their existing farms (allow restoration through fallowing) to establish new ones, preferably in forested areas thus starting another cycle of forest clearing. Where lands are in short supply and expansion is no longer a viable option, the strategy is to rehabilitate or replant the cocoa farms or explore shade variation to boost yields. Nevertheless, the practice of removing shaded trees for high-yielding monoculture cocoa systems has gained popularity in recent times, (Ruf 2011).

1.5.4 Cocoa and climate change

Cocoa does well under humid tropical growing conditions, and the yield levels are affected most by rainfall. The crop performs well in areas of annual rainfall between 1,500 mm and 2,000 mm but struggles to survive where rainfall is less than 100 mm per month for a period longer than three months (International Cocoa Organization 2013). Cocoa requires relatively high temperatures, with a maximum annual average of 30-32°C and a minimum average of 18-21°C (Adjei-Nsiah & Kermah 2012). Like other agricultural crops, cocoa growth is sensitive to temperature variations and drought (Läderach et al. 2013; Ofori-Boateng & Insah 2014). With the projected future increase in temperature and evapotranspiration and a decrease in rainfall, the overall climate suitability for cocoa is likely to decrease (Anim-Kwapong & Frimpong 2004).

Although the shifting climate is likely to have negative consequences for cocoa outputs (Läderach et al. 2013), the onset will be slow and gradual. Once it occurs, climate change impacts could induce favorable conditions for cocoa pests and diseases (Anim-Kwapong & Frimpong 2004). There is a wide range of adaptation options which are plausible but, as Anim-Kwapong & Frimpong (2004) suggested, such interventions must be tailored to farmers' capabilities and the extent to which national policies can adequately accommodate them in the long term. Maintaining optimal shade in cocoa farms as an adaptation measure can contribute to regulating temperature and humidity levels (Anim-Kwapong & Frimpong 2004). The observation by Abdulai et al. (2017) that cocoa agroforestry is less resilient under climate extremes than fullsun cocoa must inform any future climate-smart cocoa interventions in Ghana.

1.5.5 Cocoa pests and diseases

The outbreak of the swollen shoot virus and black pod in the 1940's saw a decline in production levels (Amanor 2005). Since then, pest and disease control has formed part of government measures to boost cocoa production. The focus of the pest and disease control policies is three-fold, i.e. research support, mass cocoa spraying, and accessible input markets. As a result, interventions such as cocoa disease and pest control programs (CODAPEC or Mass Spraying of cocoa farms), and the cocoa high technology program (Hi-tech), which provided free inputs and labor for the control of capsids and black pod, as well as insecticides, fungicides and fertilizers to cocoa farmers on credit were introduced (Aneani et al. 2012) in Ghana. Although the introduction of the pest and disease control program had some challenges, overall it contributed to increased productivity by 30% (Vigneri 2011).

1.6 Framing the research problem

The pressures from rapid cocoa expansion and the emergence of fullsun cocoa systems are the key drivers of deforestation and forest degradation (Asare et al. 2014), and any of them could influence land-use change patterns in the cocoa landscape. The intensity and land-use change patterns are localised at the farm level although they individually contribute to the aggregate effects on the wider cocoa landscape. Natural forest or even agroforestry cocoa can provide multiple ecological, agronomic and economic benefits to farmers (Noordwijk et al. 2014).

Regardless of the benefits, cocoa expansion and/or intensification continues to occur leading to biodiversity loss and conversion of forest (Tscharntke et al. 2011; Mohammed et al. 2016), which directly influence landscape dynamics. Although the bottom-line of expanding cocoa plantations or even fullsun system is to ultimately increase yields, the consequences of rising deforestation and forest degradation have negative ecological and socio-economic implications (Tondoh et al. 2015) in the long-term. Empirical studies have revealed that cocoa-driven deforestation contributes to soil quality decline (Winowiecki et al. 2016; Ojoyi et al. 2017), biodiversity loss (Gude et al. 2007; Arévalo-Gardini et al. 2015), increase in greenhouse gas emissions (Meyer et al. 2015; Sirikit & Garden 2013), and threats to sustenance of livelihoods.

1.6.1 Research justification

In 2017, the cocoa and chocolate companies and International Sustainability Unit (ISU) made a commitment to a deforestation-free supply chain and pledged to work with cocoa-origin governments to develop and implement a joint framework for halting deforestation and degradation (Prince of Wales, 2017). In the cocoa industry, the zero-deforestation concept is at its nascent stage, and the way it is designed and practiced will depend on the availability of reliable deforestation data on the landscape. Notwithstanding the growing concerns and the efforts being made to tackle cocoa-driven deforestation, empirical evidence to inform the design of interventions is hard to acquire. Most studies (Asare et al. 2014; Koranteng et al. 2016; Obiri et al. 2007; Norris et al. 2010) make general references to cocoa expansion as an agent of deforestation without an empirical basis to back the extent and rate of deforestation. Inasmuch as data on the role of various land-use systems play in the deforestation discourse abounds, most of these datasets are too coarse to establish direct causal relationships. Apart from understanding the spatial influence of cocoa expansion and/or intensification on the landscape, it is also important to examine its ecological implications in relation to soil quality, carbons stocks and tree diversity as well as probing into land-use choices of the farmers.

In addition, it is important to explore how farm-level interactions based on litter incorporation in soils associated with different levels of tree incorporation and species composition in an agroforestry system as well as the maturity stage of cocoa farms could influence soil nutrient parameters. Inasmuch as some works exist on carbon stocks and tree diversity indices in the cocoa landscapes of

Ghana (Mohammed et al., 2016; Dawoe et al., 2016), there is very little information on the how these parameters vary in cocoa plantations of different agroforestry practices and at different maturity stages. Therefore, understanding carbon stocks dynamics in different cocoa cultivation systems can provide useful insights when engaging farmers regarding the need to improve the practices of cocoa agroforestry and the design of the cocoa REDD+ program in Ghana. It is important to understand how socio-economic factors such as ethnicity (Knudsen & Agergaard 2016; Ruf 2011; Gockowski & Sonwa 2007), gender (Villamor et al. 2017) and land tenure (Damnyag et al. 2012) influence farmers' land-use choices. It is also worthwhile to investigate how the socio-economic status of farmers relates to their preference for specific cocoa farming systems.

1.7 Research Objectives

1.7.1 Overall objective

The overall objective of the research is to examine the extent of land-use dynamics due to cocoa extensification and/or intensification and the implications for ecological resources of the Ghanaian cocoa landscape. To achieve the overall objective, five specific objectives were defined to inform the research questions which have been categorized into:

- *"What and where questions"* - relate to gathering evidence on land-use change, i.e. detecting the dominant land-use types, typologies of cocoa plantations and their transitions over a given period.
- *"How questions"* - focus on assessing ecological consequences of cocoa-driven land-use change highlighting soil quality dynamics, carbon stocks and tree diversity variations.
- "*Who questions*" - address the role of farmers in driving land-use change and the factors that influence land-use preferences.

1.7.2 Specific objectives

The research has following specific objectives:

- Map the main land-use types, transitions and intensity trends among them.
- Examine the implication of land-use changes on the distribution of soil property levels in remnant forests and cocoa plantations and the relationships with soil texture and topography.

- Determine the extent of soil nutrient and fertility variations in different cocoa agroforestry systems.
- Assess carbon stocks, shade-tree characteristics and diversity in the cocoa plantations.
- Explore the relationships between socio-economic status of farmers, their land-use choices and the implications thereof to land-use transitions.

1.8 Thesis Outline

The thesis is organized into nine chapters. Chapter 1 sets the scene for the research by providing the context background and rationale for the study based on a literature review. The first part highlights the ecological interactions typical of the agriculture and forest landscape based on which cocoa production in Ghana thrives. The literature review investigates cocoa production, the expanding cocoa frontier, cocoa production systems and the factors affecting cocoa production in Ghana. Chapter 2 presents the overall objective and the specific objectives together with the research approach, summary of methods and description of the study area. Chapters 3-7 are the empirical chapters for each specific objective. Chapter 8 presents broad conclusions derived from these chapters, followed by Chapter 9 on recommendations for possible areas for future research, research limitations and lessons for policy uptake.

2 MATERIALS AND METHODS

2.1 Research Approach

The research workflow involved iterative steps from project proposal stage, fieldwork, thesis writing to defense (Figure 2.1). It started with an extensive literature review of scientific knowledge in five key main areas of the study. Topics covered during the literature study were spatial techniques for land-use mapping, cocoa industry in Ghana, cocoa production systems, national REDD+ policies, soil fertility, carbon stocks, biodiversity, agroforestry systems and sustainable landscapes. The literature review revealed the key research gaps on which the research problem and objectives are based. After the pre-site selection assessment, a study area was selected where it was possible to explore different dimensions of the research problem. The initial findings from the literature review were inputs into the design of research proposal, work plan and budget for approval. Oral presentation of the research proposal, work plan, and the budget was made to the academic team of the Department of Ecology and Natural Resources Management - Center for Development Research (ZEF), University of Bonn, before embarking on the fieldwork in 2015.

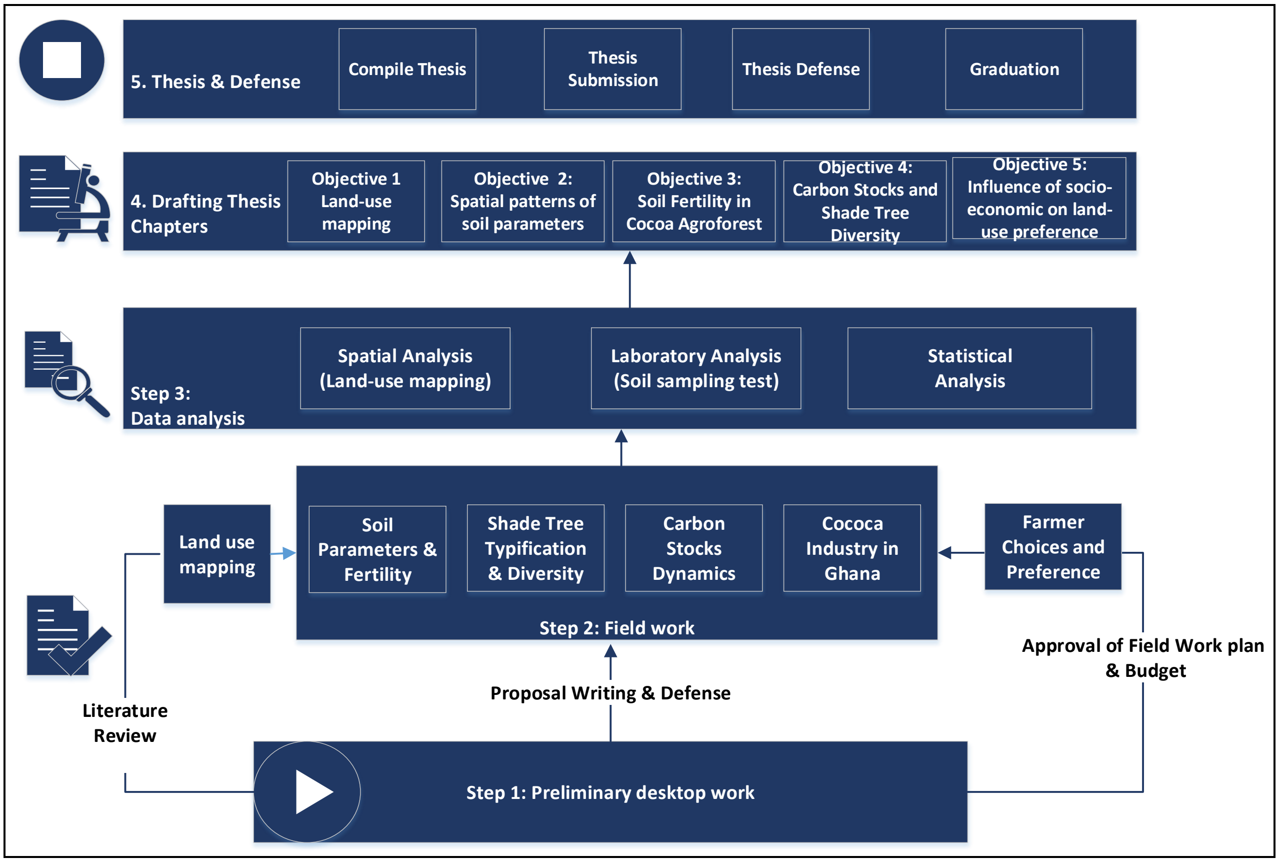


Figure 2.1. Workflow of the research from proposal writing and thesis defense

Logistics for the fieldwork included satellite images, base maps, GPS, diameter tapes, soil augur, etc. The field data collection took place in the Western Region of Ghana between April 2015 and April 2016. Following the fieldwork, spatial, laboratory and statistical analyses were performed with the view to realize the specific objectives. The results are compiled in the thesis.

2.2 Study area

This research was carried out in a cocoa growing landscape in the Western Region of Ghana. The Western Region was selected because it is the largest cocoa producing region and the only cocoa expansion frontier left (Knudsen & Agergaard 2016; Ruf 2011) in the country. The cocoa landscape in the Western Region has the characteristics (i.e. forest loss, shade variation) of a typical cocoa frontier (UNDP 2012) and was considered a suitable location for the study. Within the region, we picked the three highest cocoa producing districts, BIA East, Juabeso and Sefwi Wiawso, for the study.

The study area is located on the border of Brong Ahafo and Western Region of Ghana about 422 km from the capital city Accra. It is located between lat. 6.631822°/long. 2.634741° and 6.631420°/2.953857° covering an area of 80,507 ha (Figure 2.2). The area lies in a tropical climate characterized by warm temperatures with a mean annual temperature between 25.5°C and 26.5°C (GSS 2014). The rainfall pattern is bimodal with June and October as the major and minor season, respectively. The rainfall levels are within the range of 1250-1750 mm. The soils are mainly Oxysols and Ochrosols (Anim-Kwapong & Frimpong 2008) consistent with Acrisols in the FAO classification, with underlying Birimian parent rock. Soils have pH values ranging from 4.2 to 6.8 and a predominantly sand-clay-loam texture.

The vegetation corresponds to both moist evergreen and moist semi-deciduous zones (Forestry Commission 2015). There are three forest reserves in the study area, i.e. Krokorsua Hill Forest, Bonsam Bepo and Muro Forest covering about 32,483 ha, which are under the protection of national laws. These reserves have legally admitted villages and farms within the buffer zones that were allowed during their establishment (Marfo 2009). The rest of the area is covered by degraded forest mainly on individual or community-owned lands. The degraded forest occurs in relatively low-lying areas adjoining the three forest reserves, or is under agricultural use. Within the forest reserves, there are relics of encroachments from farming, hunting, mining and logging activities (McCullough et. al. 2005) largely attributed to weak enforcement of forest laws (Solidaridad, 2013). Both cocoa and oil palm are the two major tree crops in the study area. Cocoa plantations are the second dominant land-use with ages between 2 and 30 years, and are usually located on lower slopes. Altitudes are between 133 m and 637 m and interspersed with the Krokorsua ridge extending in a NW-SW direction. On both sides of the ridge are valleys with gentle slopes carved into a dendritic drainage pattern. The main rivers are Bia, Tano and Sui (Ghana Statistical Service 2014) flowing in NE-SW direction along the intervening low-lying areas on the western and eastern boarders

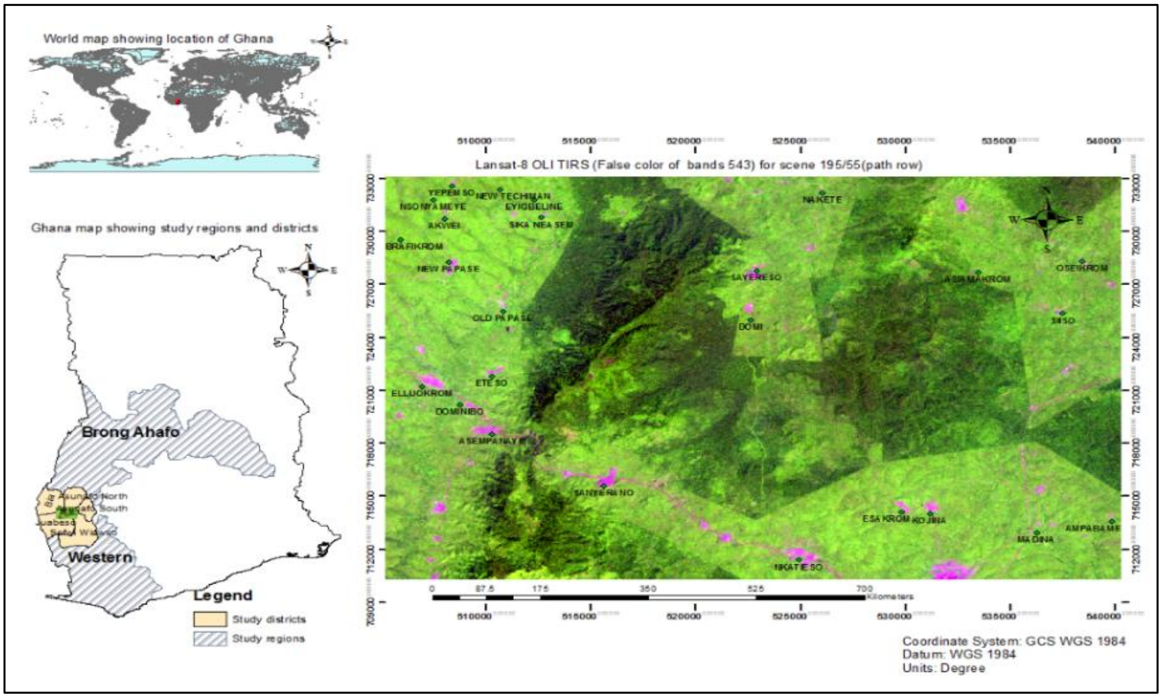


Figure 2.2. Map of Ghana showing study regions, districts and administrative regions. Landsat image in false color showing Krokorsua Hills, Muro and Bosam Bepo forest reserves, and built-up areas interspersed with cocoa plantations.

In 2010, the population of the districts was 286,574 (GSS 2014). The population is young, mostly rural (84.9%) and slightly male dominated (51.2%). Migrants make up 29.5% of the population, and the majority of them are involved in farming cocoa (GSS, 2014). There are 24 communities in the study area, 38 "admitted farms" with footpaths connecting the farms and mud-huts, a 12.3-km stream and a 3.2-km road network (Solidaridad 2013).

2.3 Summary of methods

A brief explanation of the methods and the software used in this study is presented in Table 2.1. Comprehensive description of each method and their justifications are provided under each of the results chapters (Chapters 4, 5, 6 and 7).

Table 2.1. Summary of methods and software used in the study and the corresponding specific objectives

Research Objective	**Methods**	**Techniques**	**Software**
Objective 1: Spatial analysis of analysis of land-used changes	• Image processing • Image classification • Post-classification change detection • Ground truthing • Accuracy assessment • Intensity analysis	• Image-to-image registration • Dark area subtraction • Extraction of digital elevation model • Vegetation index math • Image fusion • Pivot table of land-use and change matrix • Tabulation of error matrix • Change budget (gain, loss and persisted) matrix	• ENVI 5.0 • Google Earth • Pontius workbook version 41
Objective 2: Spatial patterns of SOC, N, P in different land-use types	• Field plot sampling design • Soil sampling • Tree-based data collection • Laboratory testing of soil parameters • Soil and carbon stocks estimation • Tree diversity index • Traditional statistics • Geostatistics • GIS Mapping	• Tree and Z-shaped soil sampling design • Drying, grinding and sieving of soil samples • Pipetted soil test method • Dry combustion, Walkley-Black, Alkaline digestion methods. • Descriptive statistics • Normality test • One-way analysis of variance • Pearson correlation • Multiple linear regression • Semi-variogram and spatial interpolation • GIS-based surface mapping • Tree species identification • Diameter at breast height measurement • Tree height measurement with laser hypsometer • Tree crown area measurement • Shannon-Weiner diversity indices for tree species, richness, eveness and abundance • Analysis of variance (ANOVA) • Linear regression	• ArcGIS 10.4.1 • Stata 14 • GenSet discovery edition
Objective 3: Influences of agroforestry on soil nutrients and fertility			
Objective 4: Dendrometric parameters, tree diversity and carbon stocks			PAST Version 3
Objective 5: Socio-economic factors and cocoa	• Household surveys • Focus group discussions • Transect visits • Statistics	• Farm and farmer identification • Farm visits • Questionnaire administration • Descriptive statistics • Logistic regression analysis	SPSS version 20

farmer's land-use preference	- Modeling of farmer preferences		

3 SPATIAL ANALYSIS OF LAND-USE CHANGES IN A DYNAMIC COCOA LANDSCAPE

3.1 Introduction

Cocoa is a predominant land-use system in the West African landscapes (Gockowski & Sonwa 2011) particularly in Ghana, Nigeria, Cameroon and Cote d'Ivoire (Wessel 2015). Cocoa farming, logging and settlement expansion are the three major drivers of deforestation in Ghana (Forestry Commission, 2016). In the last three decades, there has been a rise in cocoa production as well as harvested areas in the country (Wessel 2015; FAOSTAT 2017) through intensification and/or cocoa expansion. During the period 2000-2014, though cocoa production doubled to 800,000 tonnes annually, cultivated areas expanded by 12% (1,683,765 ha) (FAOSTAT 2016).

Cocoa is typically cultivated in forest areas to follow the "boom-bust" pattern (Ruf et al. 1998), which is closely linked to deforestation (Asare 2014). The lifespan of the "boom-bust" cycle considerably determines the pace at which cocoa-driven deforestation modifies a landscape. Several studies have associated the cycle of establishing and decommissioning cocoa farms as a key driver of deforestation (Koranteng et al. 2016; Forestry Commission 2015; Asare et al. 2014; Obiri et al. 2007; Gockowski et al. 2011; Tondoh et al. 2015) due to its expansive nature and the accompanying influx of migrants (Ruf & Zadi 1998). Farmers have found it necessary to eliminate forest tree species to effect high performance of these new varieties (Tondoh et al. 2015; Anglaare et al. 2011), and as a result, large areas of forested lands are being lost. Most cocoa systems are shifting from the traditional practice where non-cocoa trees are mainly incorporated as timber trees on the farms to fullsun systems and other cocoa systems with minimal numbers of non-cocoa trees (Acheampong et al. 2014).

As the cocoa farm ages, labor and input costs start to outweigh the declining yields and incomes, so farmers find the practice unprofitable and begin to evaluate their options (Figure 3.1). They usually abandon their farms allowing restoration through fallowing to establish new ones, preferably in forested areas, to start another cycle of forest clearing. Where lands are in short supply and expansion is no longer a viable option, the strategy is to rehabilitate or replant the cocoa farms or explore shade variations to boost yields. Usually the aim of such fiscal and technical incentive programs that the government initiates is to boost production (Omane-Adjepong and Oduro 2012). However, these may end up fueling deforestation or forest degradation. The notion of cocoa-driven deforestation has gained wide acceptance among policymakers and the cocoa industry and has informed some programs on cocoa landscape governance (Forestry Commission 2016). This is because such deforestation is notably prominent in the sustainable cocoa policy discourse due to the implications for greenhouse gas emissions and biodiversity loss (Alo et al. 2005).

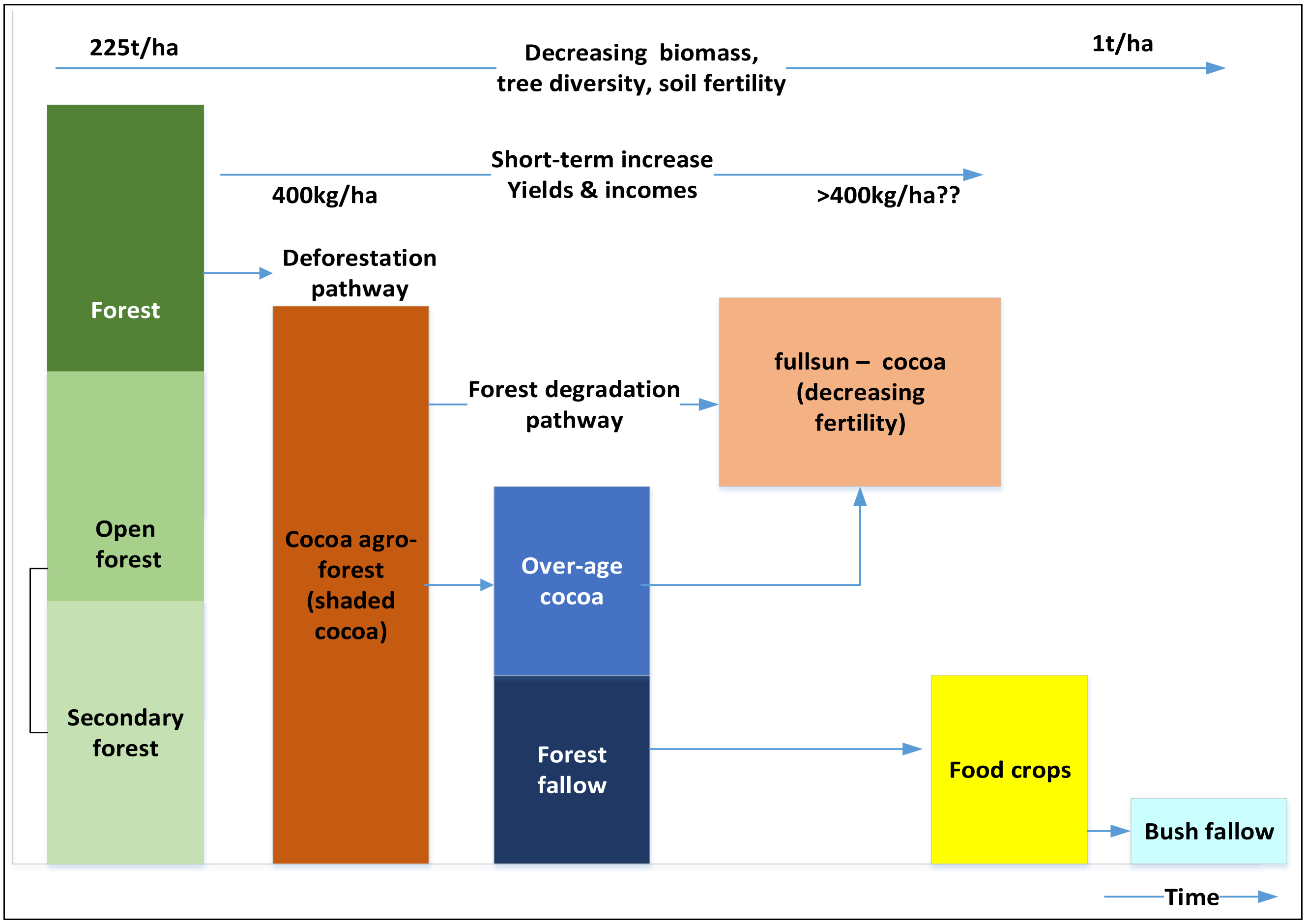


Figure 3.1. Illustration of land-use change pathways and implication for carbon stock distribution in the cocoa landscape based on Forestry Commission, 2014. Direction of arrow indicate the resultant effect of land-use change and associated ecological change in carbon stocks.

Recently, the Ghanaian government together with the World Bank designed the very first result-based payments through Reduced Emissions from Deforestation and Degradation plus (REDD+) in the cocoa landscapes (Forestry Commission 2016). The program seeks to address drivers of cocoa deforestation and at the same time boost productivity. Many actors in the cocoa industry are pressing for market standards for “zero deforestation cocoa supply chains” as a way to tackle deforestation and promote sustainable chocolate (Camargo and Nhantumbo 2016). Notwithstanding the growing concerns and the efforts being made to tackle cocoa-driven deforestation, empirical evidence on such deforestation to inform the design of interventions is hard to acquire. Most of studies (e.g., Asare et al. 2014; Koranteng et al. 2016; Obiri et al. 2007; Gockowski et al. 2010) make general references to cocoa expansion as an agent of deforestation without empirical basis to back the extent and rate of deforestation. Inasmuch as data on the role of various land-use systems play in the deforestation discourse abounds, most of these datasets are too coarse to establish direct causal relationship.

Two main reasons may possibly account for the lack of empirical evidence of cocoa-induced deforestation. First, it is difficult to delineate cocoa trees in remote sensing images (especially in cocoa agroforest farms) in natural forest due to spectral similarities with other tree species. In a typical cocoa agroforestry area, both the cocoa and on-farm trees form a multi-strata canopy that makes it difficult to extract pure spectral signatures to represent forest and cocoa. This requires innovative ways of processing remote sensing images with quality ground data to enable mapping-out of cocoa farms. Second, it is difficult to access quality (cloud-free) images for a given time period. This problem is a challenge to land-use mapping efforts in landscapes where anniversary satellite data are missing, which further accounts for the lack of reliable data to back cocoa-driven deforestation. Instead, many land-use classifications bunch together cocoa and other crops, which are then referred to as agriculture (Forest Preservation Project, 2014).

This study presents a new way to spatially segregate the agricultural land-use types to explore the implications of cocoa-induced deforestation in the cocoa-forest mosaic landscape of the high forest zone of Ghana. The results will provide the basis for assessing further implications of cocoa-driven deforestation on soil fertility, tree species diversity, carbon emissions, and land-use decisions of key actors in the landscape. The specific objectives are to: (a) identify and map dominant land-use types focusing on delineating cocoa agroforestry and fullsun cocoa, (b) examine the trends in land-use change transformation for the period 1986-2015, and (c) conduct an intensity analysis of land-use transitions for the same period.

3.2 Methodology

3.2.1 Pre-processing of satellite imagery

3.2.1.1 General image processing

The multiple-year Landsat satellite images of medium-resolution (30 m) were collected to characterize different types of land-use. Surface reflectance images of Landsat-5 TM (1986), Landsat-7 ETM (2002) and Landsat-8 OLI TIRS (2015) were downloaded from the USGS Landsat archive via earth explorer (http://earthexplorer.usgs.gov). The study area lies in scene 195/55 (path/row) of the Landsat archive. The selection of Landsat was based on its availability and quality. During the data search, the Landsat dataset were filtered by years and percentage of cloud cover of 10% threshold. Scenes from the years 1986, 1990, 2002 and 2015 that met the query statement emerged although some still had haze that needed additional cleaning. Overall, 28 individual spectral bands were downloaded of each seven bands for the individual years (Table 3.1). For 1990, 2002 and 2015, good quality images (with less than 10% cloud cover) for the dry season in December were available. The 1986 images for January were not suitable due to high cloud cover.

Table 3.1. Details of Landsat 8, 7, 5 with the band range, acquisition data and spatial resolution

Landsat Mission	Sensor	Band range	Date acquired	Spatial Resolution
Landsat-8	Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)	LC81950552015354LGN00_B1* LC81950552015354LGN00_B2 LC81950552015354LGN00_B3 LC81950552015354LGN00_B4 LC81950552015354LGN00_B5 LC81950552015354LGN00_B6* LC81950552015354LGN00_B7	2015-12-20	30 m
Landsat -7	Enhanced Thermal Mapper (ETM)	LE71950552002358EDC00_B1 LE71950552002358EDC00_B2 LE71950552002358EDC00_B3 LE71950552002358EDC00_B4 LE71950552002358EDC00_B5 LE71950552002358EDC00_B6 LE71950552002358EDC00_B7	2002-12-24	30 m
Landsat-5	Thermal Mapper (TM)	LT51950551990365MPS00_B1 LT51950551990365MPS00_B2 LT51950551990365MPS00_B3 LT51950551990365MPS00_B4 LT51950551990365MPS00_B5 LT51950551990365MPS00_B6 LT51950551990365MPS00_B7	1990-12-31	30 m
Landsat -5	Thermal Mapper (TM)	LT51950551986018XXX07_B1 LT51950551986018XXX07_B2 LT51950551986018XXX07_B3 LT51950551986018XXX07_B4 LT51950551986018XXX07_B5 LT51950551986018XXX07_B6 LT51950551986018XXX07_B7	1986-01-18	30 m

* *Bands 6 and 1 of Landsat ETM, TM and OLI, respectively, were not used in the processing*.

Automatic image-to-image registration was performed in ENVI 5.0 software using existing base map and 227 ground control points to geo-register the individual 28 bands. The geo-registration procedures made it possible to tie the four Landsat images to the study area. To ensure that the images had a consistent geographic reference system, each of the images were projected to UTM, Zone 30 North Datum WGS-84 using nearest neighbor method. The dark object subtraction (DOS) method described in Chavez (1996) and Mustak (2013) was applied to reduce haze effects to a minimum. In the DOS procedures, the subtraction parameters were set to user-defined and input with minimum reflectance values for each band generated from the raster statistics tool. A summary of the analysis steps is presented in the flow chart in Figure 3.2.

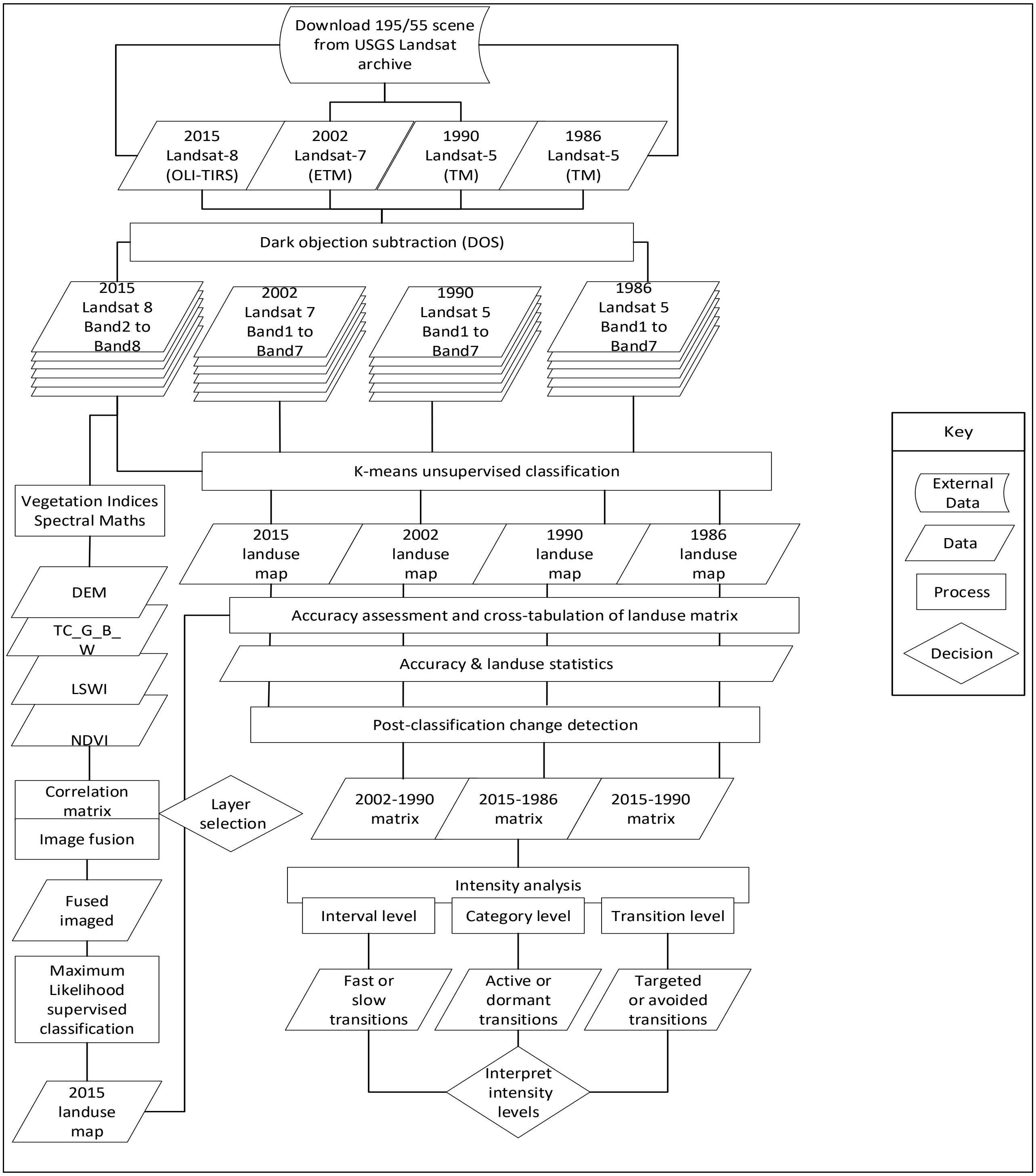


Figure 3.2. Flow chart summarising the steps and spatial analysis methods to derive land-use maps and transitions.

3.2.2 Data collection and analysis

Field data collection was carried out between May 2015 and February 2016. It aimed at gathering representative datasets in varied land-use types. In all, we collected 1,537 geographic data from purposively located plots in major land-use categories. At each location, the land-use types and conditions were recorded, and took photos to increase the reliability of the ground data during the training stage of the classification. Out of the 1,537 GPS coordinates, 227 of topographic features such as road intersections, forest boundaries, bridges, railways, etc. distributed across four precincts of the study area were used as ground control points in the automatic image-to-image geo-registration. The remaining 1,310 geographic data points were then converted to 437 feature polygons representing a specific identified land-use type in the study area.

Of the 437 feature polygons, we used 350 polygons as training sites in the supervised classification and the remaining 87 polygons for the validation of the classified land-use maps. Since the 87 validation polygons were short of the required minimum number, an extra 95 polygons were collected from google earth leading to a total of 182 polygons. This was done through on-screen digitization of visually distinct areas and backed by expert knowledge of the landscape. The feature polygons represented oil palm (OP), settlements (ST), close forest (close-FR), agroforest cocoa (AF-cocoa), land-in-transition (LIT) and fullsun cocoa (FS-cocoa) from google earth (Figure 3.3).

Close forest Fullsun cocoa Agroforest cocoa

Settlement Oil Palm Lands-in-transition

Figure 3.3. Screenshots of representative land-use types digitized from goggle earth

3.2.3 Image fusion of vegetation indices and digital elevation model

The individual 28 spectral bands were pooled into four multispectral images for each of the years 1986, 1990, 2002 and 2015. Each image was further clipped to the boundaries of the study area with equal dimensions of 1177 (sample) x 760 (line). Before conducting the supervised classification, extra image processing was done on the 2015 Landsat image to calculate vegetation indices (VIs). Two or more VI bands were put together to enhance detectability of the unique characteristics of vegetated areas (Richardson and Everitt 1992). These have the potential to provide additional landscape information beyond what the ordinary spectral bands can, because atmospheric effects can be corrected (Bannari et al. 1995). Thus, the VIs has the advantage to spectrally separate AF-cocoa and FS-cocoa from other vegetation that tends to mimic similar signatures.

Therefore, the spectral math tool in ENVI 5.0 was used to derive normalized difference vegetation index (NDVI), tasseled cap greenness (TC-G), tasseled cap brightness (TC-B), tasseled cap wetness (TC-W), and land surface water index (LSWI) vegetation indices from the 2015 Landsat image. The NDVI is known for its ability to evaluate vegetation health (Chandrasekar et al. 2010), and is calculated using the ratio of red and infrared spectral bands (Table 3.2). It is widely applied in agriculture (Labus et al. 2002), water management (Girolimetto & Venturini 2013), and ecological studies (Kariyeva & van Leeuwen, 2011). Tassel cap (TC) unlike NDVI (Kauth & Thomas 1976) has the advantage over traditional VIs because it compresses and orthogonally transforms many bands into three decorrelated bands (Baig et al. 2014). Each of the three new bands (brightness, greenness and wetness) can enhance peculiar features of objects in an image to aid in distinguishing “impervious spots" like soil and man-made structures (Baig et al. 2014), vegetated areas (i.e. forest, agriculture fields) and "moist features" like tree canopy (Zhang et al. 2002). Application of TC is common in vegetation (Bauer and Wilson 2005), urban (Homer et al. 2004), and agricultural (Oettera et al. 2000) studies. The Land Surface Water Index (LSWI) is an index derived from infrared and shortwave infrared bands (Table 3.2) with the additional advantage that areas with high moisture content like vegetation canopies can be detected (Chandrasekar and Roy 2010).

Table 3.2. Vegetation indices and equation used to derive these from the Landsat 8 images

Vegetation Indices	**Equation**	**Source**
NDVI	(NIR – R) / (NIR + R)	Girolimetto and Venturini (2013)
TC-G	(-0.2941*B)+(-0.243*G)+(-0.5424*R)+(0.7276*NIR)+(0.0713*SWIR1)+(0.1608*SWIR2))	Kauth and Thomas, (1976); Baig et al. (2014).
TC-B	(0.3029*B)+(0.2786*G)+(0.4733*R)+(0.5599*NIR)+(0.508*SWIR1)+(0.1872*SWIR2)	
TC-W	(0.1511*B)+(0.1973*G)+(-0.3283*R)+(0.3407*NIR)+(-0.7117*SWIR1)+(-0.4559*SWIR2)	
LSWI	(NIR – SWIR1) / (NIR + SWIR1)	Chandrasekar and Roy (2010)

Red = Red band; B = Blue band; G = Green band; NIR = Near infrared band; SWIR=Shortwave infrared band. TC_W - Tasseled Cap Wetness; TC_G - Tasseled Cap Greenness; TC_B - Tasseled Cap Brightness; NDVI - Normalized Difference Vegetation Index; LSWI - Land Surface Water Index

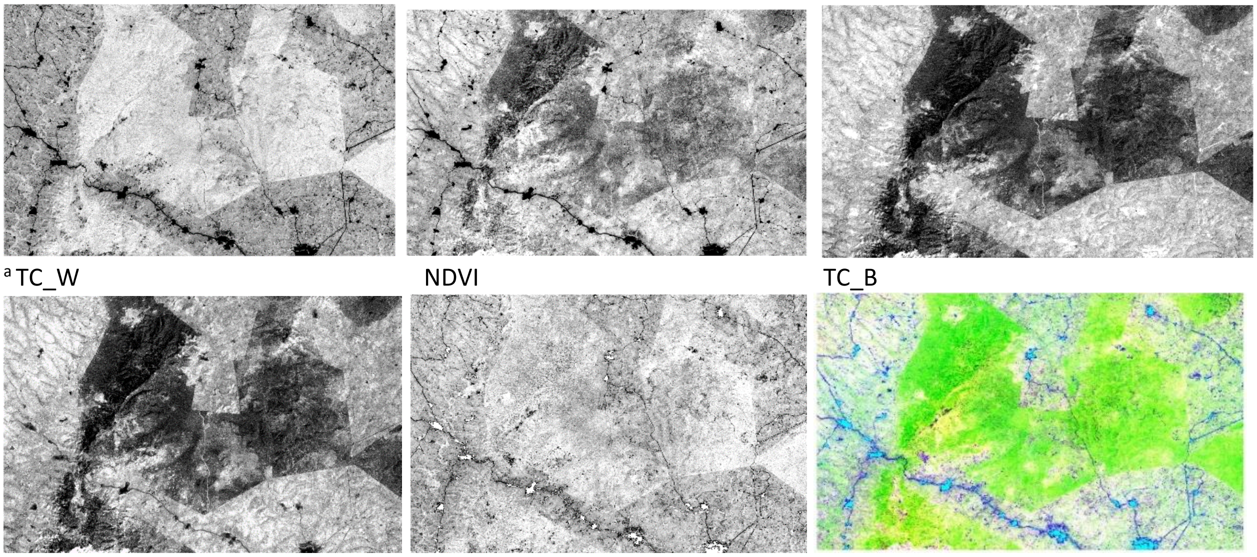
To assess the extent to which individual VIs distinctively separate vegetation based on their reflectance, we subjected the VI layers to correlation. The correlation coefficients show the ability of VIs to capture dissimilarities of features in the image that relate to each other (Table 3.3).

Table 3.3. Correlation Coefficient matrix of individual vegetation indices

[a] VI Layer	**TC_W**	**TC_G**	**TC_B**	**NDVI**	**LSWI**
TC_W	1.00	-0.45	-0.72	0.06	0.77
TC_G	-0.45	1.00	0.92	0.81	-0.13
TC_B	-0.72	0.92	1.00	0.57	-0.32
NDVI	0.06	0.81	0.57	1.00	0.26
LSWI	0.77	-0.13	-0.32	0.26	1.00

[a] VI – Vegetation Index, TC_W - Tasseled Cap Wetness; TC_G - Tasseled Cap Greenness; TC_B - Tasseled Cap Brightness; NDVI - Normalized Difference Vegetation Index; LSWI - Land Surface Water Index

There were relatively high correlations between some of the VI bands, however only between pairs of datasets. This suggests that some variations are present between the datasets and other bands which are relevant for the identification of various land-use types. Therefore, we incorporated all the individual VI bands into a fused image in the subsequent classification steps (Figure 3.4). All VI bands were layer-stacked into a 2015 composite image and fused with a 30 m-resolution digital elevation model (DEM) layer to correct for topography effects on the land-use characterisation. Thus, a vegetative index digital elevation model (VI-DEM) was created that was subsequently used for the supervised classification. Image fusion is a technique for processing two or more remotely sensed images into single image that provides more comprehensive information on the landscape than the individual images (Sahu et al. 2012).


[a] TC_W NDVI TC_B

TG_G LSWI VI fused-image

Figure 3.4. Vegetation index images and their fused image used for supervised classification

In addition, the four multispectral raster datasets were used in an unsupervised image classification to identify the main land-use types and determine trends in the changes that had occurred from 1986, 1990, 2002 to 2015.

3.2.4 Supervised image classification

The VI-DEM image-fused raster was classified into the 2015 land-use map using the supervised classification method (Lillesand et al. 2008). The procedures involved three stages. In stage 1, spectral end-members typical for close forest, open forest, agroforestry cocoa, fullsun cocoa, oil palm, lands in transition, and settlement (Table 3.4) were created from the fused image using the 350 training samples with the region of interest (ROI) tool in ENVI 5.0 Software.

Table 3.4. Land-use definitions used in the maximum likelihood algorithm and k-means classification

Land-use type	**Definition**
Closed forest (Close-FR)	Land with woody vegetation of 1 m minimum mapping unit with more than 60% crown canopy and of 5-m height. In the landscape, closed forest is mainly on reserves or outside reserves. On-reserve forests are state-protected forests designated for timber logging and protection functions. Off-reserve forests are relics of intact forest occurring outside forest reserves designated for special use for the communities (e.g., sacred groves, cemeteries etc.). The area also covers riverine vegetation in the forest reserve.
Open forest (Open-FR)	Open forest lands are forests with a crown cover between 15% and 60%. Their low crown-cover canopy is a sign of degradation resulting from planned or unplanned logging and mining activities. The area also covers riverine vegetation.
Agroforestry cocoa (AF-cocoa)	This type of land incorporates natural or planted trees that define a double-story canopy cover. Agroforestry cocoa is usually established by thinning existing natural forest or open forest.
Fullsun cocoa (FS-cocoa)	Considered as monoculture cocoa farms with only few or no natural or planted trees. It occurs when a farmer decides to shift from agroforestry cocoa to sun-loving hybrid species of cocoa by removing forest trees within the farm.
Cocoa Plantation (CC)	All cultivated cocoa areas in the landscape comprising of both agroforestry and fullsun cocoa.
Oil palm (OP)	Cultivated areas in the landscape spatially associated with lands in transition by planting oil palm (*Elaeis guineensis*).
Settlement (ST)	Non-vegetated parts of the landscape including human settlements, bare areas, mining areas, etc.
Lands-in-transition (LIT)	Land areas that are not included in the land definitions above. These are bush, shrub vegetation, and food crops. These areas are referred to as lands in transition because the current use has a short life span and is usually not the final intended economic use.

Each spectral endmember is a cluster of range of pixels that distinctively represents one land-use category of interest. Subsequently, the VI-DEM fused image was classified using MLA (Lillesand et al. 2008) with the endmember classes as training samples. Several studies have suggested the successful application of MLA in heterogeneous tropical landscapes because of the reported high accuracies in supervised classifications (Addo-Fordjour & Ankomah, 2017; Rujoiu-Mare & Mihai, 2016; Koranteng et al. 2016). In MLA classification, the highest probability for each pixel in VI-DEM fused images belonging to a particular endmember class is calculated and assigned to a specific land-use category (Rujoiu-Mare & Mihai, 2016). In the final stage, the accuracy of the land-use map was evaluated using the ground data that represented the seven land-uses.

3.2.5 Unsupervised classification

The k-mean classification (k-unsup) (Kusimi 2008; Damnyag et al. 2012) has the advantage that historical changes in land use types can be mapped. This classification allows digital clustering of the reflectance of remotely sensed images without the use of training samples that are usually collected ahead of the classification exercise. During the classification, the parameters were set to 100 classes and 5% change threshold after 25 maximum iterations. Then we combined 100 classes in a stepwise manner until five major land-use classes which represented close forest, open forest, cocoa (agroforest and fullsun plantations) lands-in-transition and settlement were derived. After that, we merged the cocoa agroforest and fullsun classes to cocoa plantation. This was because the classes with similar spectral signatures are not easy to separate across the time series with k-unsup. Unique color codes and class names were assigned to the five land-use classes. The same procedures were applied to the three Landsat scenes to produce individual land-use maps for 2002, 1990 and 1986. An accuracy assessment was performed on the images with satisfactory results, which allowed for a pixel-to-pixel change detection analysis assessment.

3.2.6 Accuracy assessment

Accuracy assessment was performed on the supervised and unsupervised maps to validate the classification results. The assessments were conducted using 182 validation points selected from the field geographic data and the digitised polygons from google earth. The approach to validate the latest 2015 land-use map differed from that for the previous years. For the 2002, 1990, and 1986 maps, results were compared with existing maps to identify unchanged areas between 1986, 1990 2002 and 2015 and the values used as inputs for ground-truthing.

3.2.7 Land-use transitions and intensity analysis

Intensity analysis was performed (Aldwaik & Pontius, 2012) to gain additional insights into the spatial configuration and temporal transitions (Zaehringer et al. 2015) of major land-use types in the study area. Some studies in Nigeria (Enaruvbe & Pontius 2015), Ghana (Alo & Pontius 2008; Braimoh, 2006), Indonesia (Villamor et al. 2014) and Rwanda (Akinyemi et al. 2016) adopted this method to examine land-use transitions over a given period. The aim in this study was to examine the underlying processes of land-use transitions in the cocoa-forest mosaic landscape in Ghana. Studies by Aldwaik and Pontius (2012), Villamor et al. (2014) and Akinyemi et al. (2016) provide considerable information on the conceptualisation of intensity analysis, which involves three logically sequenced analytical levels, i.e. interval, category and transition levels. The interval level computes overall change for a given interval for comparison to the overall change in other interval(s) to measure the pace at which the change had occurred relative to time. At the category level, the differences in size, gross loss intensity and gross gain intensity among categories within each time interval were calculated to determine which category was active or dormant. If the category intensity is greater than the uniform intensity of annual change, then the category is active during that interval. If the category intensity is less, then the category is dormant during that interval (Villamor et al. 2014).

The transition level determines how the size and intensity of a gaining category vary from other categories in each time interval (Braimoh 2006; Aldwaik & Pontius 2012; Akinyemi et al. 2016). If an observed transition intensity is greater than the matching uniform intensity, then the category targets the particular transition. If observed transition intensity is less than the matching uniform intensity, then the category avoids the particular transition. The change allocation and intensity analysis statistics (interval, category and transition) reveal the overall land-use transitions and change patterns in the cocoa-forest landscape. We conducted the intensity analysis with Pontius (2014) workbook version 41 with the 1986 and 2015 land-use matrix as input.

3.3 Results

3.3.1 Identification of dominant land-use category from supervised classification

The results show that of the total land area of 80,507 ha, forest (section of HFZ) made up the highest land percentage (40.3%), followed by agroforest cocoa (28.7%), and fullsun cocoa (11.5%) (Table 3.5).

Table 3.5. Share of land-use types from the supervised classification of 2015 Landsat 8 image

Land-use type	**Area (ha)**	**Land share (%)**
Close forest	32,482.62	40.3
Agroforest cocoa	23,075.10	28.7
Fullsun cocoa	9,246.78	11.5
Oil palm	7,394.49	9.2
Open forest	3,705.30	4.6
Lands-in-transition	3,289.32	4.1
Settlement	1,313.19	1.6

Four spatial associations from the emergent land-use classes were observed (Figure 3.5). These are (a) cocoa intrusions at low-lying spots and margins of the forest reserves, (b) mosaic character of trade-off between agroforest cocoa and fullsun cocoa, (c) oil-palm-lands-in-transition-settlement association, and (d) relics of forest-open-forest transition.

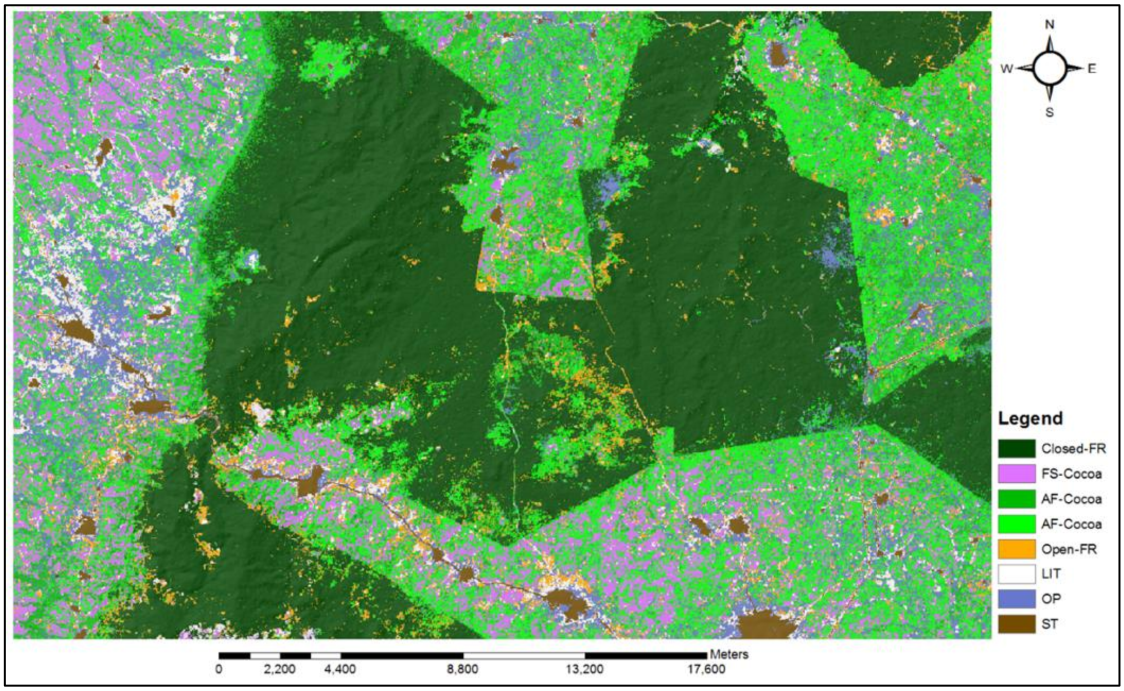


Figure 3.5 Map showing the seven-dominant land-use types in the study area

3.3.2 Land-use changes trends for the period 1986-2015

The unsupervised classification produced land-use maps covering the time series 1986, 1990, 2002 and 2015 (Figure 3.6). Together, the four maps captured the information on the sequence of change taking place in the landscape. The trends show that there were more closed-forest and open-forest areas in previous years (1986 and 1990) than in recent years (2002 and 2015), which rather had more cocoa areas. The map also reveals a persistent forest loss along the boundaries and selected spots within the Krokorsua Hills forest reserve due to expansion of cocoa farms.

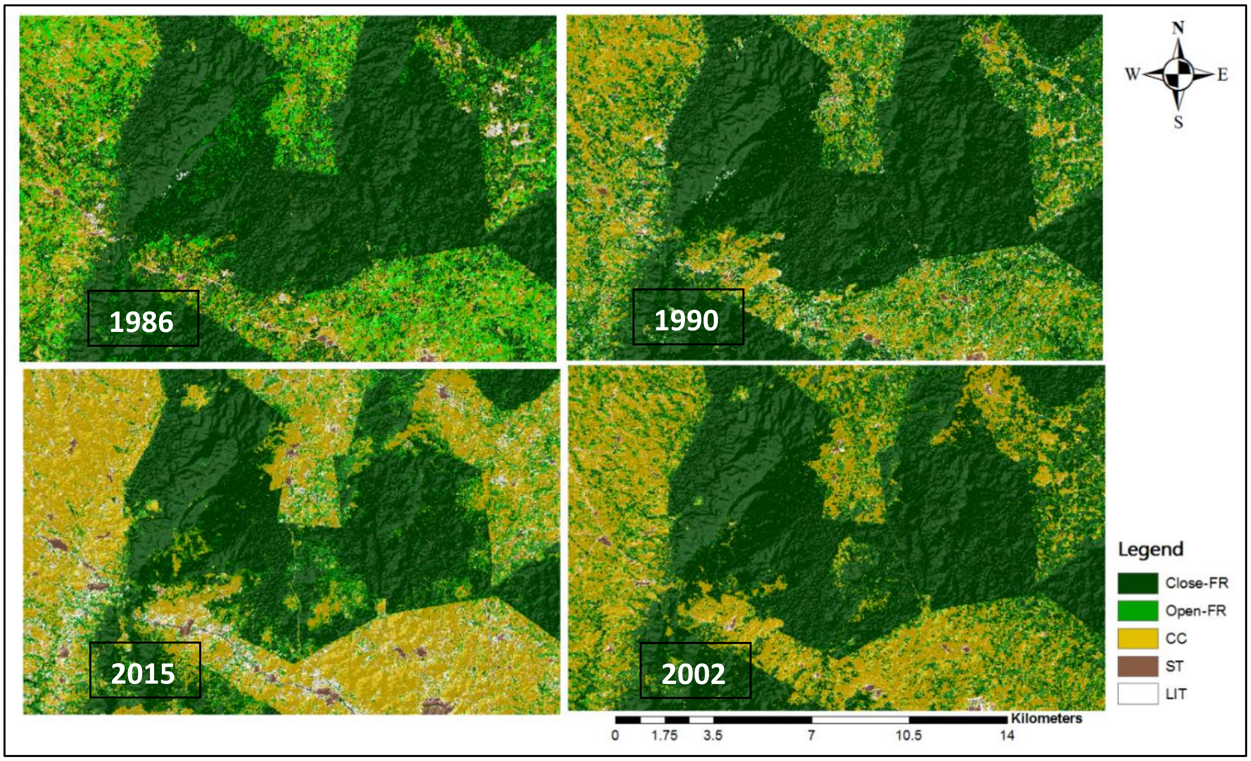


Figure 3.6. Historical maps indicating changing land-use trends in the study areas

In 2015, the landscape was dominated by forest (37.8%), followed by cocoa plantation (28.6%), settlement (17.3%), LIT (8.2%) and open-forest (8.2%). Although we observed consistent land-use changes over the mapping period, the intensities and the spread varied among the different categories. The majority of changes that took place had occurred in the forest. Forest conversions followed three main transition pathways, namely closed forest to cocoa plantation, close forest to settlement, and closed-forest to open-forest and LIT (Figure 3.7).

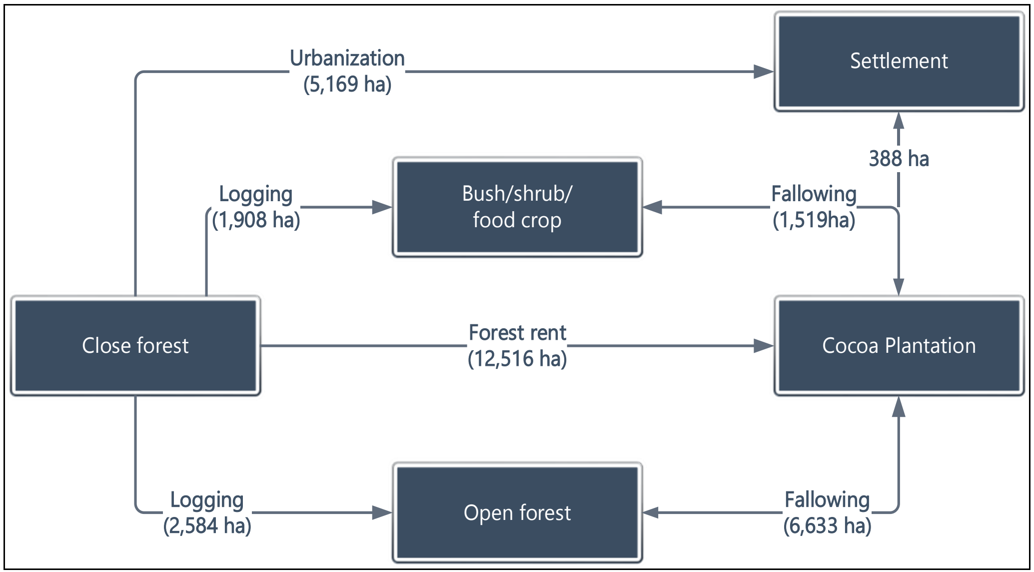


Figure 3.7. Land-use transition patterns along settlement, forest rent and logging pathways for the period 1986-2015. Area (ha) is net of gain-loss per each land-use category.

Among the forest conversion pathways from 1986 to 2015, forest conversion to cocoa was the dominant conversion, accounting for 54.7% of the area of forest loss. Within the analysis period, 51.9% of the land area remained unchanged, whereas 48.1% changed to and/or from different land-use categories. The forest covered 52,598.88 ha in 1986, but by 2015 it had reduced to 30,421.26 ha. Forest had the highest loss of 22,177.62 ha out of which 12,653.64 ha were converted to cocoa (Table 3.6). An additional 5,170 ha of forest area was lost to settlements in the same period. For cocoa, the total area gained (17,242.5 ha) was more than the cocoa area that remained unchanged (2,235.62 ha) for the same period. Out of the 17,242 ha gained by cocoa, most (73.4%) was added from close forest and 46.5% from open forest. The remaining area changed to other land-uses.

Table 3.6. Land-use matrix for the period 1986-2015

	Area (ha)					
Land-use types	Closed-forest	Open-forest	Cocoa plantation	Settlement	Lands-in transition*	Total (2015)
Closed-forest	29,463.66	782.91	136.80	0.54	37.35	30,421.26
Open-forest	3,365.68	1,771.11	1,384.20	3.78	49.89	6,574.66
Cocoa plantation	12,653.64	8,017.02	2,235.62	23.22	56.21	22,985.71
Settlement	5,170.46	103.14	411.15	8,181.79	42.79	13,909.33
Lands in transition*	1,945.44	1,402.47	1,575.44	1,539.61	152.88	6,615.84
Total (1986)	52,598.88	12,076.65	5,743.21	9,748.94	339.12	80,506.80

*Include areas mapped out as Bush/shrubs/food crops

At the landscape level, close forest and open forest cover recorded 2% annual loss as against cocoa plantation, settlement and lands-in-transition that increased by 5%, 1% and 11%, respectively. The net changes among the various land-use categories led to an estimated 3% average deforestation that translates to 2,167.88 ha per annum for the period 1986-2015.

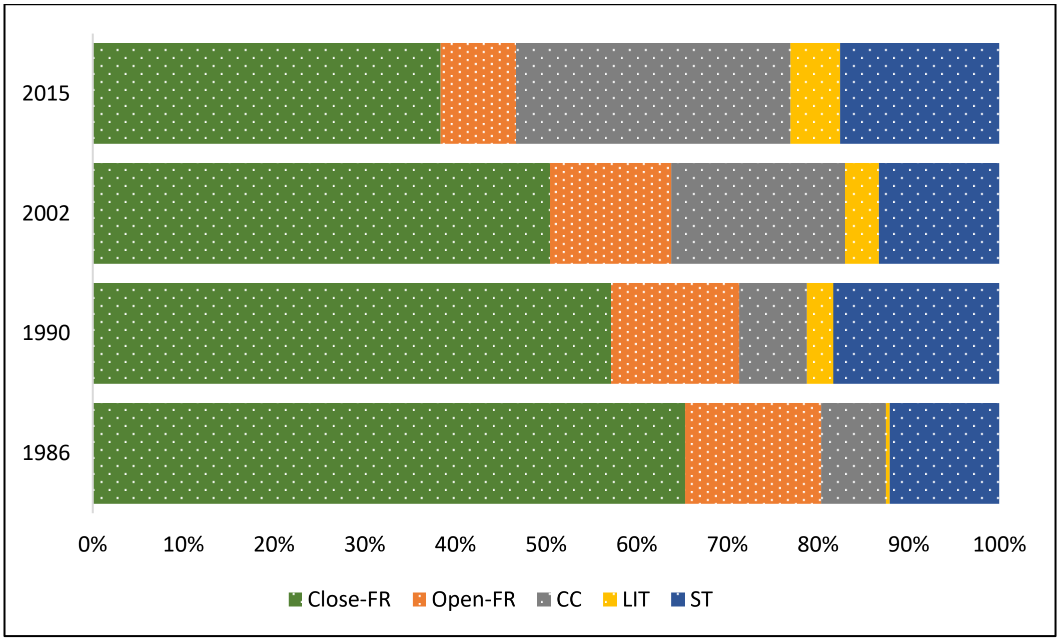


Figure 3.8. Land-use change trends for close forest, open forest, cocoa plantation, lands-in-transition and settlement for the period 1986-2015

Nonetheless, throughout the study period, close-forest still represented the major land-use type (Figure 3.8). It was about 65% of the study area in 1986, declined by 10% in 1990 and further declined to 38% by 2015. Similarly, open forest areas saw consistent decreases throughout the same period with 15% in 1986 declining to 8.4% by 2015. In contrast, cocoa plantation, settlement and LIT showed increases throughout the same period, although the pattern of change differed. While cocoa plantation and bush/shrub/food crop persistently expanded, settlement experienced a sinusoidal trend. In the case of cocoa plantation, there was an overall increase of 23.2% between 1986 and 2015.

3.3.3 Accuracy assessment

3.3.3.1 Maximum likelihood classification map

The results of the accuracy assessment were used to validate the maximum likelihood classification map (Table 3.7). Four sets of quantitative statistical parameters, i.e. overall accuracy, kappa statistics, producers and user accuracy and error of commission/omission were used. The values of all four quantitative parameters connote high accuracy levels of land-use classification. The accuracy assessment showed an overall accuracy of 82.6% with a kappa statistics coefficient of 0.73. Close forest and settlement showed high producer and user accuracy of 98.5%, followed by Agroforest cocoa and fullsun cocoa with 92.6% each. The producer and user accuracy for open forest, lands-in-transition and oil palm was relatively lower (86.5%). Close forest showed the lowest average error of commission and omission (0.6%) followed by settlement with an average of 2.4%. On the other hand, lands-in-transition, oil palm and open forest showed relatively high average errors of 14.5%, 13.3%, and 12.5%, respectively.

Table 3.7: Results of accuracy assessment of the supervised classification of 2015 land-use map based on pixel population

	Ground truth (No. of pixels)							
Land-use types	Close forest	Fullsun cocoa	Agroforest cocoa	Lands-in transition	Open forest	Oil Palm	Settlement	Total
Close forest	13851	1	40	3	3	2	0	13,900
Fullsun cocoa	11	1794	55	6	48	30	0	1,944
Agroforest cocoa	23	89	4027	31	76	26	1	4,273
Lands-in-transition	34	55	64	880	77	24	4	1138
Open forest	28	26	66	15	1511	34	15	1695
Oil palm	21	25	49	4	32	851	6	988
Settlement	2	1	1	0	27	7	1291	1329
Total	13970	1991	4302	939	1774	974	1317	25,267

These results show a better performance of the MLA classification method when it comes to detecting close forest, settlement and even cocoa plantation on such a complex landscape. These areas are easier to identify than the other land-uses because of the symmetrical shape on the remote sensing image as well as the unique spectral characteristics. Lands-in-transition, open forest and oil palm have a mosaic features, and contribute to comparatively high errors of commission and omission.

3.3.3.2 Unsupervised classification of land-use maps

Quantitative accuracy assessment of earlier land-use maps (1986, 1990 and 2002) was not possible because of the lack of access to ground truthing data. Instead, the validation of these maps was dependent on visual comparison of existing maps particularly of areas in the map that had remained unchanged throughout the time series. In all, areas in the three maps identified as close forest and settlement had greater visual agreements with existing land-use maps than lands-in-transition and open forest. As for cocoa plantations, it was not possible to compare with any existing land-use maps because none of the studies could spectrally isolate cocoa plantation as an individual land-use category. Therefore, for the analysis years where satellite data was available on goggle map, we visually identified cocoa plantation areas in both maps and crosschecked to determine their level of agreement. A greater percentage of areas identified as cocoa plantation had agreement especially when associated with forest. Unsupervised classification of the 2015 image yielded overall accuracy of 91.8% and a 0.83 kappa coefficient (Table 3.8). Settlement, cocoa plantation and LIT had more than 90% accuracy (producer and user) unlike close forest and open forest that showed accuracies between 60% and 70%.

Table 3.8. Results of accuracy assessment of unsupervised classification of 2015 land-use map

	Ground truth (No. of pixels)						User accuracy
Land-use types	Cocoa plantation	close forest	settlement	LIT	open forest	Total	
Cocoa plantation	1083	11	0	2	25	1121	96.6%
Close forest	18	55	0	2	0	75	73.3%
Settlement	1	1	53	3	0	58	91.4%
LIT	14	9	0	143	19	185	77.3%
Open forest	11	12	1	6	167	197	84.8%
Total	1127	88	54	156	231	1636	
Producer accuracy	96.1%	62.5%	98.1%	91.7%	79.1%		

Although cocoa plantations showed a high accuracy of 96%, an average of 3.65 errors of commission and omission occurred due to misclassification to close forest, LIT and open-forest. Closed-forest and open-forest had the lowest accuracy of 62.5% and 79.2%, respectively. The errors mostly resulted from the incorrect allocation of forest pixels to cocoa plantation, open forest and LIT. Misallocation of pixels of vegetative stands occurred because these have spectral similarities.

3.3.4 Transition intensity analysis

The change budget (gain, persistence and loss) for each land-use category for the period 1986-2015 revealed forest as the least gaining category and with the largest persistent and losing areas (Figure 3.9). Moreover, cocoa showed relative steadiness because it was highest gaining and the second most persistent category.

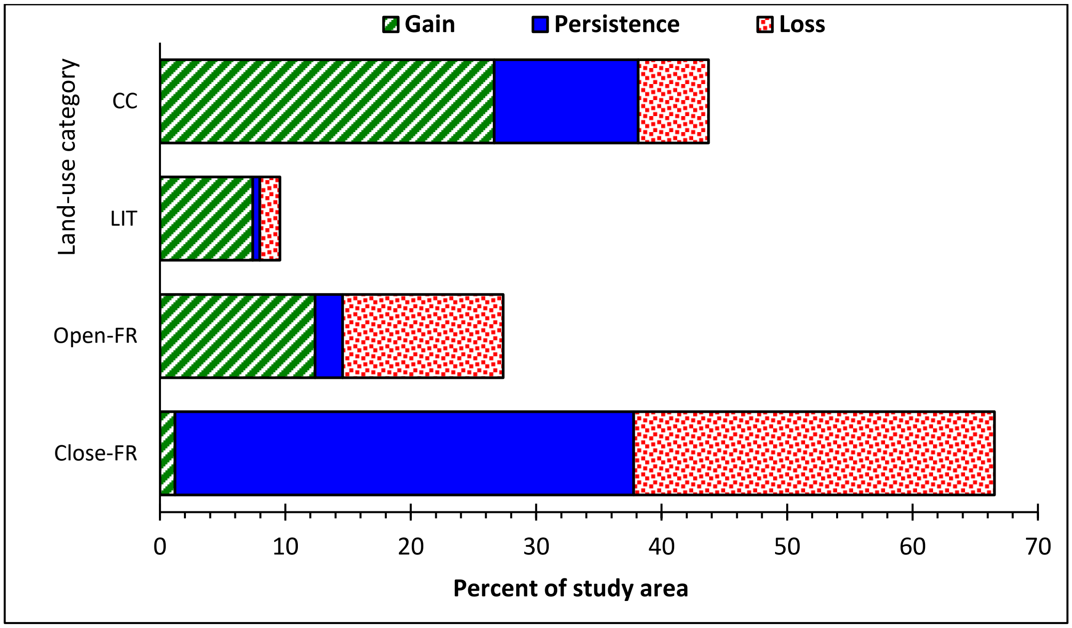


Figure 3.9. Percent gain, persistence and loss (land-use change budget) for the period 1986-2015

Areas of open-forest and LIT saw modest transition variations (Figure 3.10). For open-forest, the gain-loss percentages cancelled out whereas LIT marginally gained. The computation of category intensity determines whether gain/loss intensity is dormant or active. It is derived by comparing each category's gain intensity and loss intensity values to the overall uniform intensity of change.

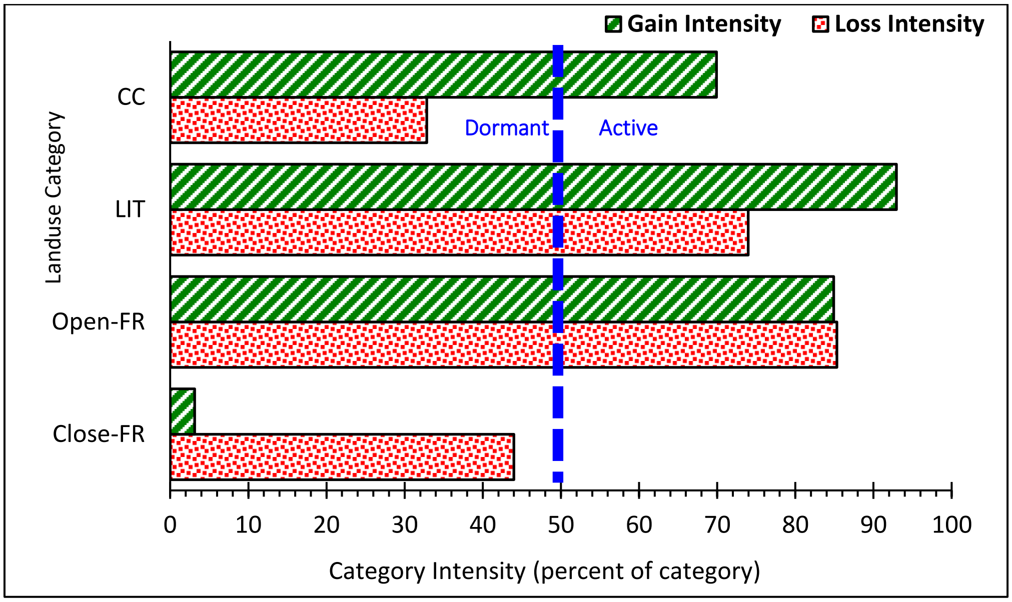


Figure 3.10. Category level intensity analysis for the period 1986-2015

The results showed cocoa as an active gainer and dormant loser. Both open-forest and LIT categories are active gainers and active losers. Closed-forest is both a dormant gainer and dormant loser. Since cocoa is the most active gainer, transition gains to cocoa usually target open-forest, LIT areas, and avoid close forest and settlement (Figure 3.11).

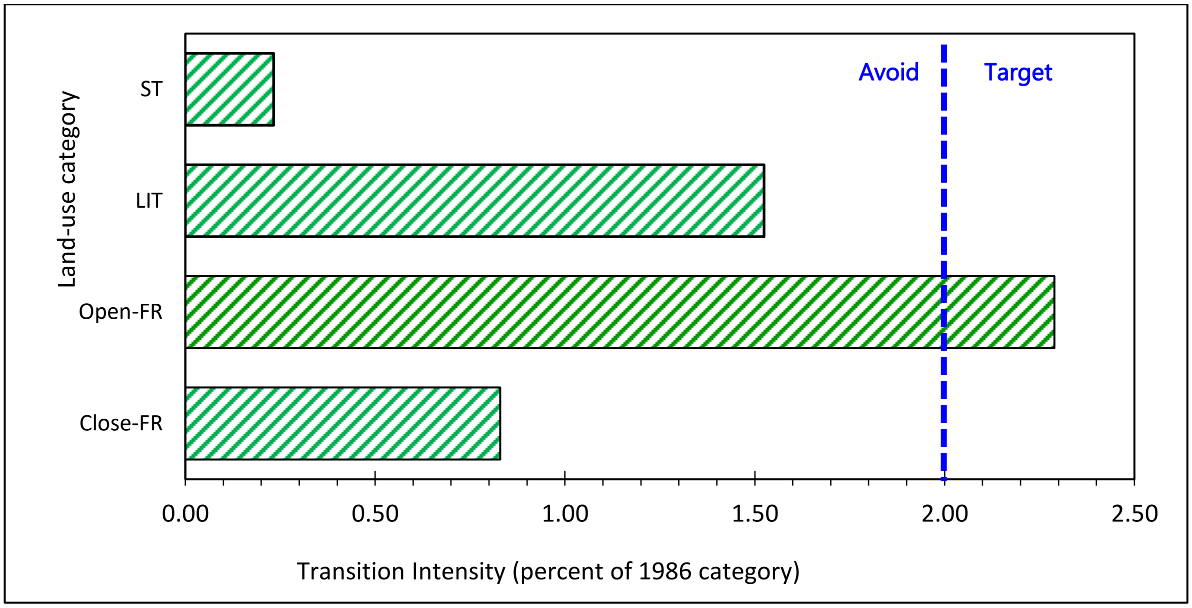


Figure 3.11. Chart showing intensity of transition of settlement, lands-in-transition, open forest and close forest areas to cocoa plantation in 1986

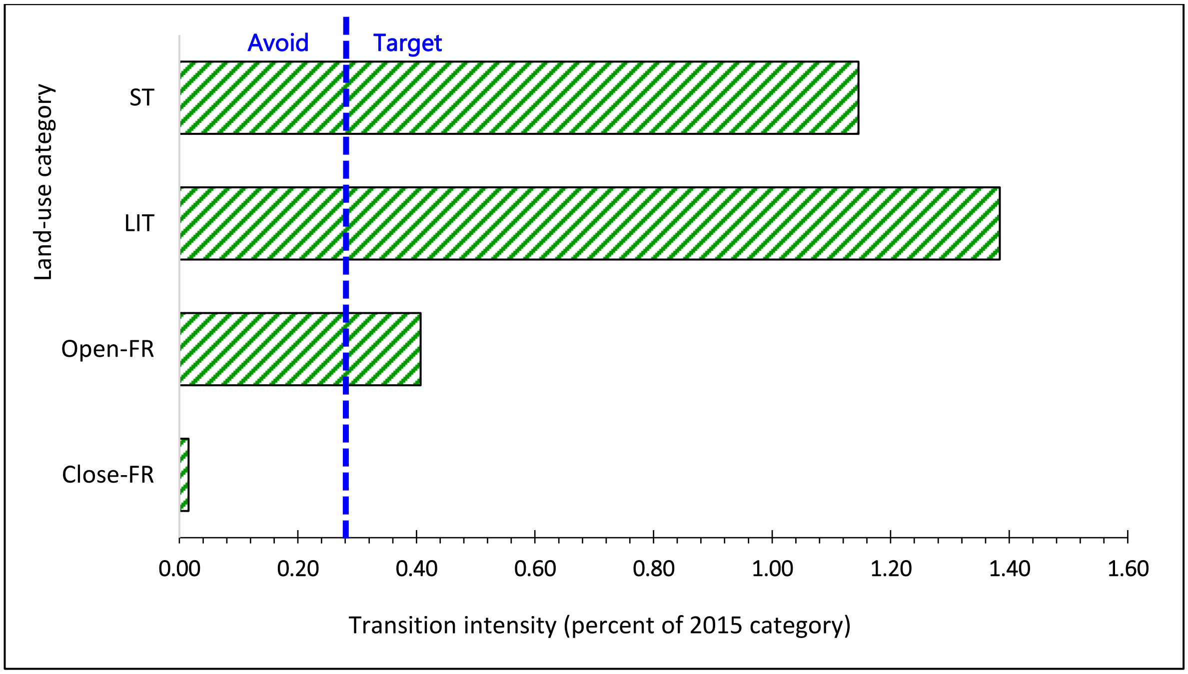


Figure 3.12. Chart showing intensity of transition of settlement, lands-in-transition, open forest and close forest areas to cocoa plantation in 2015

3.4 Discussions

3.4.1 Evaluation of land-use classifications

In 2015, we applied both MLA supervised classification and k-mean unsupervised methods to map land-use types. Although the original intention was to complement MLA supervised with k-unsupervised classification, it is worthwhile to evaluate the results from the two methods. We expected the map composition and the error matrix from the two methods to differ because they both use fundamentally different algorithms on two separate input datasets. We found that the MLA technique had the advantage that land-use variations compared to k-unsupervised could distinguish various cover classes at the coarse level. Expectedly, the results from both classifications show variations in all land-use types. The MLA method detected many more vegetated areas (Forest, Agroforest cocoa and fullsun cocoa) than the k-mean method (open forest, settlement and LIT). With the MLA method, forest was spectrally isolated from other tree crops (cocoa and oil), where reflectance is usually difficult to separate because of the similar canopy structure. Likewise, we could further delineate agroforestry cocoa as well as fullsun cocoa. This extra utility of the MLA supervised classification method is assumed to result from the inclusion of the multiple VIs and DEM dataset in the pre-processing phase.

3.4.2 Mapping out dominant land-use types

The use of VIs to create fused images for the maximum likelihood classification proved to perform better than conventional approaches. The ability to discriminate vegetation types with similar spectral signatures improved when good quality training datasets were used in the classification procedures. This is because fusing multiple VIs and elevation raster into a single image in the classification process increases the spectral variability of the different vegetation types through correction of atmospheric and elevation effects on the image. The method led to improvements in distinguishing and mapping AF-cocoa and FS-cocoa within forest and other vegetation types. This is evident in the high overall accuracy of 82.6% with kappa statistics coefficient of 0.73, which demonstrates a moderate agreement between the ground data and the classified image.

Coulter et al. (2016) used vegetation indices to map land use types in the context of the changing urban landscapes in Ghana, and reported high overall accuracy of 89% ± 3%. Although Koranteng et al. (2016) employed a different classification method, they had an overall accuracy of 85%, which is within the range obtained in this study. In this study, the image-fusion method was successfully deployed for mapping to distinguish cocoa from vegetated areas in the Ghanaian landscape with high certainty. The positive results provide a further boost to the efforts to develop the remote sensing technique to effectively aid in distinguishing cocoa plantations in mosaic landscapes. Using medium-resolution remote sensing images to map cocoa plantation from other vegetation types has long been a challenge to many landscape practitioners (Forestry Commission 2014). This is because traditionally agroforest cocoa has a multi-strata canopy structure, which creates spectral mixing problems. Usually, the easy way out is to bunch cocoa and other trees crops as open forest (MLNR 2014) if these do not meet the forest definition threshold. In the end, more areas are allocated as forest than actually existing on the ground.

Applying the image-fusion method successfully distinguished cocoa from another tree vegetation. Being able to map agroforest cocoa and fullsun cocoa in forest and other land-use types is an essential step in the evaluation of cocoa-driven deforestation. The forest constitutes a dominant land-use in the landscape, but the main parts of the forest are within forest reserve boundaries and are being heavily encroached. This finding is in agreement with McCullough et al. (2005). The encroachment is associated with areas where intensive logging has taken place in the past or admitted farms/communities have expanded over the years. The level of deterioration of the forest reserve is a manifestation of persistent governance failure in the management of the forest reserves among other underlying drivers. The bottom line is that the institutions that are mandated to manage the forest resources at the local level confront challenges that practically disable them from enforcing the forest laws. The findings reported in Kusimi (2008) and Alos et al. (2008) reinforce the observation of encroachment made in the on-reserve forest. The results (Figure 3.6) also show that there was virtually no forest in the off-reserve areas because the majority have been converted to cocoa as landowners perceive short-term positive returns over forest.

Cocoa plantation is the second dominant land-use and occurs in the landscape as a mosaic across the areas. Agroforest cocoa and fullsun cocoa are spatially distinctive because of their unique spectral signatures. The extensive agroforest cocoa areas are consistent with the traditional practice of keeping trees within the farms in this particular landscape. We also found that the spatial associations of agroforest cocoa and forest exhibited two encroachment patterns. In the first pattern, we observed patches in the forest reserve, which are indicative of persistent forest degradation. The evidence of forest-fringe fragmentation suggests that forest boundaries are the least resisted pathway when encroachment starts from outside. The second pattern mainly showed irregular patches resulting from subtle expansion of cocoa farms at the back of “admitted farms”.

The effects were detected in the land-use map as isolated degradation in the forest reserves. Fullsun represented 11.5% of the landscape and is evident of the changing dynamics in tree shade diversity on the cocoa farms (Tondoh, 2015). The results also show an “intermixed-spatial association” of agroforest and fullsun cocoa where they occur together in the off-reserve areas. This observation is consistent with the conceptualization behind “agroforest-fullsun shade modification” as an adaptation strategy to sustain and increase productivity on the farm (Ruf & Zadi 1998). Furthermore, the results reveal an “Oil palm-LIT-settlement” association that means that where oil palm occurs, it is mainly bordered by lands in transition and settlements. This is a sign of soil fertility exhaustion where profitable cocoa farming is no longer possible. Therefore, farmers choose to plant alternative tree crops.

3.4.3 Evidence of cocoa-driven deforestation

All the five-identified land-use types experienced varying degrees of changes as a result of timber logging, settlements and cocoa frontier expansion. These findings suggest years of ineffective enforcement structures at the community level due to systematic policy incompetence (Forestry Commission 2010), institutional weakness (Forestry Commission 2016), and lack of clarity regarding the prevailing resource regime (Damnyag 2012). The results further reveal two-level land-use transition by drivers that iteratively interact in accomplishing the “integration objective” defined by the actor at any given time (Noordwijk et al. 2012).

The first level is the staging phase when the conceptualization and execution of forest conversion to permanent land use, mainly cocoa plantation and settlement, occur. As the permanent transition takes place, open forest or lands-in-transition, which usually have relatively short lifespans, appear in the landscape signifying forest exhaustion or regeneration of abandoned land. This observation somewhat reinforces the growing importance of lands-in-transition in land-use planning. Usually lands-in-transition areas are interspersed within deforestation-reforestation regions on the forest-transition curve (Noordwijk & Villamor, 2014). This means that “place and time” factors play an important role in how lands-in-transition contributes to shape agroforestry landscapes.

The results further suggest that forest margins and low-lying areas are the usual the target of deforestation activities because they are the least protected by laws. The results showed that forest margin conversion to forest and to cocoa plantation was 54.6% and 77.8% of close forest and open forest loss, respectively. This is driven by the underlying economic benefits to the actor regardless of physical and legal limitations associated with it. This substantiates the reasoning behind the expansive nature of the cultivation of tree crops where enforcement of forest laws is weak (Ruf et al. 1998). The on-reserve forest becomes the ultimate target for cocoa expansion when suitable lands in the off-reserve areas are no longer available or, as is the case in most parts of the landscape (Figure 3.6), suitable lands for cocoa cultivations become increasingly scarce. The expansion tends to follow the relics of previously logged areas and at the back of admitted farms as they expand over the years. Cocoa-driven deforestation has deteriorating effects on the multi-functionality of the agroforestry landscape especially on habitats, tree species diversity, soil fertility and carbon sequestration (Minang et al. 2015). This evidence could support formulation of deforestation-free-cocoa sourcing programs that many of the industrial players are seeking to implement.

3.4.4 Transition intensity analysis

The findings from the intensity analysis reveal varied transition intensities for all land-use categories. Three distinctive transition pathways are influencing the kind of modification occurring in the landscape. Forest remains the most dominant and persistent land-use category because the majority of these areas were found in the forest reserves.

Although the existing forest protection laws helped to maintain larger forest areas, the lack of enforcement led to forest loss. This also means that the gaining and losing intensities of the forest category were dormant. The expansive nature of the method of establishing cocoa made it the highest gaining category. Even though forest transitions were dormant, forest was the single highest contributor to cocoa. Nevertheless, whenever cocoa land increased, it targeted open forest and lands-in-transition areas mainly due to their close spatial association. Cocoa plantation, open forest and lands-in-transition occur as a mosaic particularly in off-reserve private lands. The fact that cocoa, open forest and lands-in-transition are close to each other on private lands, it is far easier for the landowner to expand. In contrast, loss intensity of the cocoa category was dormant, and transition targeted open forest, lands-in-transition and settlement.

These findings reveal two major characteristics of deforestation instigated by cocoa expansion (Asare et al. 2014; Koranteng et al, 2016; Obiri et al. 2007; Gockowski et al. 2010). When cocoa expansion occurred in forest reserves, the effects were mostly episodic and localized, which coincides with the early stages of the boom-bust pattern (Ruf et al. 1998). This interpretation is derived from the intensities statistics, which indicate that most transitions avoid the forest area because it is largely dormant. On the other hand, because open forest and lands-in-transition areas are mainly vegetated due to the opening-up of natural forest and fallowing, cocoa expansion usually targets them. There was further evidence that the expansion of open forest, lands-in-transition and settlement also targeted the cocoa land-use category. Conversion of cocoa to open forest and lands-in-transition largely occurs when over-age cocoa farms are abandoned to fallow (Figure 3.7) to regain soil fertility over a given period.

3.5 Conclusions

In this research, we studied the effectiveness of the image-fusion approach to detect and isolate agroforestry cocoa and fullsun cocoa from vegetated and non-vegetated land-use, and further examined evidence of cocoa-driven deforestation. We demonstrated the ability of this method to distinguish cocoa land-use, and on that basis calculated cocoa-driven annual deforestation rates for 1986 and 2015. These findings are consistent with the hypothesis behind cocoa-driven deforestation, which mainly targets open forest and lands-in-transition areas even though there are cases of extensive encroachment in the forest. This trend of losing forest cover for cocoa is indicative of the extent of the weakness in forest governance structures and also of other underlying drivers of forest loss. The evidence of deforestation through cocoa expansion is established in this study, which thus provides justification for the assessment of implications it has for soil fertility, tree diversity and carbon emissions. Any such considerations are critical for the formulation of landscape-wide deforestation-free interventions through REDD+ or cocoa certification programs.

4 SPATIAL PATTERNS OF SOIL CARBON, NITROGEN AND PHOSPHORUS IN DIFFERENT LAND-USE TYPES

4.1 Introduction

In the West African Guinea forest region, expansion of agricultural tree crop plantations (cocoa, oil palm and rubber) is associated with an influx of migrants, mostly from the hinterland, encroaching protected areas and the remaining rainforest (Bitty et al. 2015; Goldstein & Udry 2008). Typically, cocoa is cultivated in high-forest ecological zones, which provide favorable climate and soil conditions. The traditional method of establishing cocoa farms contributes to land-use changes (Tondoh et al. 2015). Soil conditions matter for sustainability of production in existing stands and their changes relative to natural forest provide a benchmark for evaluating ecological effects of land-use dynamics (Winowiecki et al. 2016; Ojoyi et al. 2017; Pabst et al. 2013). Soils are important nutrient storage reservoirs essential for crop productivity. Soil nitrogen (N), phosphorus (P) (Wang et al. 2009) and soil organic carbon (SOC) content (Elbasiouny et al. 2014) are essential nutrient determinants of soil fertility for plant growth. The largest pool of terrestrial C is found in the soil, which besides plant productivity regulates associated ecosystem services (Elbasiouny et al. 2014).

Forest conversion to cocoa has ecological implications beyond soil fertility (Roger et al. 2014), such as effects on belowground biodiversity (Tondoh et al. 2015) and greenhouse gas emissions (Sirikit & Garden 2013). Understanding the spatial patterns of, and relations between, key soil parameters can assist in the management of dynamic tropical landscapes. The spatial distribution of soil N, P and SOC is influenced by a number of spatially explicit factors including parent material (mineralogy), topography, climate, pH, texture, vegetation and land-use types (Jenny 1994; Noordwijk et al. 1997). At the level of the soil profile, soil texture (Tan & Lal 2005; Wang et al. 2002), pH and temperature (McGrath & Zhang 2003) influence forest soil conditions (Roger et al. 2014; Patil et al. 2010) with further impacts of subsequent management practices (McLauchlan 2006; Kong et al. 2009; Gami et al. 2009; Lin et al. 2009; Rodríguez et al. 2009; Ross et al. 1999).

Empirical studies are usually based on comparisons across space (tentatively interpreted as chronosequence), rather than on long-term monitoring of soil changes at a single location starting before forest conversion. Studies typically find a combination of inherent site conditions (such as elevation as a proxy for temperature), inherent soil properties (especially texture) and land-use to control the spatial distribution of soil N, P and SOC (Liu et al. 2013; Kong et al. 2009). Thus, there is a possible confounding effect of the choice of forestland to be converted first (generally the most favorable topography and/or soils) and subsequent change due to conversion and management. Explicit attention to farmer knowledge underpinning their site selection, constrained by existing local and national law-based regulation, can inform efforts to disentangle observed spatial patterns of TN, SOC and P and separate land-use effects from à priori soil differences used in site selection for different land use (Hoang et al. 2013). Spatial variability of soil N, SOC and P has been frequently studied in Europe (Gülser et al. 2016; Patil et al. 2010; Rodríguez et al. 2009), America (Gami et al. 2009; Kong et al. 2009; Tan & Lal 2005; Wang et al. 2002) and Asia (Allen et al. 2016; Liu et al. 2013; Zhao et al. 2009; Wang et al. 2009; Gami et al. 2009; Kong et al. 2009; Lin et al. 2009). Published studies conducted in Africa (Elbasiouny et al. 2014; Ogunwole et al. 2014; Lemenih et al. 2005) are scarce, however, even though the continent has the largest area of poor soils initially derived from deforestation.

Some of the studies focused on specific land-use such as grassland (McGrath & Zhang 2003), mixed forest (Zhang et al. 2010), cropland (Liu et al. 2006), and shrubland (Rodríguez et al. 2009) as well as on multiple land-use types (Hebb et al. 2017; Wang et al. 2009). As far as we know, there are few studies (Wartenberg et al. 2017) on the spatial variability of soil properties in the context of tropical forest-cocoa mosaic landscapes, which present unique ecological and soil characteristics. In this study, the aim is to characterize variation in SOC content, total TN and P to understand how profile-level soil textural variation and landscape-level variation in elevation influence key soil characteristics across different land-use types.

Therefore, the specific objectives of this study are as follows: (a) to determine SOC, TN and P levels in remnant forest, cocoa and other dominant land-use types and their relationships with soil texture and topography, (b) to analyze spatial inter-dependency of SOC, TN and P levels, and (c) to map their spatial patterns in a study area where subsequent research will focus on farmer knowledge and a further dissection of land-use histories.

4.2 Methods

4.2.1 Pre-processing of spatial data

Statistical and geo-statistical techniques were used to analyze soil and topographical data in different land-use types. The soil sampling design was based on the 2015 land-use map (Figure 3.5).

4.2.2 Soil sampling

Soil samples were collected from November 2015 to January 2016 from major four land-use types comprising forest, high agroforest cocoa, medium agroforest and fullsun cocoa plantations using a stratified random sampling technique (Figure 4.1). A total of 199 soil samples from forest (44 samples), high agroforestry cocoa (44 samples), medium agroforestry cocoa (60 samples), and fullsun (51 samples) were collected at depths 0-15 cm and 15-30 cm.

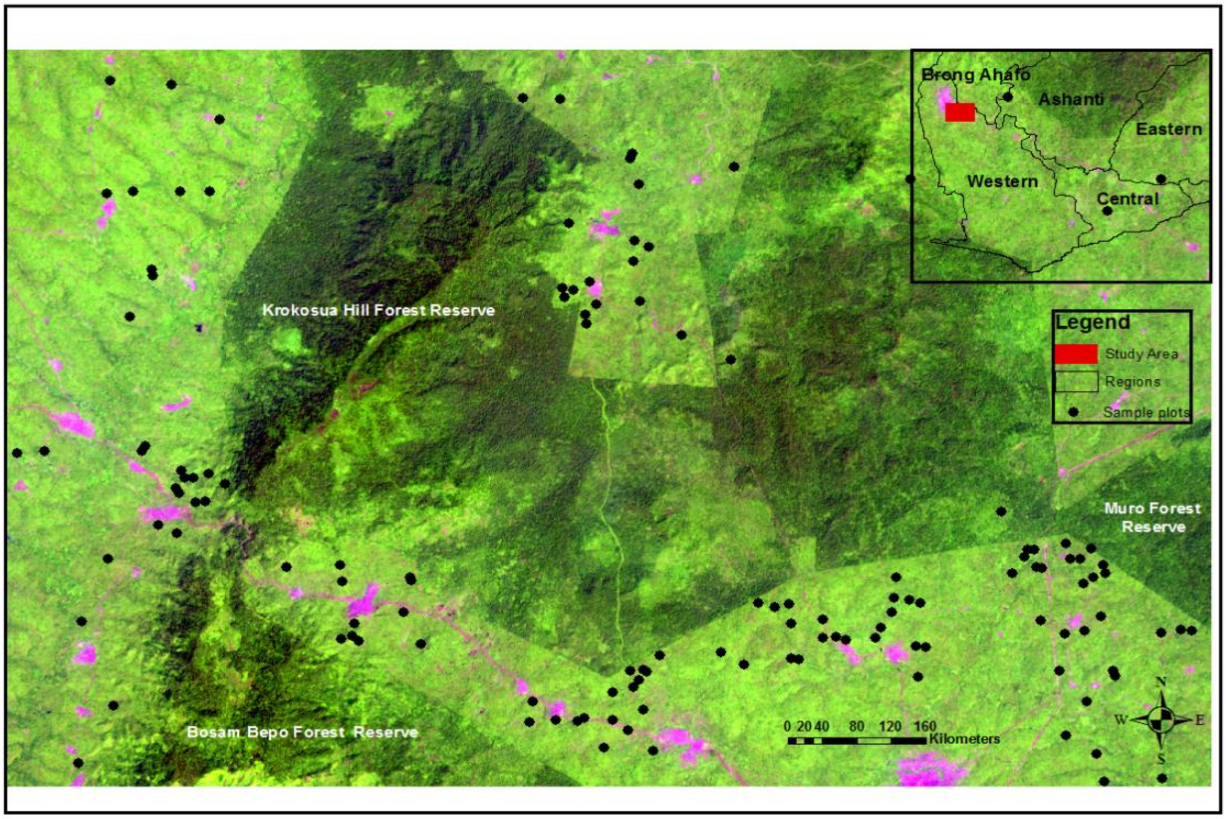


Figure 4.1. Landsat image displayed in false colour showing the study area and the spread of sample plots in black dots within cocoa plantations. The map also shows Krokorsua Hills, Muro and Bosam Bepo forest reserves, built up areas (pink colour) interspersed with cocoa plantations.

At each sampling site, square plots measuring 100 m by 100 m (1 ha) were established. Six soil samples were taken with a core sampler at the four corners of the plot and at the center for soil chemical analysis and bulk density determination for a core volume of 98 cm^3 (Blake & Hartge 1986).

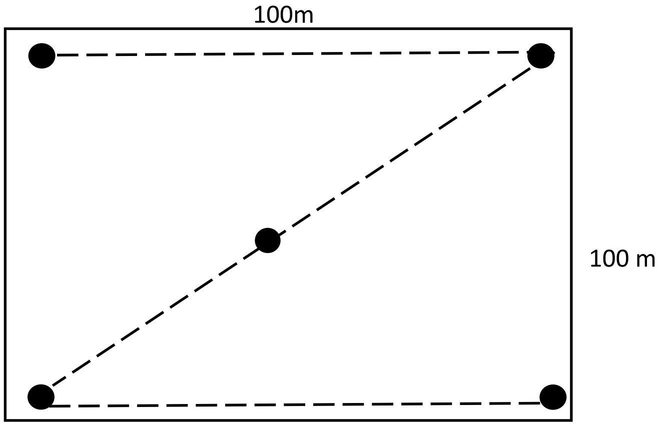


Figure 4.2 Design of the 1 hectare soil sampling plot and the arrangement of center and corner sampling points

4.2.3 Laboratory tests

Chemical and physical analyses were conducted on the soils after air drying, grinding, and sieving through a 2-mm sieve. All soil samples were analyzed for SOC, TN, P, pH, and exchangeable K, Ca, Mg and Na as well as for sand, clay and silt fractions. The pH was determined in a 1:2.5 (soil: water) suspension (Page et al. 1982). Particle size distribution was measured by the pipette method (Rowell 1995). The TN was determined by the dry combustion method (Page et al. 1982). SOC was measured using the Walkley-Black method (Nelson & Sommers 1982), while the total P concentration was determined by alkaline digestion followed by molybdenum colorimetry measurement (Murphy & Riley 1962).

4.2.4 Statistics

Using Stata 14 software, descriptive statistics was performed on soil and topographic data to calculate their means, minimum, maximum, standard deviation, coefficient of variation, skewness and kurtosis for all land-use types. A normality test of the data probability distribution was applied using the Shapiro-Wilk (S-W) normality test values (Liu et al. 2006; McGrath & Zhang 2003). The non-normal distributed dataset was log-transformed to meet the normality conditions for additional statistical analysis. One-way analysis of variance was used to test for significance in the means of the soil parameters in the various land-use types, assuming land-use randomly with respect to inherent soil properties. Means were separated using least significant difference (LSD). The Pearson correlation test was used to evaluate the strength of association between SOC, TN, P and the soil parameters clay, silt, and sand content, pH, exchange cations (K, Ca, Na and Mg) and topographical variables (slope and elevation) (Wang et al. 2009; McGrath & Zhang 2003; Roger et al. 2014; Gülser et al. 2016). Multiple linear regression was further performed to determine the statistical significance (P=0.05) between dependent variables (SOC, P, TN) and independent variables (silt, sand, clay, slope, elevation) in different land-uses (Ghani & Ahmad 2010). Soil carbon stocks (SCS) was calculated using Equation 4.1 consistent with the method adopted by (Elbasiouny et al. 2014)(Dawoe 2009)(Stevens & Van Wesemael 2008; Tornquist et al. 2009).

SCS (Mg ha^{-1}) = $10^4 \times SOC \times h \times (BD \div 100)$ Equation 4.1

where SCS is soil carbon stock (Mg ha^{-1}), SOC is concentration of soil organic carbon (%), h is soil layer depth (m), and BD is bulk density (g cm^{-3}). Eq. 1 was also used to derive Total Nitrogen stock (NS) and Phosphorous stocks (PS) by replacing SCS with the required parameters.

4.2.5 Geostatistics

We focused here on soil data for the top 15 cm. A digital elevation model (DEM) with 30-m resolution was obtained from the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global from the USGS data archive (https://dds.cr.usgs.gov/srtm/). Using ArcGIS 10.4.1 software, slope and elevation raster maps were derived from the DEM. A point-feature map for the soil dataset was created using the unique GPS coordinates for each sampling location. With the spatial analyst tool in the ArcGIS 10.4.1, slope and elevation cell values were extracted using the attribute associated with specific locations in the soil point map. During the soil sampling, not all locations in the study areas were covered, but representative samples were collected for each of the stratified land-use types. In order to estimate soil TN, SOC, and P values of the un-sampled areas and evaluate the spatial patterns, a two-step geostatistical analysis was carried out (Webster & Oliver 2007). Several authors (Elbasiouny et al. 2014; Gülser et al. 2016; Liu et al. 2006; Wang et al. 2009; Roger et al. 2014; Rodriguez-Galiano et al. 2012; Kyere 2016) applied a similar geostatistics technique in the study of spatial variability of soil properties.

In the first step, a semi-variogram was used to quantify the spatial variability of soil of regionalized variables of SOC, TN and P, and used this as input in spatial interpolation in a second step (McGrath & Zhang 2003). Both ordinary kriging and inverse distance weighting (IDW) interpolations were performed in the characterization of spatial distribution of SOC, TN and P (Robinson & Metternicht 2003). Semi-variogram was generated for each random soil variable (SOC, TN, P) in all the land-use types to evaluate their degree of spatial dependence as a factor of distance between sampling points (Gülser et al. 2016). The semi-variogram was produced using Equation 4.2 (Zhao et al. 2009; Liu et al. 2013; Al-Omran et al. 2013):

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}[Z(x_i)-Z(x_i+h)]^{2} \qquad \text{Equation 4.2}$$

where $\gamma(h)$ is the semi-variogram for the interval distance class h, N(h) is the number of pairs of sampling points separated by h, $Z(x_i)$, and $Z(x_i+h)$ are the measured soil sample values of SOC, TN and P at locations i and $(i+h)$, respectively. For each TN, C, and P semi-variogram in each land-use, the best-fitted isotropic variogram model (spherical, exponential, linear and Gaussian) was selected using the smallest residual sum of square (RSS) and their corresponding largest coefficient of determination (r^2). The autocorrelation statistics of the best-fitted variogram [nugget variance (C_O)], and structural variance [sill (C_O+C,) range (A)] were used as user-defined factors in the ordinary kriging interpolation (Wang et al. 2009). We performed the geostatistics analysis with GS+ Geostatistics for the Environmental Sciences software (version 10).

4.2.6 GIS analysis

With ArcGIS 10.4.1 software, we conducted inverse distance weighted (IDW) interpolations to produce surface maps of SOC, TN and P, and their stocks (SCS, NS and PS). Then, we evaluated the spatial patterns for each soil variable with the corresponding land-use type by a weighted sum overlay for each soil IDW surface map with the 2015 land-use map. Before the overlay, the individual soil raster maps were reclassified on an equal-interval scale of seven. The scale of seven conformed to the threshold seven classes assigned to land-use map classes in order of declining vegetation (FR>OF>High-AFS cocoa>Medium-AFS cocoa>FS>BSF>ST). In the reclassification, a unique code between 1 and 7 was assigned to all the raster maps (TNS, SOC, PS, land-use). Usually, the unique code 1 represented minimum class graduate to unique code 7 as the maximum. The reclassification made it possible to overlay both soil SCS, TNS, PS, and elevation and land-use maps in a consistent way. After the overlay of SCS, TNS and PS, mean figures were appended to each unique code for land-use type.

4.3 Results

4.3.1 Descriptive statistics

The descriptive statistics summarize the quantitative features of the soil properties in each land-use type at the landscape level (Table 4.1). The range of TN, SOC and P values is from 0.03% to 0.2%, 0.6% to 2.4% and 2.9 to 53.7 mg/kg, respectively. Carbon-nitrogen ratio (C: N ratio) values are between a minimum of 4.11 and a maximum of 130.29 with a mean of 16.18. Results reveal inherent variability in SOC, TN, and P content in soils of the same and different land-use types due to the combined influence of intrinsic factors (parent rock, elevation, climate) and extrinsic factors (land-use type, management practice) (Nyamadzawo et al. 2008). Elevation was from 144 m to 602 m along 0.6% slopes in cocoa plantations to moderately steep (42.4%) forest areas. We found significantly higher mean elevations in forest (275 m) than in agroforest cocoa (216 m) and fullsun cocoa (213 m), even though slope did not differ much among the land-use types.

Table 4.1. Minimum, maximum, mean, medium, standard deviation, skewness, kurtosis and coefficient of variation of soil properties in different land-use types.

	Texture fraction			Topography		Acidity	Bulk	Nutrients			Cation exchange				Stocks		
	Sand	**Silt**	**Clay**	**Slope**	**Elevation**	**pH**	**Density**	**TN**	**SOC**	**P**	**K**	**Ca**	**Na**	**Mg**	**SOC**	**TN**	**P**
	%				**m**	**H_2O**	**g/cm3**	**%**		**mg/kg**	**cmol/kg**				**Mg/ha**		**kg/ha**
All land-use types (n=199)																	
Min	16.64	0.44	6.24	0.58	144.00	4.30	1.11	0.03	0.58	2.83	0.02	1.64	0.19	0.10	10.70	0.54	5.73
Max	93.32	54.44	39.12	42.44	602.00	6.80	1.43	0.18	2.40	53.65	0.08	18.16	0.64	4.06	50.48	3.70	105.42
Mean	56.65	24.19	19.16	10.42	227.69	5.59	1.27	0.11	1.69	26.10	0.05	7.77	0.37	1.79	32.28	2.01	49.78
Median	58.04	24.56	18.66	9.10	217.00	00.64	1.26	0.10	1.88	25.20	0.04	7.06	0.34	1.75	35.42	1.92	48.76
SD	15.42	11.41	7.50	7.23	59.41	0.51	0.06	0.03	0.43	11.91	0.02	3.93	0.11	0.85	8.18	0.59	22.99
Skewness	-0.04	0.17	0.31	1.62	3.06	-.15	0.49	0.23	-0.71	0.13	0.70	0.89	0.78	0.44	-0.61	0.29	0.15
Kurtosis	-0.82	-0.35	-0.64	4.11	14.04	0.01	-0.43	0.21	-0.65	-0.89	0.13	0.27	-0.22	-0.09	-0.47	0.35	-0.86
CV (%)	27.23	47.15	39.13	69.43	26.09	9.21	5.02	29.13	25.28	45.64	33.66	50.60	28.86	47.32	25.33	29.43	46.18
S-W Test	a	a	a	b	b	a	b	a	a	a	b	b	b	b	a	a	a
Forest (n=44)																	
Min	36.80	18.56	7.24	1.82	189.00	4.30	1.19	0.040	1.00	6.06	0.03	2.64	0.24	0.44	30.55	0.70	10.64
Max	48.09	41.40	39.12	42.10	469.00	6.44	1.27	0.170	2.18	25.69	0.06	13.48	0.39	3.12	87.01	3.09	50.48
Mean	42.08	30.41	26.13	13.47	275.14	5.63	1.23	0.109	1.92	17.05	0.05	8.55	0.31	1.80	65.45	2.02	31.29
Median	41.58	30.24	26.26	11.76	261.50	5.67	1.23	0.110	1.94	17.17	0.05	8.64	0.31	1.80	45.79	2.03	31.81
SD	3.02	4.35	6.64	7.76	60.94	0.33	0.02	0.021	0.17	4.66	0.01	2.58	0.04	0.53	3.25	0.41	8.24
Skewness	0.14	0.01	-0.67	1.69	1.83	-1.28	0.23	-0.34	-3.92	-0.08	-0.75	0.06	0.15	-0.10	-4.15	-0.35	0.04
Kurtosis	-0.37	1.38	1.23	4.29	3.48	6.04	0.45	3.011	20.66	0.36	2.27	-0.11	-0.33	1.25	22.36	2.88	0.50
CV (%)	7.18	14.29	25.42	57.61	22.15	5.82	1.50	19.55	8.85	27.30	11.86	30.12	11.41	29.17	9.16	20.12	26.32
S-W Test**	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Cultivated (=155), Area(32,300.1 ha)																	
Min	16.64	0.44	6.24	0.58	144.00	4.30	1.110	0.03	0.58	2.83	0.02	1.88	0.19	0.10	10.70	0.54	5.73
Max	93.32	54.44	34.76	42.44	602.00	6.80	1.430	0.18	2.40	53.65	0.08	18.16	0.64	4.06	50.48	3.70	105.42
Mean	60.48	22.33	17.18	9.55	214.22	5.57	1.283	0.10	1.63	28.66	0.04	7.52	0.39	1.79	31.38	2.01	54.96
Median	63.60	20.56	16.12	8.55	210.00	5.61	1.270	0.10	1.71	28.31	0.04	6.20	0.37	1.72	32.90	1.89	54.58
SD	15.15	12.00	6.49	6.86	51.73	0.56	0.067	0.03	0.46	12.10	0.02	4.14	0.11	0.92	8.91	0.63	23.13
Skewness	-0.55	0.51	0.45	1.67	4.68	-0.03	0.156	0.32	-0.36	-0.29	0.81	1.03	0.52	0.46	-0.30	0.34	-0.26
Kurtosis	-0.12	-0.27	-0.42	4.42	31.53	-0.45	-0.653	-0.08	-1.08	-0.71	-0.19	0.31	-0.70	-0.41	-0.94	0.00	-0.64
CV (%)	25.05	53.75	37.78	71.80	24.15	9.98	5.187	31.49	28.05	42.21	38.09	55.12	29.66	51.45	28.38	31.66	42.09
S-W Test**	a	b	b	b	b	a	a	a	a	a	b	b	b	b	a	a	a
Fullsun cocoa (n=51). Area (9,246 ha)																	
Min	25.24	0.44	6.24	0.58	144.00	4.30	1.20	0.040	0.58	2.83	0.02	1.88	0.19	0.44	10.70	0.73	5.73

	Texture fraction			Topography		Acidity	Bulk	Nutrients			Cation exchange				Stocks		
	Sand	Silt	Clay	Slope	Elevation	pH	Density	TN	SOC	P	K	Ca	Na	Mg	SOC	TN	P
	%				m	H_2O	g/cm3	%		mg/kg	cmol/kg				Mg/ha		kg/ha
Max	93.32	48.64	34.76	42.44	556.00	6.80	1.37	0.170	2.40	47.75	0.08	18.08	0.63	4.06	45.21	3.09	95.23
Mean	59.44	22.70	17.85	9.54	213.45	5.57	1.27	0.102	1.59	27.41	0.04	7.95	0.40	1.80	30.21	1.94	51.96
Median	61.68	20.56	16.59	7.74	208.00	5.58	1.24	0.100	1.70	27.40	0.04	6.98	0.38	1.69	32.40	1.88	52.79
SD	14.36	11.24	6.49	7.15	59.70	0.59	0.06	0.028	0.50	13.26	0.02	4.12	0.12	0.85	9.27	0.53	25.25
Skewness	-0.43	0.36	0.53	2.08	3.94	-0.03	0.73	-0.08	-0.29	-0.09	0.66	0.79	0.21	0.83	-0.30	-0.11	-0.04
Kurtosis	-0.16	-0.50	0.25	7.76	21.60	-0.46	-0.90	-0.04	-1.15	-1.27	-0.22	-0.06	-0.74	0.27	-1.02	-0.19	-1.21
CV (%)	24.16	49.50	36.34	74.97	27.97	10.62	4.40	27.36	31.30	48.39	37.16	51.84	29.38	47.16	30.69	27.53	48.60
S-W Test**	a	a	a	b	b	a	B	a	a	a	b	b	a	a	a	a	a
Medium shade agroforest cocoa (n=60). Area (16,476.99 ha)																	
Min	16.64	2.14	6.44	0.81	158.00	4.33	1.11	0.03	0.70	3.63	0.02	2.36	0.21	0.10	12.71	0.54	7.46
Max	91.72	51.44	29.76	31.86	262.00	6.80	1.41	0.18	2.27	48.40	0.08	17.78	0.64	3.78	44.39	3.70	98.01
Mean	59.43	23.70	16.79	9.77	208.35	5.54	1.29	0.11	1.64	29.46	0.05	6.89	0.37	1.78	31.64	2.02	56.61
Median	62.01	22.62	14.26	9.12	208.00	5.49	1.28	0.10	1.73	29.97	0.04	5.61	0.37	1.74	32.99	1.90	55.14
SD	15.89	13.03	6.24	6.50	27.35	0.56	0.07	0.03	0.41	11.37	0.02	3.91	0.12	0.97	8.17	0.67	21.64
Skewness	-0.70	0.44	0.46	1.02	0.22	0.22	-0.18	0.23	-0.47	-0.38	0.98	1.29	0.83	0.18	-0.36	0.32	-0.40
Kurtosis	-0.14	-0.62	-0.79	1.17	-0.63	-0.22	-0.32	-0.4	-1.04	-0.31	-0.23	1.16	-0.16	-0.80	-1.04	-0.14	-0.23
CV (%)	26.74	54.99	37.14	66.52	13.13	10.07	5.09	32.6	24.78	38.60	39.11	56.65	31.04	54.26	25.81	33.36	38.22
S-W Test**	a	a	b	b	a	a	A	a	a	a	b	b	b	a	a	a	a
High shade agroforest cocoa (n=44). Area (6,577.11 ha)																	
Min	29.12	1.44	6.72	1.73	155.00	4.44	1.11	0.030	0.70	3.63	0.02	2.40	0.25	0.22	12.71	0.59	7.68
Max	91.72	47.84	30.92	35.45	602.00	6.50	1.43	0.180	2.37	53.65	0.08	18.16	0.61	3.84	50.48	3.49	105.42
Mean	63.13	19.94	16.93	9.27	223.11	5.63	1.30	0.106	1.66	29.03	0.04	7.86	0.40	1.80	32.38	2.06	56.19
Median	65.82	18.60	15.96	7.35	215.00	5.67	1.29	0.100	1.73	29.04	0.04	6.55	0.37	1.72	32.91	1.88	58.00
SD	15.03	10.96	6.77	7.14	65.44	0.52	0.08	0.037	0.48	11.81	0.02	4.46	0.11	0.96	9.47	0.69	22.72
Skewness	-0.50	0.53	0.32	1.98	4.71	-0.41	-0.11	0.567	-0.34	-0.42	0.73	1.04	0.54	0.58	-0.26	0.48	-0.34
Kurtosis	0.03	0.19	-0.77	4.94	27.02	-0.48	-0.70	-0.01	-1.21	-0.12	-0.06	0.21	-0.99	-0.33	-0.92	-0.12	0.00
CV (%)	23.81	54.99	40.00	76.97	29.33	9.22	5.85	34.56	28.91	40.67	38.44	56.74	28.29	53.50	29.25	33.64	40.44
S-W Test**	a	a	a	b	b	a	A	a	a	a	b	b	b	a	a	a	a

**. S-W Test - Shapiro-Wilk Test, a = normal distribution based on S-W test, b = non-normal distribution based on S-W test

The frequency distribution of pH, soil texture, nutrient levels and nutrient stock variables in all land-use types was normal as indicated by low skewness and corresponding Shapiro-Wilk test values. In general, soil texture was dominated by sand (mean 56.7%), followed by silt (mean 24.2%) and clay (mean 19.2%). The t-test revealed that the soil texture in forest sites differed significantly from that on sites converted to other land-use: soils under forest had less sand (42.1%) compared to agroforest (61.3%) and fullsun cocoa (59.3%), and concomitant higher silt and clay contents. Similarly, forest soil had a significantly lower bulk density of 1.21 g/cm^3 compared to 1.29 g/cm^3 in agroforest cocoa and 1.27 g/cm^3 in fullsun cocoa plots.

4.3.4 Pearson correlation analysis

The correlation coefficients of SOC, TN and P against selected texture and topographic parameters in different land-use types were calculated (Table 4.2). Under all land-use types, we found a weak but statistically significant correlations ($p < 0.05$) among soil nutrient variables. SOC and TN were positively correlated (although C: N ratios ranged from 16.18 to 130.29), whereas SOC and P showed a negative correlation. In the same vein, both SOC and P content correlated significantly with all texture parameters (sand, clay and silt) with clay having the strongest association. Similarly, SOC and elevation correlated positively under all land-use types even though each land-use type showed variation in spread. Under forest conditions, TN had a strong significant ($p < 0.05$) correlation with P, clay, sand and pH. Apart from clay content that correlated negatively with TN, the remaining parameters showed a positive correlation.

The particularly strong correlation between TN and P, clay and pH is typical of forest soils. In the same way, P correlated significantly with sand, silt, clay and pH. Although under cocoa agroforest, TN correlated significantly with sand, clay and SOC, the strength of the association is weak. In contrast, SOC shows a statistically significant strong association with sand and clay. Under medium-AFS cocoa and FS-cocoa, only SOC and silt had statistically significant negative correlations, while TN and slope correlated better ($p<0.05$) with SOC although the strength of the association was weak. Similar values were reported by Xue et al. (2013), who highlighted SOC influence on N mineralization. The different correlation levels indicate inherent interactions that exist between soil nutrient content and texture variables (Wei et al. 2008). Clay content influenced SOC distribution particularly in forest and high agroforest cocoa due to decomposition and accumulation of organic matter (Sausen et al. 2014) on the surface of the soil.

Table 4.2. Pearson correlation of sand, clay, silt, pH, bulk density, elevation and slope against soil TN, P and SOC) in different land-use types

Soil Parameters	**All land-use (n=199)**			**Forest (n=44)**			**Cultivated areas (n=155)**			**High-AFS Cocoa (n=44)**			**Medium-AFS Cocoa (n=60)**			**FS-Cocoa (n=51)**		
	TN[a]	SOC[a]	P	TN	SOC	P	TN	SOC	P	TN	SOC	P	TN	SOC	P	TN	SOC	P
TN	1.00	0.26**	0.06	1.00	0.03	0.85**	1.00	0.27**	0.05	1.00	0.36*	-0.12	1.00	0.32*	-0.02	1.00	0.12	0.29*
SOC	0.26**	1.00	-0.25**	0.03	1.00	0.01	0.27**	1.00	-0.16*	0.37*	1.00	-0.05	0.32*	1.00	-0.19	0.12	1.00	-0.23
P	0.06	-0.25**	1.00	0.85**	0.01	1.00	0.05	-0.16*	1.00	-0.12	-0.05	1.00	-0.02	-0.19	1.00	0.29*	-0.23	1.00
Sand	-0.02	-0.48**	0.28**	0.45**	-0.26	0.51**	-0.02	0.41**	0.10	-0.39**	-0.56**	0.15	0.16	-0.02	-0.02	0.11	-0.39**	0.19
Silt	0.02	0.35**	-0.19**	0.13	-0.08	0.43**	-0.02	0.31**	-0.11	0.29	0.48**	-0.11	-0.10	0.03	0.03	-0.18	0.29*	-0.28*
Clay	0.01	0.45**	-0.28**	-0.68**	0.55**	-0.72**	0.09	0.38**	-0.03	0.45**	0.52**	-0.12	-0.18	-0.04	-0.04	0.07	0.35*	0.05
pH	0.04	-0.03	0.10	0.93**	0.11	0.83**	-0.06	-0.05	0.08	-0.05	-0.31*	-0.10	-0.17	-0.02	-0.02	0.07	0.02	0.31*
BD	-0.04	-0.11	0.01	-0.01	0.24	0.16	-0.04	-0.03	-0.17*	-0.21	-0.05	-0.29	0.07	0.07	-0.17	0.01	-0.21	-0.12
Alt	0.01	0.20**	-0.18*	-0.09	0.03	-0.01	-0.11	0.11	-0.01	-0.04	-0.03	0.04	0.11	0.11	-0.07	-0.06	0.20	-0.01
Slope	0.01	0.15*	-0.14	0.12	-0.03	0.17	-0.03	0.11	-0.08	0.03	0.03	0.02	-0.11	-0.11	-0.11	-0.15	0.29*	-0.21

*** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed). [a] Total N – Total Nitrogen; [b] SOC – Soil Organic Carbon; [c] P – Phosphorus; [d]BD- Bulk Density*

4.3.5 Multiple linear regression analysis

A multiple regression was run to relate SOC, TN, and P as dependent variables to silt, clay content, pH and elevation as explanatory variables at the landscape level and within land-use types. The R^2 value for SOC was slightly higher than that of TN and P in all land-use types. The regression results (Table 4.3), reveal that, in most cases, the predictive variable of SOC, TN, and P performed better in FR than in cultivated areas as seen in the high R^2 coefficient of SOC, TN, and P in FR. The results indicate that the model can explain 95% of TN, 76% of SOC and 87% of P variability in forests although we observed varied contribution from predictive variables (Table 4.3). The high variability of TN in forest soils was equally accounted for by pH (49.9%) and clay content (49.9%). Similarly, we found that the variability of SOC in forest soil could be most explained by clay content (95%) and TN (89.8%). The same observation was made for P in forest soil, where TN contributed 68.7%. This correlation between SOC, TN, pH and clay underlines the strong correlation among soil properties (Table 4.3) in the forest.

Table 4.3. Multiple stepwise regression analysis of soil SOC and N, P against texture and topographic variables in different land-use types

Dependent variable	**Predictor**	**R^2**	**Adjusted R^2**	**S.E^a**	**F**	**Sig**	**Summary**	**Land-use type**
TN	Silt, Clay,**	0.10	0.76	0.29	4.27	0.0010	F (5,193) = 4.27 *p*< 0.0005	All land-use types
	SOC, P$^{\#\#}$,	0.95*	0.94	0.01	92.96	0.0000	F (7, 36) = 92.96 *p*< 0.0005	Forest
	Elevation,	0.10	0.62	0.31	2.70	0.016	F(6, 148) = 2.70 *p* <0.0005	Cultivated
	Sand, pH**	0.28	0.14	0.03	1.99	0.0830	F (7, 36) = 1.99 *p*< 0.0005	High AFS cocoa
		0.26	0.16	0.03	2.59	0.0225	F (7, 52) = 2.59 *p*< 0.0005	Medium AFS cocoa
		0.17	0.05	0.02	1.45	0.2164	F(6, 44) = 1.45 *p*< 0.0005	FS Cocoa
SOC	Silt$^{\#\#}$, Clay**	0.35	0.33	0.35	20.37	0.0000	F (5,193) = 20.37 *p*< 0.0005	All land-use types
	TN**, P$^{\#}$	0.76*	0.71	0.09	15.89	0.0000	F (7,36) = 15.89 *p*< 0.0005	Forest
	Elevation	0.29	0.26	0.39	10.04	0.0000	F(6, 148) = 10.04 p < 0.0005	Cultivated
	Sand, pH	0.48	0.38	0.38	4.72	0.0008	F (7,36) = 4.72 *p*< 0.0005	High AFS cocoa
		0.32	0.23	0.36	3.55	0.0034	F (7, 52) = 3.55 *p*< 0.0005	Medium AFS cocoa
		0.32	0.23	0.44	3.46	0.0069	F(6, 44) = 3.46 p< 0.0005	FS Cocoa
P	Silt*, Clay,	0.12	0.10	11.29	5.47	0.0000	F (5,193) = 5.47 *p*< 0.0005	All land-use types
	TN**, SOC,$^{\#}$	0.87*	0.84	1.69	34.34	0.0000	F (7, 36) = 34.34 *p*< 0.0005	Forest
	Elevation,	0.05	0.008	12.04	1.25	0.3016	F (6, 148) = 1.25 *P*<0.0005	Cultivated
	Sand$^{\#}$, pH	0.06	-0.12	12.49	0.34	0.9262	F (7, 36) = 0.35 p< 0.0005	High Shade AFS cocoa
		0.06	-0.07	11.75	0.47	0.8525	F (7, 52) = 0.47 *p*< 0.0005	Medium Shade AFS cocoa
		0.30	0.21	11.82	3.16	0.0115	F(6, 44) = 3.16 p< 0.0005	FS Cocoa

[a] Standard error of the estimate. *High degree of correlation. Order of contributions to explanation of variability in TN in forest category (** Clay =49.92%, **pH=49.96%, $^{\#}$SOC=19.2% and $^{\#\#}$P= 27.6%). Order of contributions to explanation of variability in SOC in forest category (** Clay =95%, **TN=89.8%, $^{\#}$P=14.1% and $^{\#\#}$Silt= 41.3%). Order of contributions to explanation of variability in P in forest category (** TN =68.7%, $^{\#}$Silt=34.5%, $^{\#}$SOC=7.5% and $^{\#\#}$Sand= 22.3%).

A few studies reported similar strong relationships among SOC, TN, clay and pH (Wang et al. 2009; Liu et al. 2013) under mixed land use. We further observed consistent strong correlation between SOC and TN, SOC and clay, and TN and pH regardless of land-use type. This can explain the importance of clay and pH with respect to N fixation, decomposition and accumulation of litter biomass (Wang et al. 2009), which largely influenced distribution and levels SOC and TN.

4.3.6 Geostatistical analysis

4.3.4.1 Semi-variogram

In the autocorrelation analysis, the average variance between SOC, TN and P sampling locations were calculated at a defined rate of change of distance from each other (lag interval). The spatial structure statistics showed varying degrees of spatial dependency between SOC, TN and P across the landscape as well as each land-use type (Table 4.4). The type of land use also influenced the best-fitted theoretical model for each soil parameter using the highest R^2 value and the smallest reduced sum of squares (RSS).

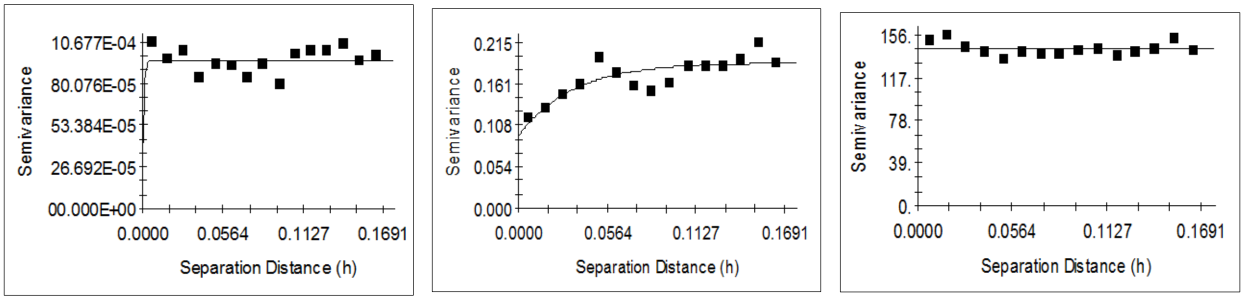
Table 4.4. Spatial structure parameters SOC, TN and P at the landscape level and within each land-use types

Soil variable	**Best fitted model****	**Spatial structure statistics**					**Spatial dependence (SD)[b]**	**Land-use types**
		Nugget [C_O]	**Sill [C_O+C][c]**	**Nugget/Sill ratio [%][a]**	**R^2**	**RSS**		
TN	Gaussian	0.0004	0.0010	41.05	0.16	9.18E-08	Moderate	All land-use types
SOC	Exponential	0.0941	0.1892	49.74	0.69	3.19E-03	Moderate	
P	Linear	143.17	143.17	100.00	0.00	536	Weak	
TN	Gaussian	0.0000	0.0003	3.57	0.62	5.17E-08	Strong	Forest
SOC	Gaussian	0.0004	0.0143	2.58	0.57	1.15E-08	Strong	
P	Gaussian	3.1800	15.7200	20.23	0.67	81.9	Strong	
TN	Gaussian	0.0007	0.0054	13.78	0.57	6.16E-07	Strong	High Agroforest
SOC	Gaussian	0.0386	0.2332	16.55	0.58	0.0309	Strong	
P	Gaussian	38.2	91.400	41.79	0.36	5207	Moderate	
TN	Exponential	0.0001	0.0011	10.91	0.02	8.50E-07	Strong	Medium Agroforest
SOC	Exponential	0.0001	0.1762	0.06	0.56	9.33E-03	Strong	
P	Linear	134.3316	134.3316	100.00	0.42	11689	Weak	
TN	Exponential	0.0004	0.0023	17.52	0.38	4.30E-07	Strong	Fullsun
SOC	Spherical	0.1247	0.3944	31.62	0.67	0.0217	Moderate	
P	Exponential	12.4	122.9000	10.09	0.12	6526	Strong	

[a] Nugget /sill ratio (%) = ([CO /[CO+C]) x 100. [b] SD classes derived based on (Cambardella et al. 1994). SD is categorized as strong (<25%), moderate (25%-75%, and weak (>75%). **Models are all isotropic. [c] Total semi-variance (sill)

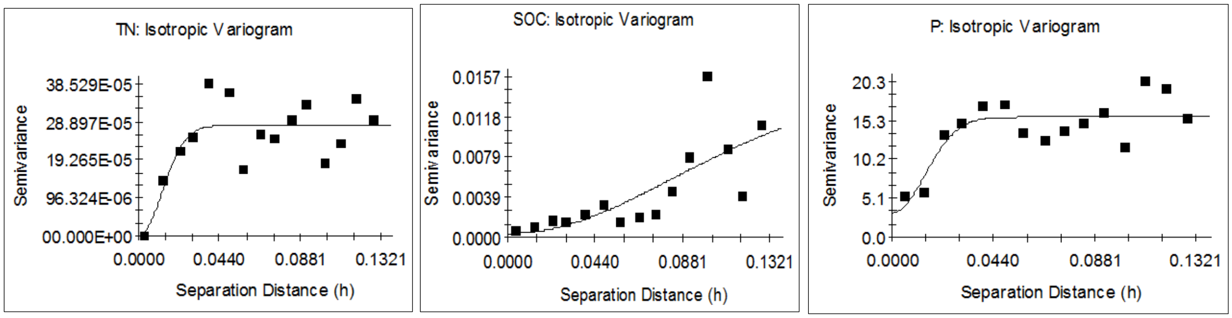
Nugget statistics, which explain levels of experimental error, i.e. field variation within a minimum sampling space, were mostly low and wide-ranging for TN (4E-03 to 7E-03) and SOC (4E-03 to 0.12) both at the landscape level and in specific land-use types except for P, which usually showed high values (3.2 to 143.2). The total spatial variation soil of parameters is captured by the sill values (Figure 4.3). Both at the landscape level and within each land-use type, the sill values for TN and SOC tended to be small, unlike P that showed consistently high values.

All land-use types

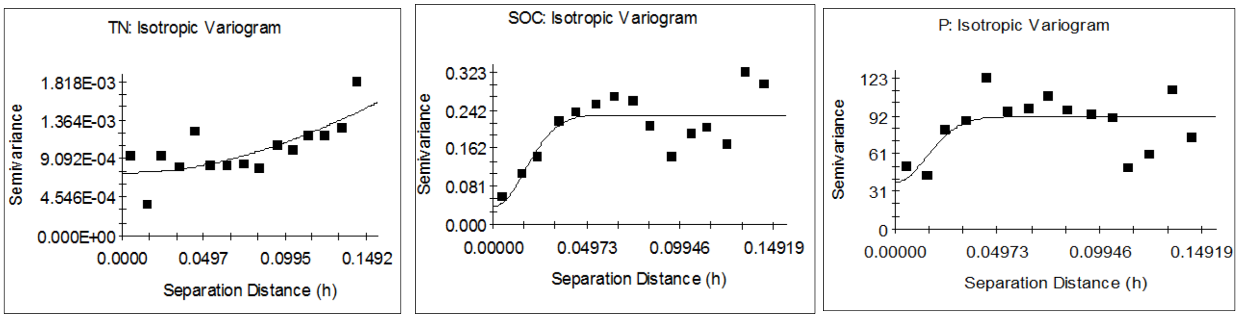


TN SOC N

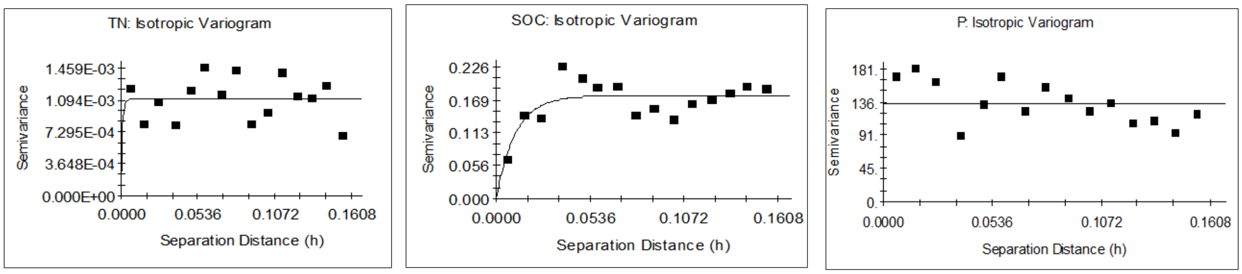
Forest



High Agroforest cocoa



Medium Agroforest cocoa



Fullsun cocoa

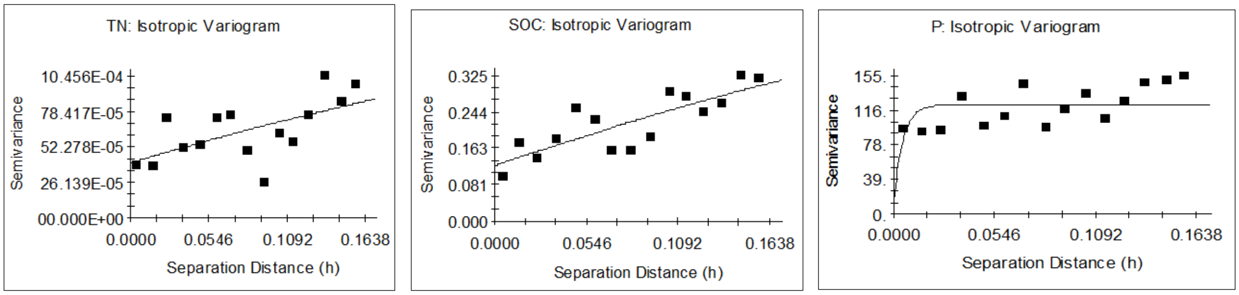


Figure 4.3. Semi-variogram of SOC, TN and P at landscape level and under different land-use types

4.3.5 Spatial interpolation

Surface raster maps from the ordinary kriging interpolation show the distribution of SOC, TN and P within forest and the cocoa areas (Figure 4.4). Most of the remaining forest was within the boundaries of the Krokorsua Hills, and Bosam Bepo and Muro reserves as against the cocoa areas, which largely occurred outside the reserves. The TN content was characteristically low, and distribution followed an irregular spatial pattern defined by neither land use nor topography. This could be the effect of the sparingly applied low-N fertilizer in the cocoa fields.

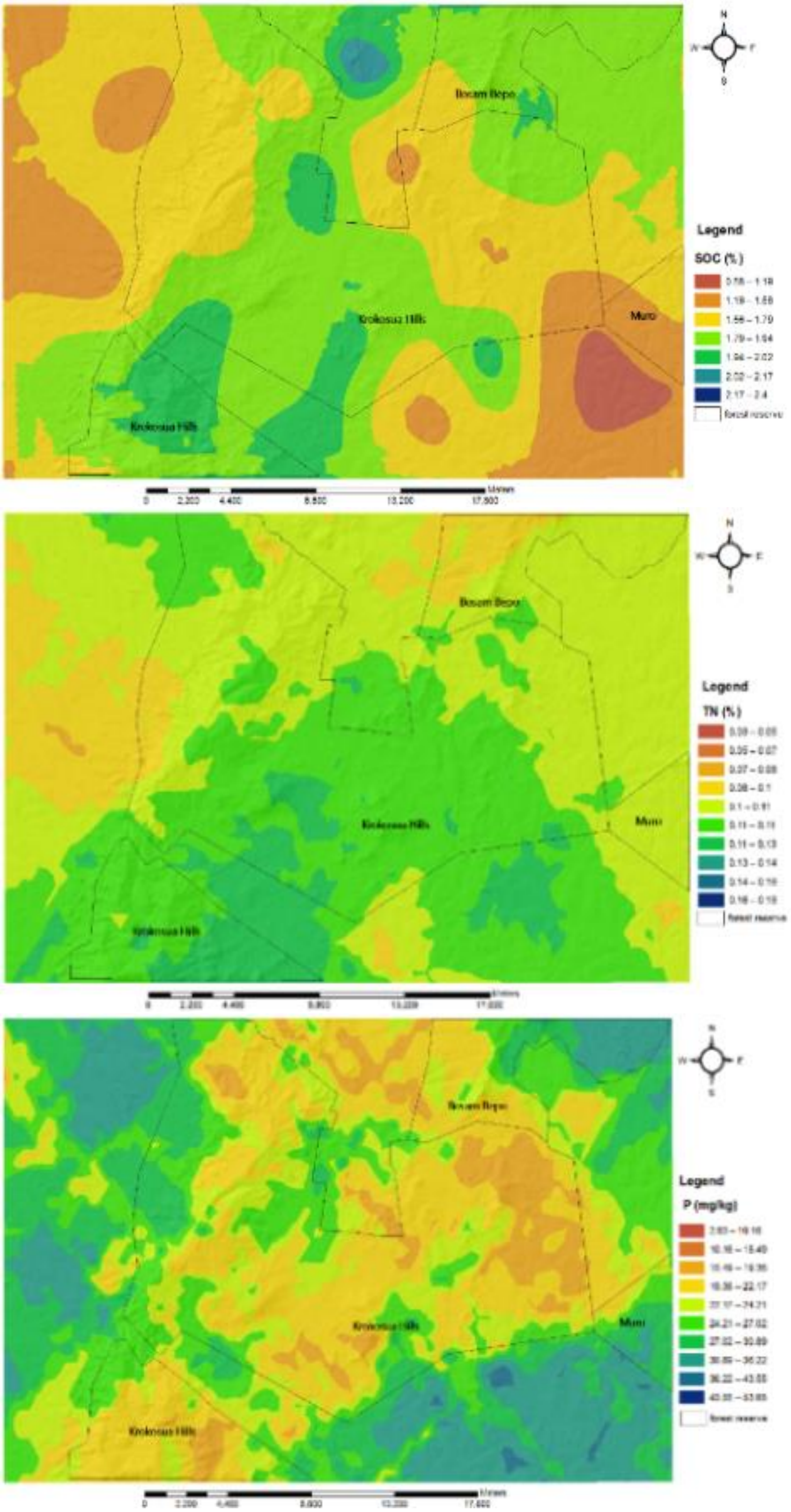


Figure 4.4. Spatial pattern of soil SOC, TN, and P in forest and cocoa areas at the landscape level

4.3.6 GIS Analysis of soil carbon, total nitrogen and phosphorous stocks

The raster maps from the GIS analysis reveal the degree to which different land-use types influence the spatial patterns of soil carbon stocks (SCS), TN and P stocks (Figure 4.5). The TN stocks values differed marginally among land-use types. Cultivated areas mostly showed slightly higher TN stocks (>1.99 Mg/Ha) compared to FR and OF. In the cultivated areas, TN stocks in AFS-cocoa (>2.06 Mg/ha) and oil palm were the highest followed by FS cocoa. FR and open-forest soils had higher SCS (>32.08 to < 34.98 Mg/Ha) than the cultivated fields, which showed relatively lower SCS values (<32.07Mg/Ha).

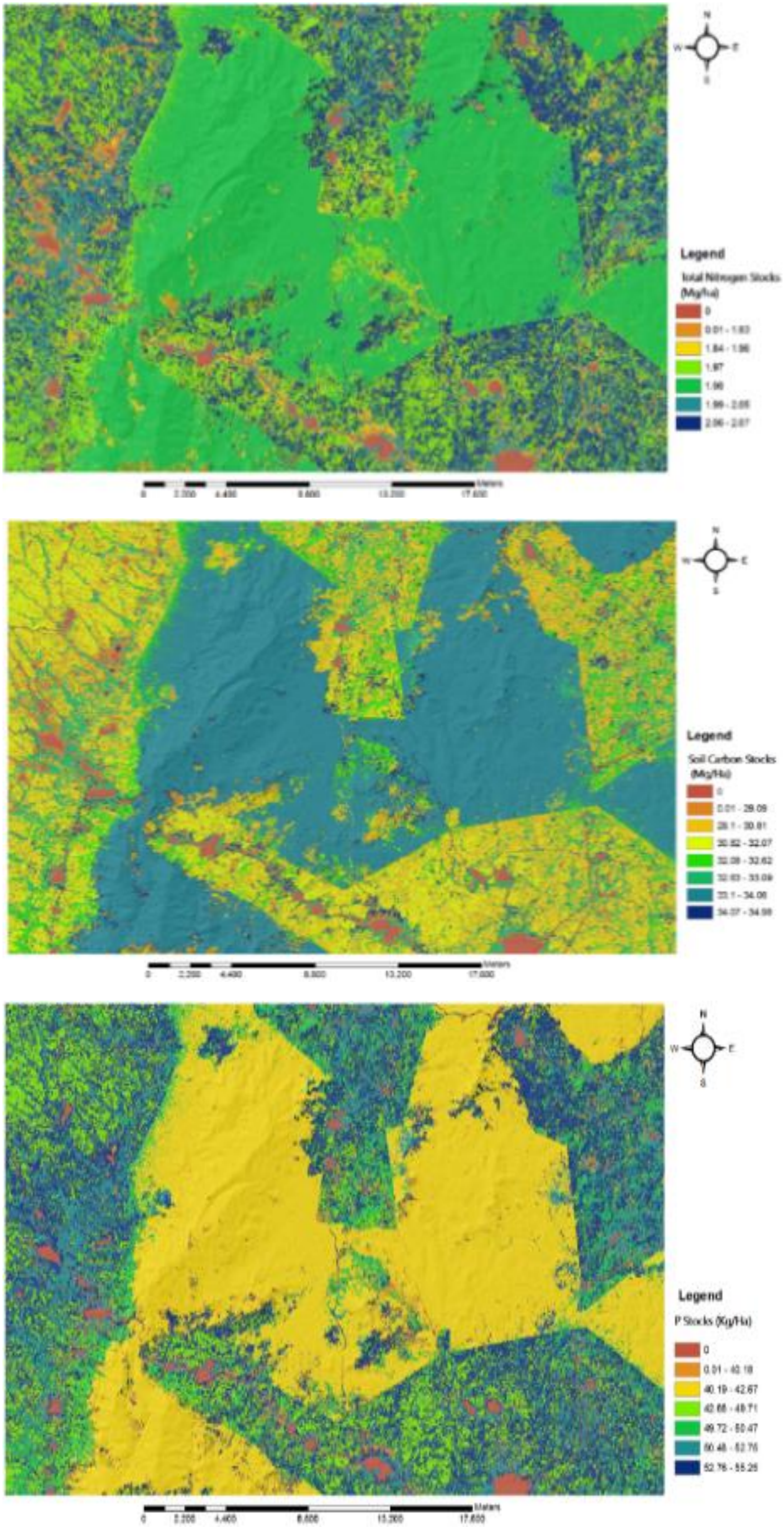


Figure 4.5. Spatial distribution of soil carbon, nitrogen and phosphorous stocks in different land-use types

4.4 Discussions

4.4.4 Distribution of soil properties

The natural variability of soil properties can be influenced by their spatial distribution. In the following, the farm management effects on the measured soil properties are highlighted. Given that the soils in the study area are mainly Oxisol (Ghana Statistical Service 2014) and Ochrosol (Anim-Kwapong & Frimpong 2004) corresponding to Acrisols on underlying Birimian parent rock, it is possible that the parent material had only little influence on the soil characteristics. On the contrary, the farm management practices, which include weeding, burning of farm residues or decomposition of farm residues, fertilizer application, and tree management could influence the availability and mineralization of plant material, and thus could determine soil chemical and physical properties. Our finding confirms the results of Hebb et al. (2017) showing that the conversion of native land-use is likely to lead to high BD due to changes in the soil structure.

In terms of overall heterogeneity of the soil variables, the variability indices of SOC, TN, and P were 25%, 29%, and 46%, respectively, at the landscape scale although the trend did not differ much for individual land-use types. Overall, pH and BD showed the lowest coefficient of variation compared to the other variables in all land-use types. Comparable findings of less variable pH are reported in Roger et al. (2014) and Sun et al. (2003). In this study, a decreasing order of mean SOC and TN from FR > high-AFS cocoa > medium-AFS cocoa to FS-cocoa was observed. In contrast, mean P declined in the order medium-AFS cocoa > high-AFS cocoa > FS cocoa > forest. Independent sample t-test analysis showed similarities between means of TN in forest, agroforest cocoa and fullsun cocoa ($p > 0.05$). However, SOC and P in forest were higher than the average of AFS and FS-cocoa ($p < 0.05$), with no statistically significant difference between AFS and FS-cocoa ($p > 0.05$).

The relatively high variation of SOC and P in forest soils compared to cocoa areas (medium-AFS cocoa > high-AFS cocoa) suggest scope for farmers to purposely select sites for conversion. The reduction in SOC in cocoa areas relative to forest is likely due to the combined effects of a more sandy soil texture, reduced litter fall and root system turnover (Tornquist et al. 2009). In contrast, the significantly higher P in cultivated areas may be because of the effects of fertilizer application, which is increasingly becoming a common practice among cocoa farmers due to government subsidies (Asare et al. 2016). Actually, most soils in the high forest zone are limited in P, hence most cocoa fertilizers are rich in P (Asare et al. 2016).

4.4.5 Statistical relationships among soil properties

Studies by Liu et al. (2013) and Gami et al. (2009) also looked at interactions among SOC, TN, P and soil texture, and reported similar statistically significant associations to the findings in this study. However, the strongly positive and statistically significant correlation between SOC and clay consistently stand out. They agree with results for Sumatra (Noordwijk et al. 1998; McLauchlan 2006). Given the higher clay content of forest soils, a higher SOC content is to be expected than for other land-use types even in the absence of direct land-use effects on SOC. McGrath & Zhang (2003) reported a significant correlation between SOC and elevation and further suggested that the typical high precipitation at high elevations creates suitable conditions for accumulation of humus and SOC. Phosphorous significantly correlated with sand, clay and silt content even though the strength of the associations are weak. Notably, the results show no significant correlation among topographic variables soil nutrients (TN, SOC and P) in individual land-use types. This is in agreement with Wang et al. (2009), who found a similar significant correlation between TN and P of soils under grasslands. SOC significantly correlated with clay content.

4.4.6 Spatial patterns of soil properties

We derived the spatial level dependency of SOC, N and P based on the class of nugget ratios calculated from nugget semi-variance divided by sill (total semi-variance) and expressed in percentage. Carbardella et al. (1994) categorized nugget ratios into three classes of <25%, between 25% and >75% to denote strong, moderate and weak spatial dependency, respectively. The nugget ratios obtained in this study show moderate spatial dependence for SOC and TN, and weak spatial dependence for P at the landscape scale. The nugget ratio for SOC (2.6%), TN (3.6%), and P (20.2%) showed strongest spatial dependence in forest compared to the cocoa areas. Within the forest, SOC showed a high spatial dependence followed by TN and P.

Both high agroforest cocoa and medium agroforest cocoa exhibited strong spatial dependence for TN and SOC and weak spatial dependence for P. Under FS cocoa, TN and P had strong spatial dependence whereas SOC was moderate. The results suggest that probably the landscape level is not the optimal scale to completely reveal the responsive interaction between SOC, TN and P pattern and dynamic extrinsic factors such parent rock, climate, elevation and vegetation (Roger et al. 2014). We found no conclusive evidence that the spatial distribution of SOC, TN and P followed a consistent pattern controlled by either land-use type or elevation. However, in most forest soils, we observed high SOC ranging from 1.82% to 2.4%. The geographic spread of SOC fits well with locations where there are relatively high elevation levels and forest vegetation along the NE-SW direction of the study area. The P pattern differs from that of SOC. The results show consistently high P values (24.2 to 53.6 mg/kg) across the cultivated areas. We attribute this to the possible effects of fertilizer application to cocoa farms (Asare et al., 2016).

4.5 Conclusions

This study combined traditional statistics, geostatistics and GIS techniques to explore the spatial pattern of soil SOC, TN and P under different land-use types and topography. The traditional statistics reveal unique relationships in the soil and how factors interact differently at the landscape level and within each land-use type. Through geostatistics it was possible to evaluate spatial relationships of soil properties in the sampled locations and to use the results in ordinary kriging interpolation to generate unique surface raster maps for each soil parameter. Furthermore, with GIS we produced maps depicting spatial patterns of SOC, TN and P. The results all confirm the high SOC content in the forest and its strong association with clay, TN and pH irrespective of the scale. Although the spatial pattern of TN did not follow any pattern influenced by land-use type or topography, we found strong interactions between TN and pH that invariably affected its variability in the landscape. The data was also conclusive on high P values in cultivated cocoa areas due to the effect of fertilizer application on the cocoa farms. We found no evidence of influence of topography on the spatial pattern of TN, SOC and P in the cocoa-forest mosaic landscape of the high forest zone of Ghana.

5 INFLUENCE OF AGROFORESTRY SYSTEMS ON SOIL NUTRIENTS AND FERTILITY OF SMALLHOLDER COCOA FARMS

5.1 Introduction

Cocoa agroforestry that maintains higher proportions of non-cocoa trees in a diverse structure is increasingly being viewed as a sustainable land-use practice as it complements the conservation of biodiversity (Alger 1998; Duguma 1998; Parrish et al. 1998; Power and Flecker 1998; Rice and Greenberg 2000; Leakey 2001; Schroth et al. 2004). Whatever the reasons farmers have for planting or retaining trees in the farm, they nearly always fulfill several functions simultaneously (Schroth & Sinclair 2003). Thus, cocoa agroforestry is known to meet ecological and economic objectives (Ruf 2011) as well as providing environmental benefits (Asare & David 2011) such as shade and soil protection to the farm (Leakey & Tchoundjeu 2001).

In Ghana, most cocoa systems have been established as agroforestry systems. But fullsun or monoculture cocoa has gained popularity (Cunningham & Arnold 1962; Boyer 1973; Gockowski & Sonwa 2011) among Ghanaian cocoa farmers. A number of factors account for farmers' decisions to incorporate trees in cocoa systems as agroforest or opt for fullsun systems. These include tree tenure and legislation (Amanor 2005), land tenure (Acheampong et al. 2014), and uncertainty of farmers about the ecological services of non-cocoa trees to cocoa systems (Ruf 2011). Invariably, the choice and level of shade tree incorporation in cocoa farms, has transformed the landscape in Ghana into a mosaic cocoa cropping system.

Ruf (2011) defined a mature complex cocoa agroforest as "a cocoa farm which has more than 15 mature timber trees per hectare (and possibly as many as 60-80, including non-timber trees), usually giant trees more than 15 m tall, which are native to the natural tropical forest." These cocoa agroforests represent a wide range of flora, including fruit trees, shrubs, and other plants, generating at least three levels of canopy storage, one below that of cocoa and, more importantly, one or two above. The fullsun system often has only one level of canopy, i.e. cocoa trees.

In this system, almost all the large natural forest trees have been felled or burned. However, it is worthy to note that the cocoa landscape does not only comprise the complex agroforest and the fullsun system. There are various variations of tree incorporation in the cocoa systems that may include farms with some yam varieties below the cocoa trees and a few plantain and fruit trees, such as avocado, citrus (less than 10) and a few timber and other non-timber species (5-6 trees/ha emerging above the cocoa) isolated in an ocean of more than 1000 cocoa trees per hectare (Ruf 2011; Acheampong et al., 2014; Dawoe et al. 2015). The density of both non-cocoa trees and cocoa trees and the type of trees (species composition of non-cocoa trees) are important, as more trees will produce more litter and different tree species produce different amounts of litter (Hartemink & Donald 2005; Fontes et al. 2014). The amount of litter produced also depends on the age of the cocoa plantation, as older systems have more litter fall (Hartemink & Donald 2005; Dawoe et al., 2010). Considerable amounts of carbon and nutrients are maintained in the soil through litter production of both cocoa and non-cocoa trees (Hartemink & Donald 2005; Dawoe et al., 2010; Fontes et al. 2014). Thus, agroforestry systems, be they complex, simple or fullsun have the potential to infuse litter into soils and hence mineralization and nutrient release.

Agroforests may also reduce soil degradation and increase nutrient availability through litter cycling and nitrogen fixation (Evans & Murray 1953; Cunningham & Arnold 1962; Ahenkorah et al. 1974; Beer et al. 1998; Isaac, Timmer & Quashie- Sam 2007; Ofori-Frimpong et al. 2007). A great part of the knowledge on the fertility of cocoa soils and how shading and agroforestry have influenced the soil nutrients was generated from experimental trials (Ofori-Frimpong et al., 2007; Ahenkorah et al. 1974), whereas studies mostly focused on upper canopy trees, which are frequently described as shade trees (Isaac et al. 2007; Blaser et al. 2017). However, there is an interest in exploring how different levels of tree incorporation in terms of stem numbers and species composition as determined by farmers in various models of agroforestry (complex and simple) and fullsun systems could influence soil nutrients.

After all, fertilizer application in cocoa systems is a recommended practice, but farmers do not often apply fertilizers on their farms (Isaac et al. 2007) due to a combination of factors such as cost, access and availability. Thus, non-cocoa trees in cocoa-based farms serve as a major source of organic material inputs to the soil and aid in improving soil fertility. It is therefore important to explore how farm level interactions, based on litter incorporation in soils associated with different levels of tree incorporation and species composition in an agroforestry system (complex, simple and fullsun) as well as maturity stage of cocoa farms, could influence soil nutrient parameters, and the possible implications they could hold for cocoa extension support. The study seeks to explore how agroforestry practices in cocoa systems in different phases of cultivation could influence soil properties. The specific objectives of this study are: (a) to determine the extent of soil nutrient variation in cocoa farms at different levels of tree incorporation, (b) to determine the status and variation of soil nutrient in different phases of cocoa cultivation over time, and (c) to determine the extent to which different levels of tree incorporation in different phases of cultivation influence soil nutrient status in cocoa farms.

5.2 Methodology

5.2.1 Experimental design and data collection

Soil samples were collected from November 2015 to February 2016. The landscape was stratified into forest and areas cultivated with cocoa. The areas cultivated with cocoa were further stratified into different agroforestry systems based on the level of tree incorporation in line with the classification of Ruf (2011). These are high cocoa agroforestry systems or complex cocoa agroforestry system, medium agroforestry system or simple cocoa agroforestry system, and fullsun cocoa. Within each cocoa cultivated area, the cocoa farms with different age classes were also identified and grouped into age chronosequence (young and establishment phase, matured and old). These age classes were modified from the age classification of Tondoh et al. (2015) and Isaac et al. (2005). This was done through farmer interviews and farm inspections.

A total of 115 farms were sampled, out of which 36 were fullsun cocoa, 41 were medium shade agroforest and 38 were high shade agroforest cocoa. An equal number of age stratifications was sampled for the medium agroforest cocoa and high agroforest cocoa; however, 16 farms were sampled in the young age class for all the cultivated areas. This was because farmers were mostly not creating new farms, either through rehabilitation or through expansion into new areas. A list of the non-cocoa tree species associated with each of the regimes is presented as supplementary material. At each sampling site, square plots measuring 100 m by 100 m (1 ha) were set up. Six soil samples were taken with a core sampler at the four corners of the plot and at the center for soil chemical analysis and bulk density determination. A total of 199 soil samples were collected from forest (44 samples), HAF (44 samples), MAF (60 samples), and FS (51 samples) at depths 0-15 cm and 15-30 cm. Out of the 44 samples from HAF agroforestry system, 12 samples were taken from young farms, 17 from matured farms and 15 from old farms.

Table 5.1: Definition of agroforestry systems and cocoa cultivation phase

Land-use/agroforestry description	**Legend**	**Definition**
Forest	FR	Undisturbed tropical forest
Fullsun cocoa	FS	Only cocoa trees with no other tree species incorporated. Mostly single canopy
High agroforestry cocoa (complex agroforest)	HAF	Multi strata cocoa system with tree density ranging from 18-28 tree/ha
Medium agroforestry system	MAF	Double strata cocoa with tree density ranging from 5-12 trees/ha
Young farm (establishment stage)	YF	Less than 5 years old
Matured farm	MF	Between 5 to 18 years old
Old	O	More than 18 years old

5.2.2 Laboratory tests

Chemical and physical analyses were conducted on the soils after air drying, grinding, and sieving through a 2-mm sieve. All soil samples were analyzed for SOC, TN, P, pH, and exchangeable K, Ca, Mg and Na as well as for sand, clay and silt fractions. The pH was determined in a 1:2.5 (soil: water) suspension (Page et al. 1982). Particle size distribution was measured by the pipette method (Rowell 1995). The TN was determined by the dry combustion method (Page et al. 1982). SOC was measured using the Walkley-Black method (Nelson & Sommers 1982), while the total P concentration was determined by alkaline digestion followed by molybdenum colorimetry measurement (Murphy &

Riley 1962). Bulk density was determined by the core method (Blake & Hartge 1986). Soil textural classes was determined by the hydrometer method (Allen et al., 1974).

5.2.3 Statistical analysis

Data on soil physical and chemical parameters for two depths (0-15 and 15-30 cm), agroforestry systems and the interactions between age and agroforestry regime were subjected to normality tests. Those that were not normally distributed were subjected to logarithm transformations before conducting two-way analysis of variance using GenStat discovery edition. The means were separated using LSD at 5% significance level.

5.3 Results

5.3.1 Soil physical properties variation in different cocoa agroforestry systems

There was no significant difference in the mean content of sand and silt particles in the farms under FS, MAF, HAF and forests sites ($P < 0.053$; df = 3; F = 2.592 and $P < 0.408$; df = 3; F = 0.969, respectively). However, the soil from the forest had a significantly higher clay content than that under FS, MAF, and HAF. Within FS, MAF and HAF, the was no significant difference in clay content ($P < 0.014$; df = 3; FR = 3.638). On the other hand, soil bulk density was significantly lower in the forest sites than in the cultivated cocoa areas. In the cocoa farms, there was no significant difference in soil bulk density ($P < 0.002$; df = 3; FR = 5.208). In terms of age, sand particle content was marginally significantly different ($P = 0.053$; d = 3; FR = 2.593) between the forest sites and the cultivated areas. There was no significant difference in sand particles among the different cultivated areas.

There was also no significant difference in silt particles among the different agroforestry regimes and between these and the forest sites ($P = 0.157$; df = 3; F = 1.753). Clay particle content on the other hand was significantly higher in the forest sites than in the agroforestry systems ($P = 0.002$; df = 3; F = 5.195), with the agroforestry areas showing no statistically different clay particle content. Soil bulk density at the forest sites was also significantly lower than in the agroforestry areas ($P = 0.01$; df = 3; F = 3.89), with the agroforestry areas showing no significant difference. With regard to the influence of soil depth on soil physical properties, it was observed that sand particles did not show any statistically significant variation (P = 0.424; df = 1; F = 0.642). This was similar to silt (P = 0.476; df = 1; F = 0.511). However, clay content and soil bulk density were significantly higher (P = 0.006; df = 1; F = 7.78 and P = 0.000; df = 1; F = 206.059, respectively) in the lower soil depth (15-30 cm) than in the upper soil layer (0-15 cm) (Table 5.2).

Table 5.2. Soil physical properties variation in forest and cocoa Agroforestry systems

Soil physical property	**Land-use types**			
	FS	**MAF**	**HAF**	**Forest**
Sand %	58.02 ±1.84	57.38±1.92	58.94 ±1.85	13.05±4.87
Silt %	23.21±1.63	23.78±1.70	21.37±1.47	8.85 ±3.22
Clay %	18.76±0.82	18.84±0.85	19.69 ±0.99	11.4±4.46
Bulk density (g/cm^3)	1.38±0.17	1.40±0.02	1.43±0.02	1.27±0.02
	Age of cocoa agroforest			
	Mature	Old	Young	Forest
Sand %	58.40 ±1.80	58.41±1.55	56.71±2.60	44.93±4.87
Silt %	23.10±1.56	21.13±1.26	26.02 ±2.35	28.09±3.22
Clay %	18.50±0.77	20.46 ±0.84	17.27±1.11	26.98±4.46
Bulk density (g/cm^3)	1.40 ±0.01	1.42 ±0.01	1.39±0.02	1.30±0.02
Soil physical property	Depth (cm)			
	0-15	15-30		
Sand %	58.32±1.54	56.61±1.48		
Silt %	23.72±1.21	22.43±1.32		
Clay %	17.10±0.73	20.10±0.78		
Bulk density (g/cm^3)	1.30 ±0.01	1.50±0.01		

5.3.2 Soil chemical properties variation in different cocoa agroforestry systems

The agroforestry systems and forest sites did not show any statistically significant difference in soil pH (P = 0.643; df = 3; F = 0.558), N(P = 0.140; df = 3; F = 1.843), C(P = 0.338; df = 3; F = 1.128), P(P = 0.085; df = 3; F = 2.23), K(P = 0.977; df = 3; F = 0.067), Ca(P = 0.75; df = 3; F = 0.405), Mg(P = 0.397; df = 3; F = 0.992), Na(P = 0.327; df = 3; F = 1.157). With regard to age, soil pH, N, C, P, K, Ca, and Mg, there was no statistically significant difference between the young, matured and old farms or the forest sites (P = 0.387; df = 3; F = 1.015), (P = 0.977; df = 3; F = 0.069), (P = 0.308; df = 3; F = 1.207), (P = 0.082; df = 3; F = 2.257), (P = 0.223; df = 3; F = 1.47), (P = 0.768; df = 3; F = 0.38) (P = 0.432; df = 3; F = 0.92).

However, there was a significant difference in exchangeable sodium (Na) between the matured and young cocoa farms, as well as between the young and old cocoa farms (P = 0.034; df = 3; F = 2.943), but not between matured and old farms or between the agroforestry systems and the forest sites. The comparison of the nutrients between the depth classes showed no significant difference in soil pH, K, and Na between the upper and lower soil depths (P = 0.467; df = 1; 0.532), (P = 0.438; df = 1; F = 0.603), (P = 0.369; df = 1; F = 0.811). However, there was a statistically significant difference between N, C, P, calcium (Ca), and Mg in the upper and lower soil depths (P <0.0001; df 1; F = 15.386), (P = P <0.0001; df = 1; F = 68.574), (P P <0.0001; df = 1; F = 20.666) (P = P <0.0001; df = 1; F = 23.165) (P = P <0.0001; df = 1; F = 14.629) (Table 5.3).

Table 5.3 Variability of soil chemical properties in forest and agro-forestry systems

Soil chemical property	**Land-use types**			
	FS	MAF	HAF	Forest
pH	5.59±0.07	5.47±0.09	5.56±0.07	5.69±0.23
N (%)	0.09±0.00	0.10±0.00	0.10±0.01	0.099±0.01
Organic carbon (%)	1.35 ±0.07	1.38±0.06	1.41 ±0.07	1.67±0.13
P (mg/kg)	22.02 ±1.69	25.71±1.61	24.40 ±1.50	16.00±2.70
EXCH. K (cmol/kg)	0.05±0.00	0.05±0.00	0.05 ±0.00	0.048±0.00
EXCH. Ca (cmol/kg)	6.44±0.57	6.10 ±0.52	6.74±0.54	7.43±1.47
EXCH. Mg (cmol/kg)	1.56 ±0.13)	1.68±0.20	1.49±0.12	2.22±0.73
EXCH. Na (cmol/kg)	0.39 ±0.02	0.36±0.02	0.40 ±0.02	0.35±0.04
Soil chemical property	**Age of cocoa agroforest**			
	Matured	Old	Young	Forest
pH	5.63 ±0.07	5.47±0.08	5.49±0.10	5.69±0.23
N (%)	0.098±0.00	0.096±0.00	0.097±0.01	0.099±0.01
Organic carbon (%)	1.37±0.06	1.36±0.06	1.45±0.08	1.67±0.13
P (mg/kg)	22.44±1.44	24.58±1.45	26.68±2.16	16.00±2.70
EXCH. K (cmol/kg)	0.049 ±0.00	0.048±0.00	0.039±0.00	0.048±0.00
EXCH. Ca (cmol/kg)	6.72 ±0.52	6.19±0.43	6.29±0.83	7.43±1.47
EXCH. Mg (cmol/kg)	1.60±0.17	1.62±0.12	1.44±0.17	2.22±0.73
EXCH. Na (cmol/kg)	0.40±0.02	0.39±0.02	0.32±0.01	0.35±0.04
Soil chemical property	**Depth (cm)**			
	0-15	15-30		
PH	5.58±0.06	5.51±0.07		
% TOTAL N	0.11±0.00	0.09±0.00		
% ORG. C	1.67±0.04	1.13±0.05		

P (mg/kg)	27.65±1.24	19.81±1.20
EXCH. K (cmol/kg)	0.048±0.00	0.046±0.00
EXCH. Ca (cmol/kg)	7.91±0.49	5.09±0.33
EXCH. Mg (cmol/kg)	1.96±0.13	1.27±0.12
EXCH. Na (cmol/kg)	0.39 ±0.02	0.37±0.01

5.3.3 Soil physical properties variation in cocoa agroforestry and age systems

There was no significant difference in the interaction between the agroforestry systems and age of the cocoa farm on the sand and silt content of the soil (P = 0.13; df = 4; F = 1.812) and (P = 0.569; df = 4; F = 0.734), respectively (Figure 5.1). However, there was a significant difference in the interaction between agroforestry system and age of cocoa farm on the clay content of the soil (P = 0.11; df = 4; F = 3.361). The forest soils and soil under HAF showed a significantly higher clay content than the other age regimes in the different agroforestry systems. Soil bulk density on the other hand, was significantly lower in the forest soils than in the other soils, but there was no significant difference in the soil bulk density under the interaction between agroforestry system and age regime (P = 0.466; df = 4; F = 0.898).

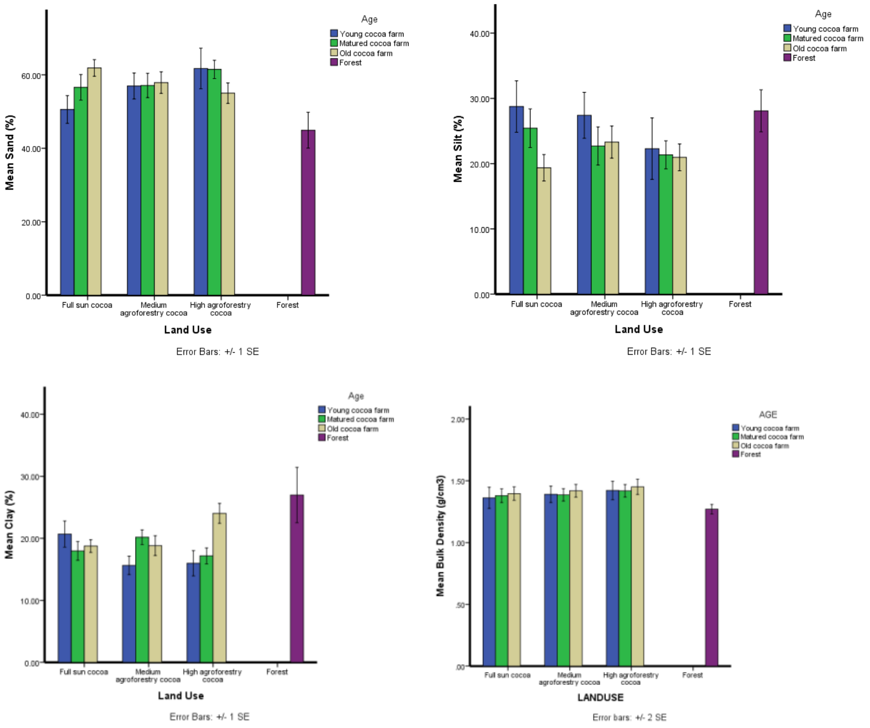


Figure 5.1. Physical properties variation in cocoa agroforestry and age classification systems

5.3.4 Soil chemical properties variation in different cocoa and age systems

The interaction between agroforestry system and age of cocoa farm did not have any significant influence on the pH, total N, organic carbon, total P, and exchangeable K, Mg, and Na (P = 0.984; df = 4; F = 0.095), (P = 0.822; df = 4; F = 0.382), (P = 0.079; df = 4; F = 2.117), (P = 0.175; df = 4; F = 1.602), (P = 0.192; df = 4; F = 1.538), (P = 0.773; df = 4; F = 0.449), (P = 0.337; df = 4; F = 1.143) (Figure 5.2). However, exchangeable Ca was significantly influenced by the agroforestry systems and age interaction (P = 0.005; df = 4; F = 3.82). The results show that Ca content in old cocoa farms under fullsun systems and that of young cocoa farms under MAF was significantly lower than in the other age regimes under the various agroforestry systems or in forests.

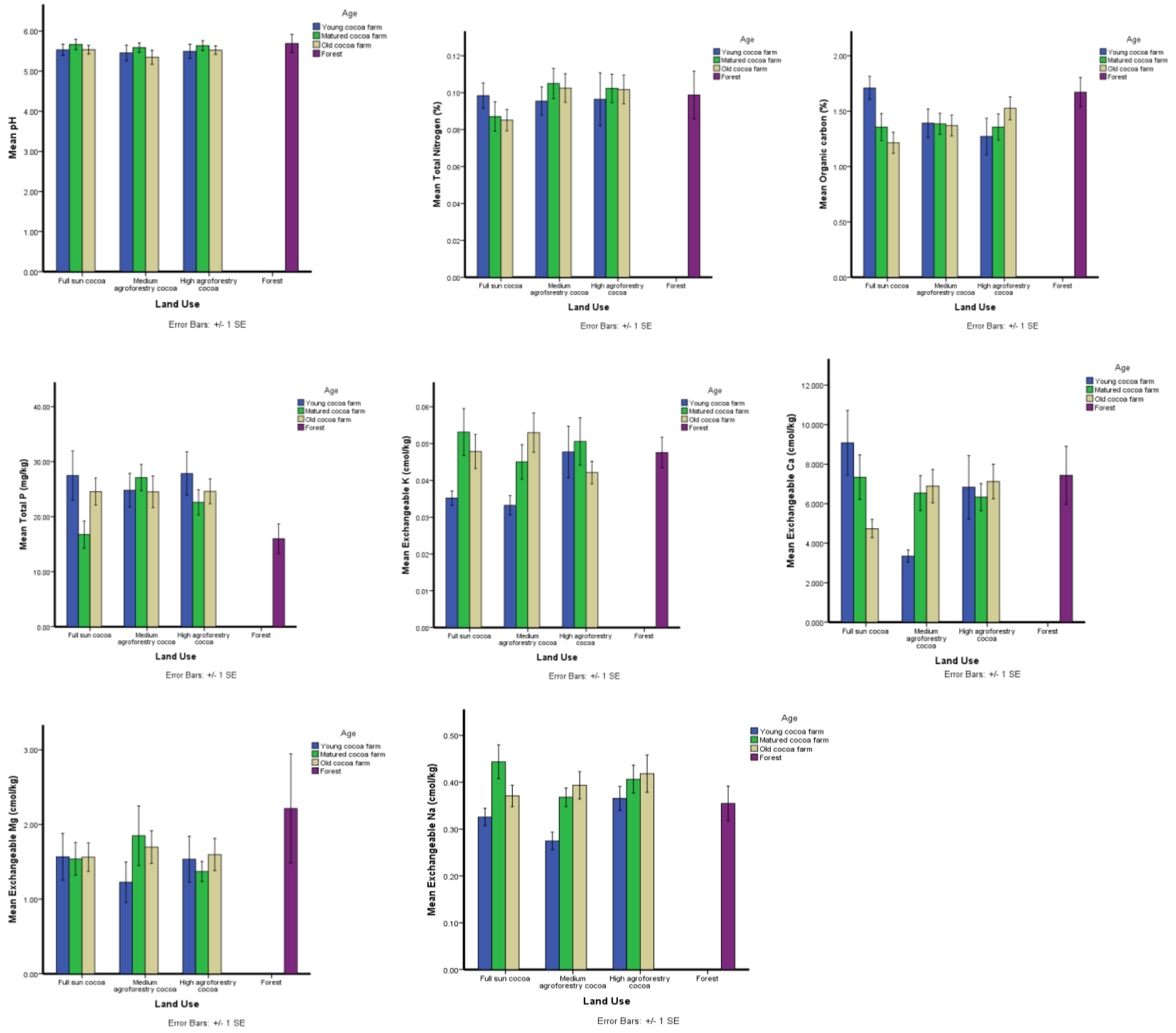


Figure 5.2. Chemical properties variation in different cocoa land-use and age classification systems

5.3.5 Soil physical properties in different cocoa agroforestry system and soil depths

The results showed no significant difference in the relationships between agroforestry system and soil depth on the sand, silt, clay and soil bulk density properties of the soils (P = 0.911; df = 3; F = 0.179), (P = 0.761; df = 3; F = 0.389), (P = 0.664; df = 3; F = 0.528), and (P = 0.595.632; df = 3; F = 0.632), respectively (Figure 5.3).

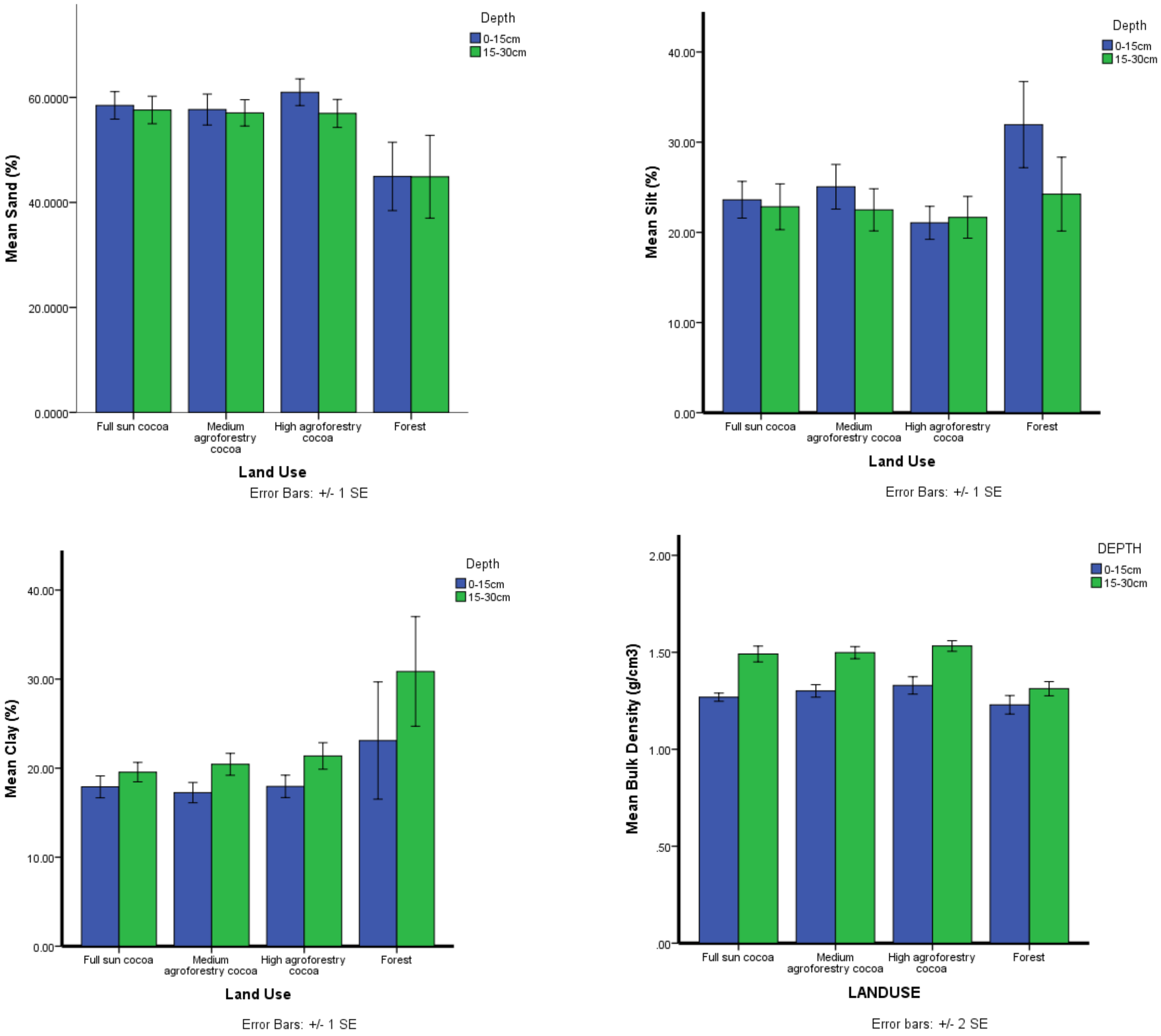


Figure 5.3. Physical properties in different cocoa land-use types and soil depths

5.3.6 Soil chemical properties in different cocoa agroforestry and soil depths

There was no significant difference in the influence of the interaction between agroforestry system and soil depth on soil pH, TN, SOC, total P, and exchangeable K, Ca, Mg, and Na (P = 0.701; df = 3; F = 0.473), (P = 0.986; df = 3; F = 0.48), (P = 0.576; df = 3; F = 0.662), (P = 0.947; df = 3; F = 0.122), (P =

0.557; df = 3; F = 0.693), (P = 0.969; df = 3; F = 0.083), (P = 0.13; df = 3; F = 1.903), and (P = 0.804; df = 3; F = 0.329), respectively (Figure 5.4).

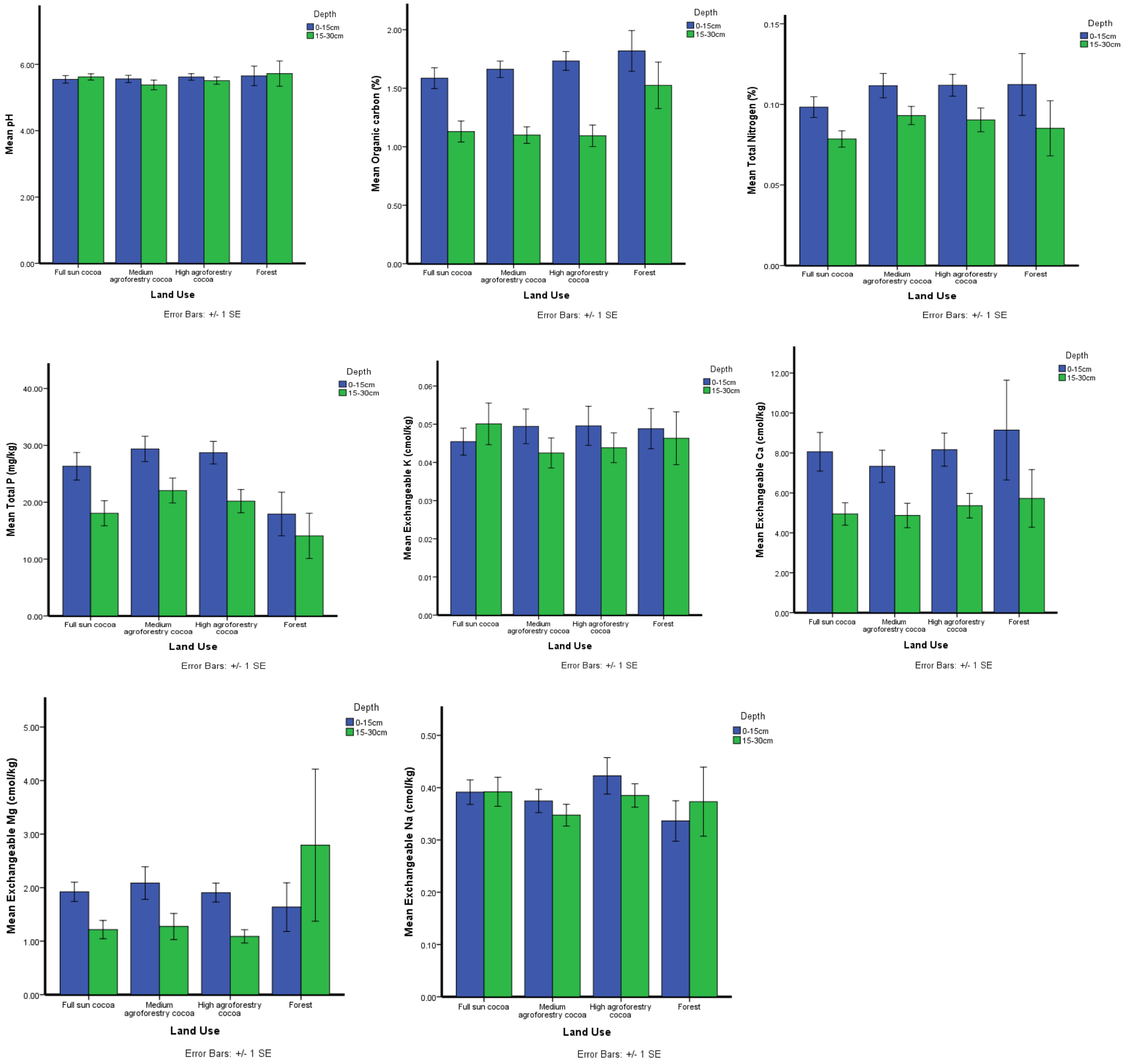


Figure 5.4. Chemical properties in different cocoa land-use types and soil depths

5.3.7 Soil physical properties variation in different aged cocoa agroforestry and soil depths

There was no significant difference in the influence of the interaction between different aged agroforestry system and soil depth on the sand, silt, clay and soil bulk density of the soils (P = 0.847;

df = 3; F = 0.269), (P = 0.823; df = 3; F = 0.303), (P = 0.569; df = 3; F = 0.673), (P = 0.587; df = 3; F = 0.645), respectively (Figure 5.5).

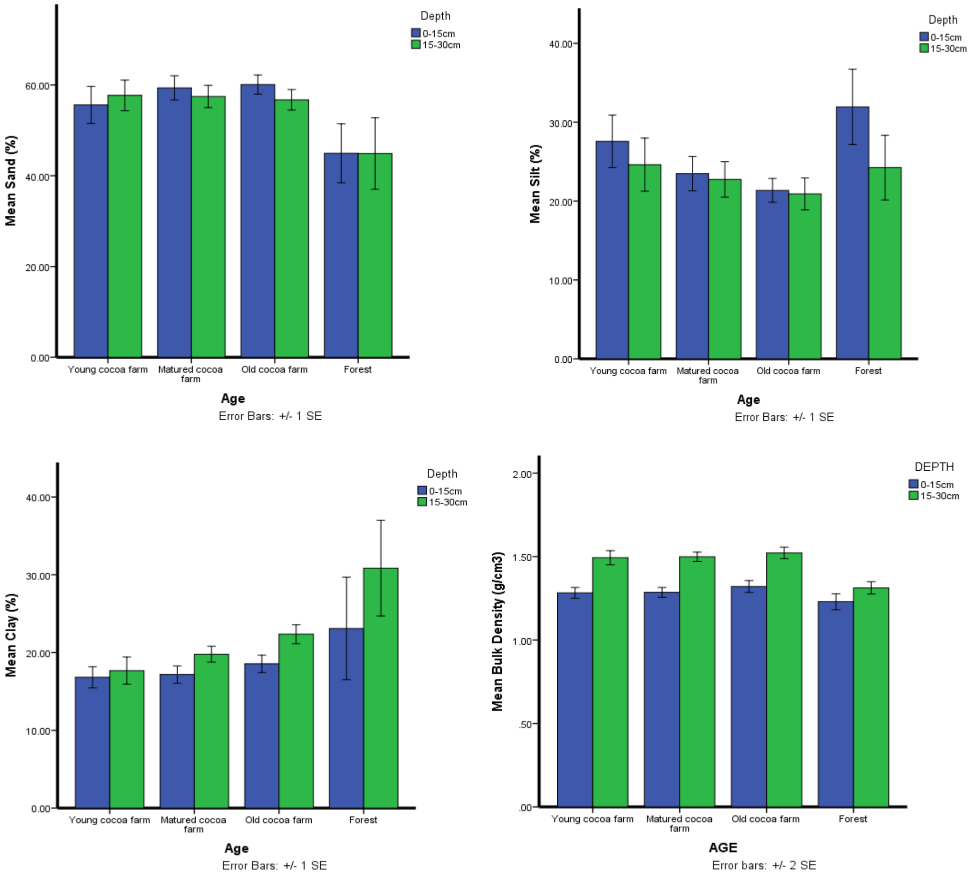


Figure 5.5: Physical properties variation in different-aged cocoa and soil depths

5.3.8 Soil chemical properties variation in different aged cocoa agroforestry systems and soil depth classification

The results showed no significant difference between the various agroforestry aged system and soil depth on soil pH, TN, SOC, total P, and exchangeable K, Ca, Mg, and Na (P = 0.565; df = 3; F = 0.681), (P = 0.957; df = 3; F = 0.105), (P = 0.737; df = 3; F = 0.423), (P = 0.952; df = 3; F = 0.114), (P = 0.888; df = 3; F = 0.212), (P = 0.950; df = 3; F = 0.116), (P = 0.067; df = 3; F = 2.414), (P = 0.868; df = 3; F = 0.241), respectively (Figure 5.6).

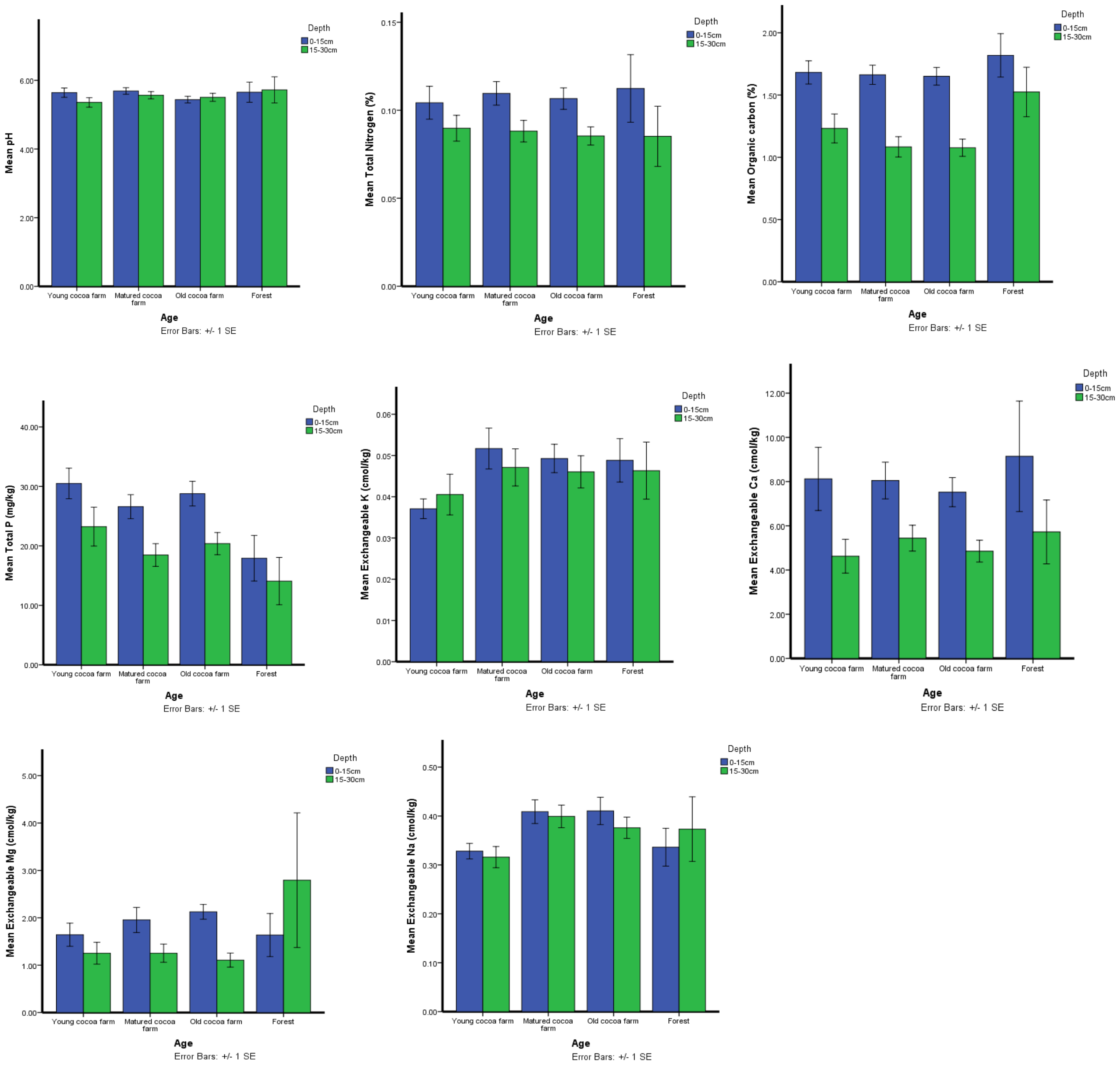


Figure 5.6 Chemical properties variation in different-aged cocoa and soil depths

5.3.9 Soil physical properties variation in different aged cocoa, soil depths and land-use

There was no significant difference in the influence of the interaction between agroforestry system, age of cocoa and soil depth on the sand, silt, clay and soil bulk density of the soils (P = 0.711; df = 13; F = 0.751), (P = 0.974; df = 13; F = 0.383), (P = 0.106; df = 13; F = 1.536), and (P = 0.865; df = 13; F = 0.584) respectively (Figure 5.7).

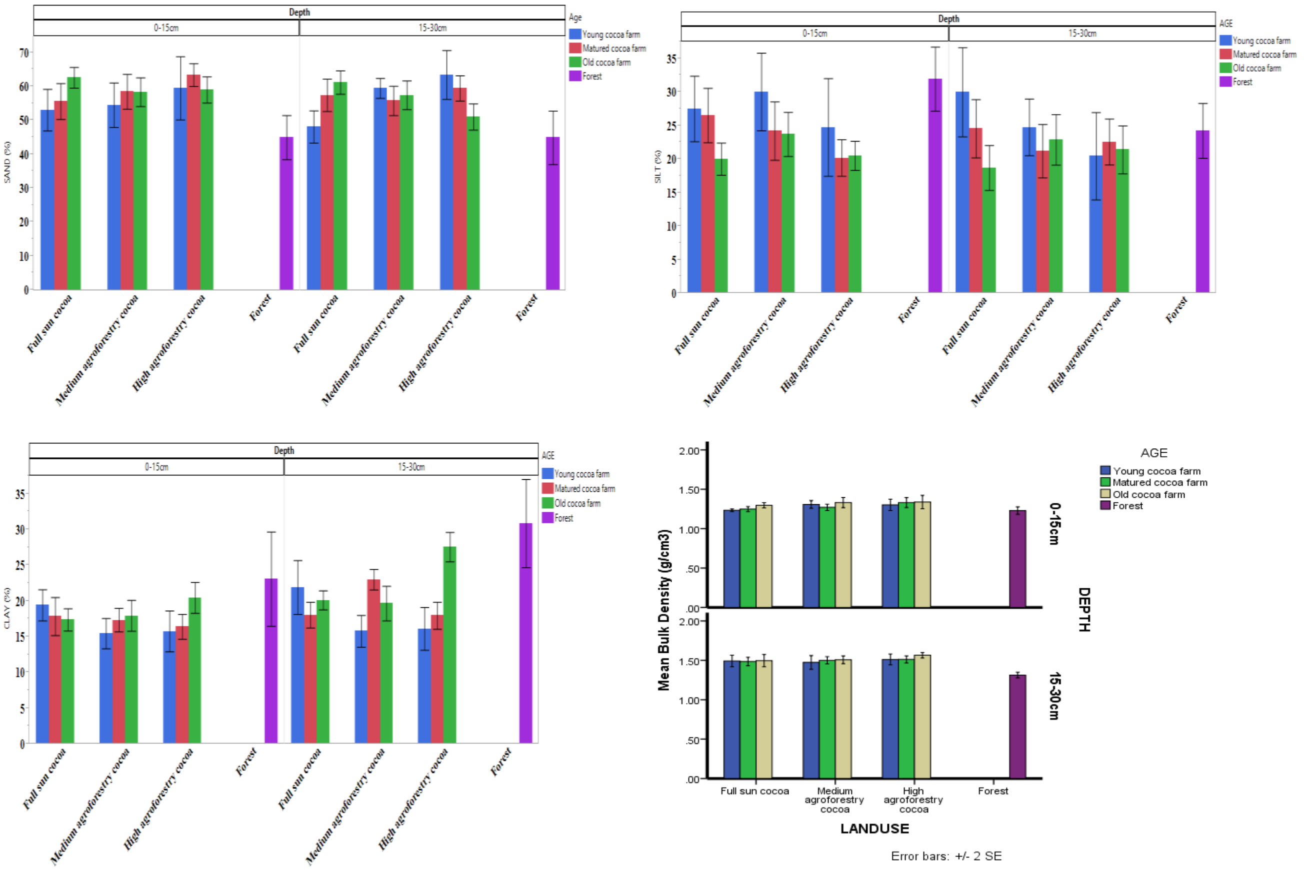
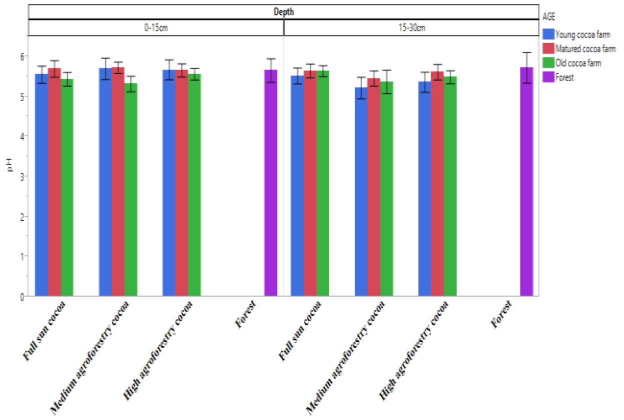
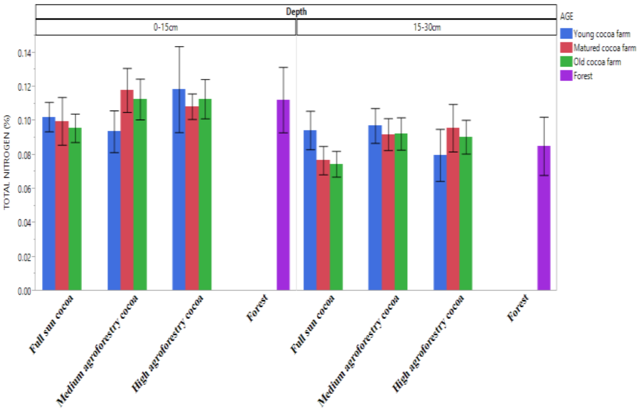


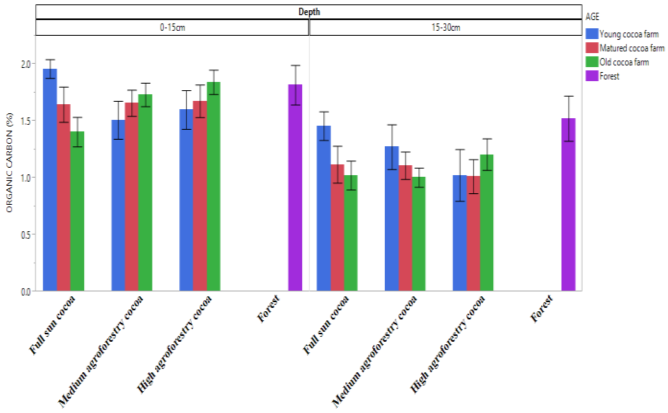
Figure 5.7. Physical properties variation in different-aged cocoa, soil depth and land-use classification

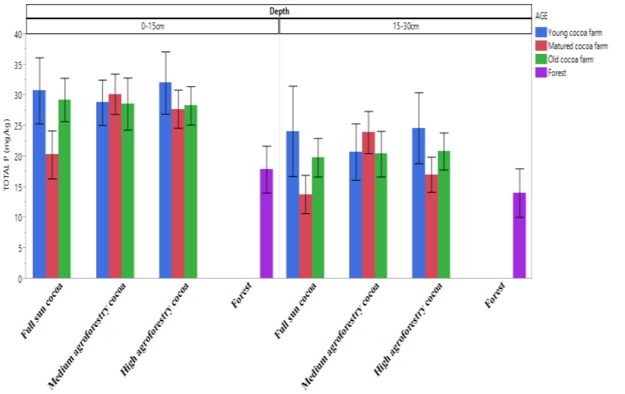
5.3.10 Soil chemical properties variation in different-aged cocoa, soil depth and land-use

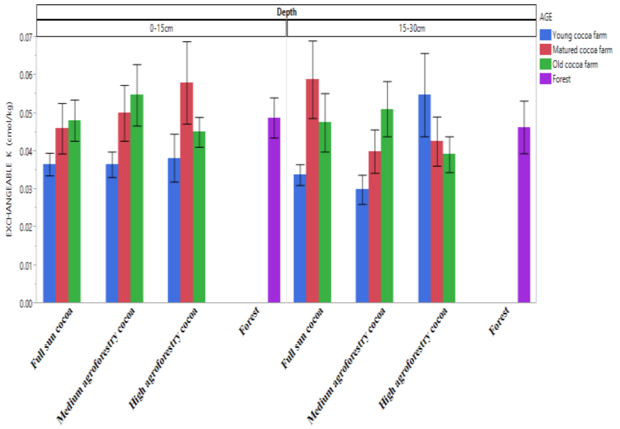
There was no significant difference in the influence of the interaction between agroforestry system and soil depth on soil pH, TN, SOC, total P, and exchangeable K, Ca, Mg, and Na (P = 0.99; df = 13; F = 0.314), (P = 0.989; df = 13; F = 0.317), (P = 0.321; df = 13; F = 1.147), (P = 0.879; df = 13; F = 0.566), (P = 0.461; df = 13; F = 0.991), (P = 0.116; df = 13; F = 1.508), (P = 0.537; df = 13; F = 0.916), and (P = 0.929; df = 13; F = 0.489), respectively (Figure 5.8).

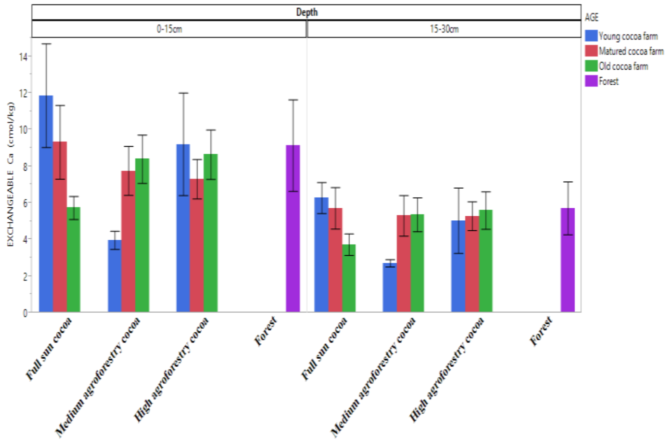

Depth
0-15cm
15-30cm
AGE
Young cocoa farm
Matured cocoa farm
Old cocoa farm
Forest
pH
0
1
2
3
4
5
6
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest


Depth
0-15cm
15-30cm
AGE
Young cocoa farm
Matured cocoa farm
Old cocoa farm
Forest
TOTAL NITROGEN (%)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest


Depth
0-15cm
15-30cm
AGE
Young cocoa farm
Matured cocoa farm
Old cocoa farm
Forest
ORGANIC CARBON (%)
0.0
0.5
1.0
1.5
2.0
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest


Depth
0-15cm
15-30cm
AGE
Young cocoa farm
Matured cocoa farm
Old cocoa farm
Forest
TOTAL P (mg/kg)
0
5
10
15
20
25
30
35
40
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest


Depth
0-15cm
15-30cm
AGE
Young cocoa farm
Matured cocoa farm
Old cocoa farm
Forest
EXCHANGEABLE K (cmol/kg)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest


Depth
0-15cm
15-30cm
AGE
Young cocoa farm
Matured cocoa farm
Old cocoa farm
Forest
EXCHANGEABLE Ca (cmol/kg)
0
2
4
6
8
10
12
14
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest
Full sun cocoa
Medium agroforestry cocoa
High agroforestry cocoa
Forest

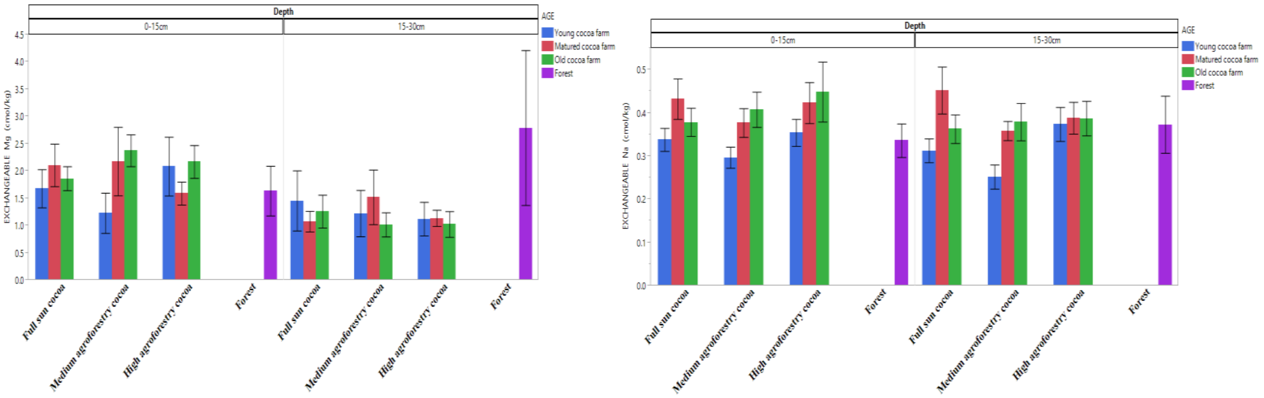


Figure 5.8. Chemical properties variation in different aged cocoa land-use types and soil depths

5.4 Discussions

5.4.1 Extent of variation in soil nutrients and physical properties on cocoa farms with different levels of tree incorporation

A major underpinning of this study is the fact that cocoa agroforestry as practiced by farmers where individual, isolated non-cocoa trees are planted randomly in varying densities should be able to provide soil fertility and soil physical benefits, especially those farms with higher densities of non-cocoa trees. Most studies that found linkages between soil fertility and shade trees did so at the tree level (Isaac et al 2007; Blaser et al. 2017), even though Blaser et al. (2017) demonstrated that tree level benefits of non-cocoa trees cannot be used to accurately estimate the magnitude of the collective effect of larger numbers of these trees at the plot scale, which more closely represents the scale at which farmers implement and manage their agroforest.

There is also farmer perception that the hybrid cocoa variety is incompatible with shade (Ruf 2011) and other forest governance issues, which has resulted in the dominance of non-timber species over timber species in most cocoa farms (Acheampong et al. 2014; Dawoe et al. 2015). Thus, most cocoa farms in the western cocoa landscape of Ghana do not necessarily exhibit the kind of agroforestry description that could relate to canopy structure, and hence shade provision, as has been outlined in studies such as by Blaser et al. (2017). However, they have many non-cocoa trees such as *Newbouldia laevis*, fruits and foods (Sonwa et al. 2014), which have been deliberately incorporated into the farms and sometimes exceed 20 stems per hectare (Acheampong et al. 2014; Dawoe et al.

2015) but provide no shade services to the cocoa farm. It is imperative to also state that the development of soil fertility under simpler, tree-based systems, such as monoculture plantations of tree crops, shaded coffee, and cocoa plantations, has repeatedly been studied, with varying results (Schroth et al. 2001). Isaac et al (2007) observed that soil exchangeable K was increased under *N. laevis*, while available P decreased and TN status was unaffected under all shade treatments. Furthermore, Ofori-Frimpong et al. (2007) observed that exchangeable K contents of soils under the cocoa systems were lower than in the remnant native forest although the differences were not significant. However, at the farm level, this study did not find significant differences in soil fertility parameters between the various agroforestry systems. Soil fertility status was similar for different cocoa agroforestry systems, irrespective of the level of tree incorporation of non-cocoa trees. The findings clearly confirm the observation of Blaser et al. (2017) that non-cocoa trees, be they for shade purposes or other ecosystem and socio-cultural services, do not have beneficial soil fertility implications for cocoa systems.

However, Blaser et al. (2017) demonstrated that individual shade trees can have localized positive effects on some important soil fertility parameters. In particular, SOC and N are higher directly under individual shade trees. However, the authors suggested that localized increases in soil fertility directly under individual shade trees do not necessarily translate into uniform benefits in soil fertility at the plot scale, which in our study is represented by the different farms studied. In particular, higher densities of shade trees did not result in greater improvements in soil fertility at the plot scale. Blaser et al. (2017) further indicated that the difference in the effects of individual shade trees versus shade trees within larger plots is important because cocoa trees in agroforests are not generally grown only directly under individual shade trees, but are instead grown haphazardly with respect to the shade trees in an agroforest. Thus, farm level manifestation of cocoa agroforests in the north-western cocoa landscapes of Ghana does not offer significant soil fertility benefits to the cocoa system. This observation was also confirmed by Asare et al. (2016), where shaded and unshaded plots (cocoa agroforest and fullsun systems) showed no significant differences in soil nutrients.

The findings of this research at the farm level are consistent with those of other studies that find no difference in SOC stocks and other soil nutrients between cocoa agroforests and monocultures (or fullsun cocoa systems) (Gockowski & Sonwa, 2011; Jacobi et al. 2014; Mohammed et al. 2016; Blaser et al 2017) or in coffee systems (Souza et al. 2012; Noponen et al. 2013). One major premise upon which cocoa agroforestry is being promoted is the fact that tree incorporation in cocoa systems could result in improvements in soil nutrient status through the decomposition and mineralization of litter material from the non-cocoa trees, and thus serve as an additional source of nutrients beyond that of the cocoa litter material. This will lead to differences in soil fertility between cocoa agroforests and monocultures, and ultimately limit the need for inorganic fertilizer application for improved yield. However, some studies on cocoa systems suggest that the nutrient balance in many cocoa farms is negative, especially for K (Appiah et al. 1997; Hartemink 2005), which further suggests that shade trees alone are unlikely to be able to sustain sufficient levels of P and K for cocoa production.

Thus, findings from this study point in the direction of the study by Blaser et al. (2017) to suggest that growing cocoa in agroforests is unlikely to completely obviate the need for the addition of inorganic fertilizers. Together, these findings suggest that cocoa agroforestry might ultimately have limited benefits for soil fertility at the level of the cocoa farm. According to Blaser et al. (2017), the absence of clear beneficial effects of shade trees at the plot scale could occur because cocoa is itself a small perennial tree only 5-8 m in height. Cocoa trees are planted in 3 m by 3 m intervals, which amounts to approximately 1111 trees/ha. Given the high number of cocoa trees relative to non-cocoa trees on the farms, and also that the cocoa trees produce substantial amounts of litter, these might, therefore contribute substantially to the formation of soil organic matter regardless of the presence of shade trees. For example, cocoa litter has been shown to increase SOC more than that of intercropped rubber trees (Monroe et al., 2016), and this could also be the case with respect to other shade tree species. Also, the fact that other studies observed soil fertility benefits directly under the non-cocoa trees, but not at the plot level could also be the result of the sampling approach adopted. The sampling protocol adopted in this study ensured that after collecting soil samples at various locations of the farm, these samples were bulked to form a composite sample, and thoroughly mixed before a sub-sample was collected for laboratory analysis.

It is possible that by bulking the samples, more fertile soils (which mostly occur under shade trees) are added to less fertile soils (which mostly occurred under cocoa canopies only). We did not observe significant differences in most soil parameters in the different agroforestry systems. It is possible that cocoa litter material production had an effect on soil aggregates. According to Six et al. (2000; 2004), increased soil aggregation should physically protect soil organic matter, improve nutrient retention, and reduce runoff and erosion, thereby leading to beneficial effects on soil organic matter dynamics and nutrient cycling. It has long been held that upper-story non-cocoa trees could tap nutrients from lower soil depths and make these nutrients available to cocoa through litter decomposition and mineralization. However, the combination of the high litter production of cocoa trees and, to an extent, the sampling approach that was adopted in this study could explain why cocoa agroforestry does not seem to have soil fertility benefits at the farm level though studies have shown significant fertility improvements at the tree level (Blaser et al. 2017; Isaac et al., 2007). Judging from the findings of this research and those of Blaser et al. (2017) as well as Isaac et al. (2007), it is possible that agroforestry's contribution to soil fertility improvements could be that soil fertility benefits could be localized around specific trees on the farm.

5.4.2 Influence of cocoa maturity phases on soil fertility status

Unlike most studies that focused on specific age regimes, our study moved beyond the ages of the cocoa and rather looked at different phases of cocoa maturity, which included the young, mature and old phase. These phases capture different age ranges rather than specific ages, as was in the case of studies by Isaac et al. (2005) and Dawoe (2009). The intention was to gain a very good understanding of the soil fertility issues at various phases of cocoa maturity and how these could inform a better understanding of its implications for cocoa yield. Though we did not find any study that had looked at soil fertility issues at the different phases that also capture the age ranges, the study of Isaac et al. (2005) provides a very good indication of the limited changes in soil bulk density which could be associated with cocoa under different phases of maturity.

This could be due to the fact that cocoa litter could be playing a much more significant role than has been previously observed, as the accumulation and distribution of soil organic matter and its associated nutrients are controlled by residue inputs, decomposition processes and mineralization rates (Isaac et al., 2005). In a study by Dawoe (2009) on cocoa farms of different ages (3, 15 and 30 years), it was observed that soil nutrients were not significantly different among the three age classes and the native forest. This was the case for available P, and exchangeable Ca, K, and Mg. The findings regarding single age regimes of cocoa agree with our findings, which show that when it comes to soil nutrients, the age under cultivation does not play a role. Dechert (2003) and Ahenkorah et al. (1987) observed that there was no appreciable level of Ca and Mg after 20 years of cropping. The lack of differences in soil fertility parameters in different phases of cocoa cultivation could be due to the fact that cocoa leaves could be a major source of nutrients through decomposition. Cocoa farmers mostly apply inorganic fertilizers, although in an unregimented manner because of access and cost issues. It is thus possible that most of the farms had received fertilizer, which could have evened out the effects of possible nutrient differences in various phases of cocoa cultivation.

5.5 Conclusions

Cocoa agroforestry has been considered to play many ecological, environmental and socio-economic roles in farming systems. However, the findings in this study show that at the farm level, irrespective of species composition and number of non-cocoa trees, soil fertility benefits do not depend on whether the farming system under consideration is fullsun cocoa or complex agroforest. Furthermore, though cocoa experiences various phases of cultivation from establishment through maturity to the old stage, and is characterized by various ecological and farm management interventions, soil fertility does not differ. It was hypothesized that the interaction between agroforestry system and cocoa establishment phase could have an implication for the fertility of cocoa cultivation systems. However, the results show that such farm level interactions do not lead to soil fertility benefits.

6 VARIATION IN DENDROMETRIC PARAMETERS, TREE DIVERSITY AND CARBON STOCKS IN COCOA AGROFORESTRY SYSTEMS

6.1 Introduction

Cocoa plantations have been shown to have an incredible carbon storage capacity and rich tree biodiversity (Somarriba et al. 2013; Gbala et al. 2017). Available data on global carbon stocks for cocoa plantations put it within the range of 12 to 228 Mg ha^{-1} (Somarriba et al. 2013), of which the main part is contained in the soils (Mohammed et al. 2016). Unlike soils under cultivated cocoa that have less variability in carbon stocks, a number of farm management factors affect the way aboveground carbon stocks occur in the cocoa plantations. A couple of recent works have pointed out the influence of farm age (Smiley & Kroschel 2017; Somarriba et al. 2013), cultivation system or land-use type (Gbala et al. 2017), and shade tree stem density (Kessler et al. 2012) on carbon stocks distribution. In addition to fixing carbon, non-cocoa trees are known to offer direct ecological and financial benefits to farmers (Kessler et al. 2012).

If non-cocoa trees in cocoa plantations are well managed, they have the potential to deliver multiple productivity, climate and ecological benefits (Kessler et al. 2012; Kongsager et al. 2013). Despite this knowledge, the practice of removing shade trees to make room for high-yielding monoculture cocoa systems has gained popularity in recent times (Ruf 2011). This is evident both in Ghana and Cote D'Ivoire, where 28.1% and 27.9% of smallholder cocoa farms, respectively, are without shade trees leading to loss of carbon stocks and tree diversity (Gockowski & Sonwa 2011). In as much as there has been some understanding on the loss of carbon stocks and tree diversity in the cocoa landscapes of Ghana (Mohammed et al. 2016; Dawoe et al. 2016), there is very little information on the how these parameters vary in cocoa farms in different agroforestry practices. Furthermore, as the cocoa farm evolves through different maturity stages, little is known about the question of which tree species are preferred by farmers to be incorporated in these cocoa systems.

Cocoa farming as it is practiced in Ghana involves various levels of tree incorporation, from simple to multi-strata as well as unshaded systems (Ruf 2011).

As early as the establishment stage, farmers determine which tree species are incorporated, and continue to undertake farm maintenance operations throughout the maturity cycle of the cocoa farm (Asare & Asare, 2008). In Ghana’s REDD+ strategy, special attention has been given to the drivers of cocoa-driven deforestation and to emissions from forest degradation (Forestry Commission 2015). Therefore, understanding carbon stocks dynamics in different cocoa cultivation systems such as cocoa agroforestry and monoculture can provide useful insights into the mechanisms that can be explored to engage farmers in improving cocoa agroforestry and the design of the cocoa REDD+ program in Ghana. The objective of this study is to assess the variability of carbon stocks, tree characteristics, and diversity in smallholder cocoa plantations. This includes estimating the aboveground and soil carbon stocks in shade and cocoa trees, exploring the relationships between tree parameters and carbon storage, and determining the floristic diversity of shade trees.

6.2 Methodology

6.2.1 Field plot design

To understand the dynamics of agroforestry in terms of species diversity and carbon stocks in the context of an existing forest cover type, the study area was located in the cocoa landscape around the Krokorsua Hills Forest Reserve. First, it was divided into quadrants to ensure that the sample plots were adequately represented on the four sides of the reserve. These were labeled as site 1, site 2, site 3 and site 4 with each representing north, east, south and west directions. For each site, the dominant land-use types were stratified into forest and cocoa plantation. The cocoa plantations were divided according to agroforest cocoa and monoculture or fullsun cocoa plots. The agroforest cocoa plots were further categorized by their shade system into high-shade agroforestry cocoa and medium-shade agroforestry cocoa. Both agroforest and fullsun cocoa plots were further grouped according to the age regime (old, matured and young) of the cocoa plantation. In each land-use type, a 100 m x 100 m plot was randomly laid. A total of 112 plots were established with 28 in each of the four sites with four replicates each per agroforestry type and three replicates each per age site except forest (Table 6.1).

Table 6:1: Plot distribution according to land-use type and age on a selected site

Site	Land-use	Age category	Replicates(R)	Total plots
Site 1*	Forest (FR)	-		1
	High Agroforestry cocoa (HAF)	HAF Young	R1, R2, R3	9
		HAF Mature	R1, R2, R3	
		HAF Old	R1, R2, R3	
	Medium Agroforestry cocoa (MAF)	MAF Young	R1, R2, R3	9
		MAF Mature	R1, R2, R3	
		MAF Old	R1, R2, R3	
	Fullsun cocoa (FS)	FS Young	R1, R2, R3	9
		FS Mature	R1, R2, R3	
		FS Old	R1, R2, R3	

* Site 2, site 3 and site 4 have the same plot arrangement

Within every plot, a 25 m x 25 m subplot was randomly demarcated and established. Soil samples were collected at the four corners and centre of the main plot (Figure 6.1).

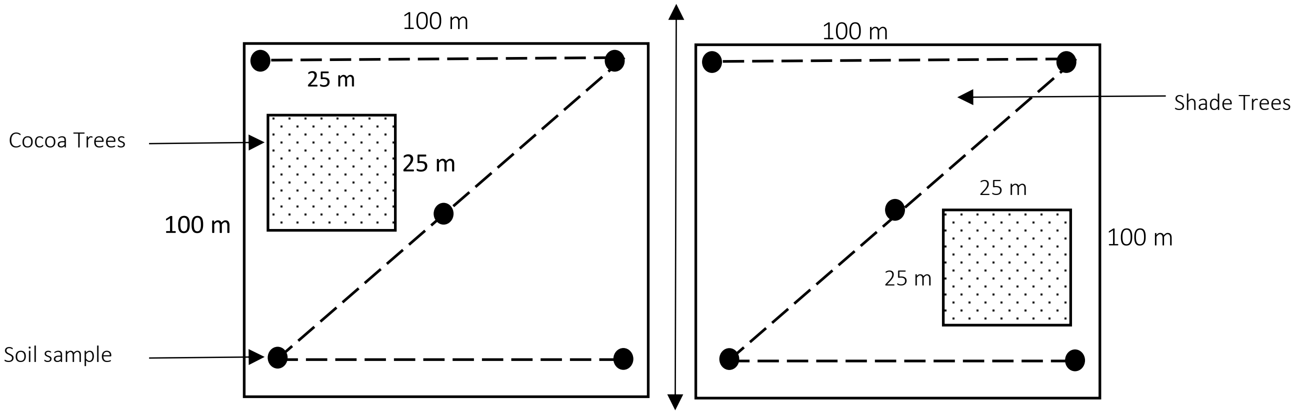


Figure 6.1. Layout of soil sampling plots

6.2.2 Data collection for aboveground carbon stocks for shade and cocoa trees

Plot-level data collection captured physical measurements of non-cocoa trees (on main plots), cocoa trees (on subplots). All shade trees with diameter at breast height (DBH at 1.3 m) of <5 cm were identified with their scientific and local names by an experienced botanist. The tree DBH was measured with a diameter tape and the heights measured with a laser hypsometer (Nikon Laser Hypsometer). The crown area (CA) of each upper canopy tree within the main plot was estimated by measuring the diameter of the crown from eight different directions following the cardinal points and the subdivisions within the cardinal points, i.e. north-south, east-west and then north-west, northeast, south-west and south-east following the approach of Dawoe et al. (2016). The total crown cover (CC) for the shade trees was expressed as a percentage of the main plot. The measured crown area (CA) was used in the calculation of the CC for the shade trees using Equation 6.1:

CC = $(\frac{TCA}{Farm\ Size})/1000$ Equation 6.1

where TCA is the total of CA of all trees per plot.

Within the sub-plot, DBH and height of the cocoa trees were measured using the same technique as for the upper canopy trees. Aboveground biomass (AGB) of upper canopy trees and cocoa trees was derived based on allometric equation for moist forest (Chave et al. 2005) (Equation 6.2)

Biomass (kg) = $\exp -2.977 + \ln(x * z^2 * h)$ Equation 6.2

where x is species specific density, z is DBH, and h is height.

We then applied available specific wood densities of tree species from the World Agroforestry Centre's Wood Density global database (Zanne et al. 2009). The AGB of cocoa and shade trees was converted to carbon stocks by multiplying with the 5 default conversion factor (IPCC 2006). The total aboveground carbon stock for each plot was estimated by summing up aboveground carbon stock figures for cocoa and shade trees.

6.2.3 Soil carbon stocks

Soil samples from the main plot from 0-15 cm and 15-30 cm depths were mixed into a composite sample for nutrient analysis. Representative portions of the composite sample were taken, bagged, and labeled for laboratory analysis. Additional soil samples were collected from the centre of the main plot for bulk density analysis. Chemical and physical analyses were conducted on the samples after air drying, grinding, and sieving through a 2-mm sieve.

They were analysed for SOC, pH, and fraction of sand, clay and silt. The pH was determined in a 1:2.5 (soil: water) suspension (Page et al. 1982). Particle size distribution was measured by the pipette method (Rowell, D 1995). Soil organic carbon was measured using the Walkley-Black method (Nelson & Sommers 1982). Soil textural classes were determined by the hydrometer method (Allen et al., 1974). Soil carbon stock (SCS) was determined using Equation 6.3 (Elbasiouny et al. 2014; Dawoe 2009; Stevens & Van Wesemael 2008; Tornquist et al. 2009).

SCS (Mg ha^{-1}) = $10^4 \times SOC \times h \times (BD \div 100)$ Equation 6.3

where SCS is soil carbon stock (Mg ha^{-1}), SOC is soil organic carbon (%), h is soil depth soil (m), and BD is bulk density (g cm^{-3}). The SCS at both depths were summed up to give the total carbon stock for a specific sample plot. The overall carbon stocks were estimated by adding the total aboveground carbon stocks and the total soil carbon stocks.

6.2.4 Quantifying tree biodiversity

Tree species richness, evenness and abundance in MAF, HAF and forest were calculated using the method described in Dawoe et al. (2016). Shannon-Weiner diversity indices (H', Hmax and J) for trees were calculated based on the formula in Equation 6.4 using PAST statistical software (version 3). After H' has been obtained using Equation 6.4, H max, can be interpreted as the maximum possible value of H', and J' the evenness (H'/H max).

H' = $-\sum_{i=1}^{s}(p_i \, x \ln p_i)$ = $-\sum_{i=1}^{s}(\frac{n_i}{N} \, x \, ln \frac{n_i}{N})$ Equation 6.4

where S is the total number of species in the study area, N is the total number of individuals, and n_i is the number of individuals of the *ith* species, $\frac{n_i}{N}$ is equivalent to p_i, which is the probability of finding the *ith* species.

6.2.5 Statistical analysis of carbon stocks and tree diversity

The Paleontological Statistics Software Package for Education and Data Analysis (PAST) Version 3 (Hammer et al. 2001) was used for the statistical analysis of carbon stocks in cocoa trees, shade trees and soils by land-use and farm age. The measured dendrometric parameters of shade trees (i.e., crown area, height, and stem diameter) were also analyzed. Prior to the statistical analysis, the normality of probability distribution for each parameter was tested using the Shapiro-Wilks technique (Liu et al. 2006; McGrath & Zhang 2003). Non-normal distributed data were log-transformed to meet the normality conditions for additional statistical analysis. Analysis of variance (ANOVA) was applied to test for significance in the means of the variables separated at 5% significance levels. We further performed linear regression to determine the statistical significance of the relationship of (a) carbon stocks and diameter, and carbon stocks and crown cover of shade trees, and (b) total carbon stocks and stem diameter of shade trees.

6.3 Results

6.3.1 Carbon stocks of cocoa agroforestry systems at different stages of maturity

In general, the results obtained in the study show that the total carbon stocks in forest is 23% higher than the carbon content in cocoa plantations. The mean total carbon stocks for forest were 136.84 ± 3.97 Mg ha^{-1} whereas those of cocoa plantations were 85.56 ± Mg ha^{-1}. The total carbon stocks corresponded well with stem density in each land-use type (Figure 6.3). As expected, in both forest and cocoa plantations, soil carbon stocks constituted more than 80% of the total carbon stocks (Figure 6.2). In the forest, total aboveground carbon stocks were marginally higher than the amount stored in cocoa plantations. The mean aboveground carbon stocks in forest of 23.57 ± 2.13 Mg ha^{-1} were comparatively greater than the sum of means in shade trees (14.93 ± 3.18 Mg ha^{-1}) and cocoa trees (7.33 ± 1.54 Mg ha^{-1}). Within the cocoa plantations, HAF had a significantly high ($F = 25.17$, df = 3, $P< 0.0001$) carbon stocks of 97.75 ± 8.35 Mg ha^{-1} followed by MAF (88.35 ± 9.14 Mg ha^{-1}) and FS cocoa (71.30 ± 9.05 Mg ha^{-1}).

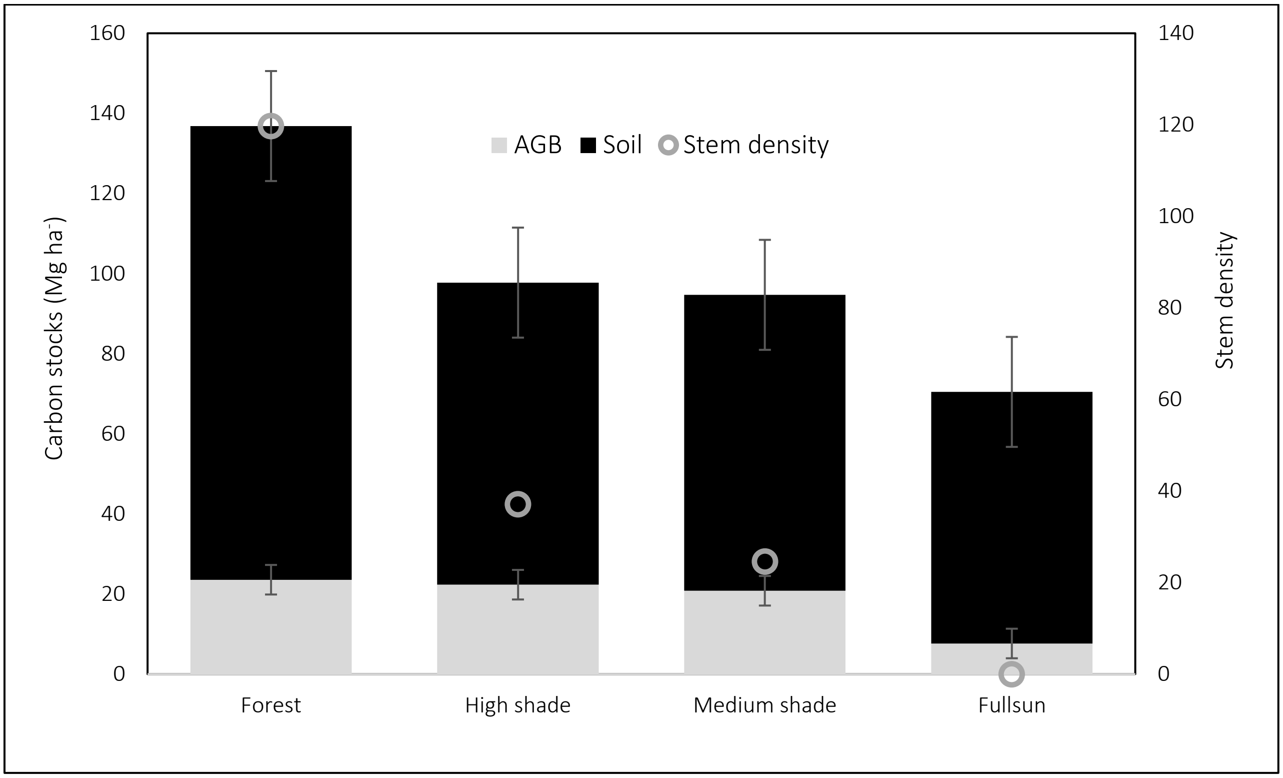


Figure 6.2. Carbon stocks in forest and cocoa agroforest of varying tree density and shade levels. Columns show mean carbon stocks (+1 SE) in aboveground carbon stock and soil carbon stocks. Aboveground carbon stocks is the sum of carbon stocks in shade and cocoa trees.

Farm age also influenced the distribution of carbon stocks in the different agroforestry systems. In general, the old cocoa plantations tended to store more carbon as opposed to matured and young plantations. The mean total carbon stocks in the old cocoa plantations were consistently high in all agroforestry and monoculture systems. On average, we recorded 97.61 Mg ha^{-1} in old, 86.37 Mg ha^{-1} in matured and 72.37 Mg ha^{-1} in young cocoa plantations (Table 6.1). The mean carbon stocks of cocoa trees only in the different agroforestry systems were significantly different from each other (F=5.493, df = 2, $P < 0.005$). However, for aboveground carbon stocks, there was no significant difference in mean carbon stocks of the shade trees in the different agroforestry systems (F = 2.942, df = 2, $P > 0.05$).

Table 6.1 : Mean aboveground, soil and total carbon stocks (Mg C/ha) in forest and cocoa plantations of different shade and age classes

			Aboveground carbon stocks (Mg ha^{-1})		**Soil carbon stocks (Mg ha^{-1})**		
Management Type	**Land-use types**	**Age**	**Shade tree**	**Cocoa tree**	**0-15 cm depth**	**15-30 cm depth**	**Total carbon stocks (Mg ha^{-1})**
Forest	Forest		23.57 ± 2.13	-	48.57 ± 4.17	64.70 ± 2.18	136.84 ± 3.97
Agriculture	Cocoa plantation		14.93 ± 3.18	7.33 ± 1.54	46.66 ± 7.09	32.87 ± 6.08	85.56 ± 8.82
Agroforest cocoa	High shade cocoa		17.34 ± 3.27	6.44 ± 1.48	49.41 ± 6.98	31.45 ± 5.79	97.75 ± 8.35
		Young	8.39 ± 1.5	1.59 ± 0.63	39.97 ± 5.89	33.94 ± 5.89	83.89 ± 8.15
		Mature	16.96 ± 2.36	5.29 ± 0.49	50.31 ± 7.86	26.53 ± 6.62	99.09 ± 8.57
		Old	21.87 ± 2.67	9.27 ± 1.22	52.57 ± 6.83	33.07 ± 5.85	101.97 ± 9.08
	Medium shade cocoa		11.96 ± 3.22	7.81 + 1.37	47.77 ± 7.12	38.22 ± 6.34	88.35 ± 9.14
		Young	2.89 ± 1.22	3.34 ± 0.35	57.54 ± 4.63	49.68 ± 4.28	67.09 ± 8.96
		Mature	11.08 ± 1.84	7.26 ± 1.07	46.67 ± 7.35	32.18 ± 6.99	81.69 ± 9.51
		Old	18.13 ± 2.57	10.2 ± 1.17	49.21 ± 6.49	42.65 ± 5.79	104.14 ± 8
Monoculture cocoa plantation	Fullsun cocoa		-	7.65 ± 1.79	41.25 ± 7.22	28.18 ± 5.78	71.30 ± 9.05
		Young	-	2.17 ± 1.45	35.49 ± 7.65	28.46 ± 6.71	66.12 ± 9.76
		Mature	-	6.00 ± 1.18	31.45 ± 6.58	22.27 ± 5.7	55.89 ± 8.38
		Old	-	11.4 ± 1.45	49.3 ± 6.57	31.32 ± 5.25	86.73 ± 8.06

The age of the cocoa trees immensely influenced basal area values and the aboveground carbon stocks among the agroforestry systems. The findings suggest that basal area (BA) and aboveground carbon stocks increase with increasing age of cocoa plantations (Table 6.2). Consequently, old cocoa plantations showed higher BA and aboveground carbon stocks than matured cocoa and were the lowest in young plantations. The BA of HAF cocoa differed significantly with age (F= 44.9, df = 2, P <0.0001). A similar significant difference was observed in HAF cocoa carbon stocks by age (F=29.11, df=2, P<0.0001). The MAF system showed a significantly high basal area (F=43.22, df=2, P <0.000) as well as carbon stocks (F=27.43, df=2, P <0.000). Similarly, in the case of fullsun cocoa, the contribution of cocoa to carbon stocks differed significantly with age (F=65.67, df=2, p<0.0001)

Table 6.2: Basal area and aboveground carbon stocks of cocoa in different agroforestry systems

Land-use types	Age of cocoa plantation	Basal area of cocoa trees (m^2)/ha	Aboveground carbons stocks of cocoa (Mg C/ha)
High agroforestry cocoa	Young	7.18 ± 0.61	2.40 ± 0.30
	Mature	11.61 ± 1.01	6.12 ± 1.09
	Old	15.73 ± 0.57	11.14 ± 1.48
Medium agroforestry cocoa	Young	8.57 ± 0.60	3.62 ± 0.50
	Mature	13.01 ± 0.62	7.42 ± 0.77
	Old	15.07 ± 0.64	10.57 ± 1.24
Fullsun cocoa	Young	4.67 ± 0.61	1.56 ± 0.57
	Mature	10.86 ± 0.59	5.09 ± 0.43
	Old	13.52 ± 0.67	8.71 ± 1.14

The shade tree parameters varied with the age of the cocoa plantations. The highest mean shade tree height was recorded on old farms in both MAF (17.60 ± 0.9 m) and HAF (17.64 ± 1 m) compared to young MAF (11.19 ± 0.6 m) and HAF (11.36 ± 0.7 m) (Table 6.3). Similar trends of higher DBH and crown cover (%) were observed on old cocoa farms than on the matured and young cocoa farms (Table 6.3). However, stem density distribution did not follow any clear pattern in the individual cocoa farms.

Table 6.3: Mean shade-tree variables and corresponding carbon stocks in different cocoa agroforestry systems

Cocoa plantations	Tree Height (m)	DBH (cm)	Crown Cover (%)	Stem Density (No./ha)	Shade trees carbon stocks (Mg C/ha)
MAF Young	11.19 ± 0.6	24.57 ± 1.1	4.55 ± 1.2	15.50 ± 1.1	2.89 ± 1.2
MAF Mature	15.34 ± 0.5	43.45 ± 1.9	7.67 ± 1.2	15.44 ± 0.9	11.08 ± 1.8
MAF Old	17.60 ± 0.9	53.47 ± 2.0	10.11 ± 1.8	13.36 ± 0.9	18.82 ±3.4
HAF Young	11.36 ± 0.7	28.40 ± 0.9	23.13 ±3.3	38.33 ± 2.1	8.39 ± 1.5
HAF Mature	14.81 ±0.8	37.08 ± 1.4	13.68 ± 1.7	31.0 ±2.2	16.96 ± 2.4
HAF Old	17.64 ± 1	46.59 ± 2.1	14.99 ± 2.5	24.0 ± 1.5	6.4±3.7

6.3.2 Tree biodiversity assessment: species dominance, diversity and distribution

A total of 1950 shade trees were recorded in the study area with 135 species and 38 plant families (Annex 1). The shade trees in HAF numbered 947 belonging to 75 species. There were 522 trees of 59 species in MAF, and 481 trees of 91 species in forest (FR). In FR, the highest number of species was observed followed by HAF and MAF. *Newbouldia laevis* (P.Beauv.) Seemann ex Bureau (family Bignoniaceae) was the dominant species in both MAF and HAF cocoa with a total of 171 trees (31.1% of all trees) and 268 (25.8% of all trees), respectively, whilst *Mansonia altissima* (A. Chev.) A. Chev. exhibited the highest number of trees (6.9%) in FR. A higher number of *N. laevis* trees were recorded in the matured cocoa farms followed by old and young cocoa farms for both MAF and HAF (Table 6.4). In general, matured farms had more shade trees in both MAF (158) and HAF (283). This was followed by 145 in young farms in HAF and 105 in the old farms in MAF.

Table 6.4: Dominant species in medium shade and high shade agroforestry cocoa farms and forest

	MAF			**HAF**			**Forest**
Species	**young**	**matured**	**old**	**young**	**matured**	**Old**	
Newbouldia laevis	36	67	59	36	149	58	-
Morinda lucida	9	10	7	33	37	2	-
Terminalia superba	7	15	8	20	16	16	-
Persea Americana	6	13	15	16	16	8	-
Milicia excelsa	1	4		22	9	5	-
Ceiba pentandra	-	6	4	9	14	4	-
Terminalia ivorensis	2	1	3	4	7	6	-
Bombax buonoposenze	8		4	2	6	2	-
Citrus senensis	1	17			13	1	-
Amphimas pterocarpoides	1	14	5	3	6	2	-
Mansonia altissima	-	-	-	-	-	-	33
Celtis mildbraedii	-	-	-	-	-	-	26
Sterculia rhinopetala	-	-	-	-	-	-	25
Cleidion gabonicum	-	-	-	-	-	-	25
Triplochiton scleroxylon	-	-	-	-	-	-	21
Pterygota macrocarpa	-	-	-	-	-	-	20
Trichilia preureana	-	-	-	-	-	-	18
Ricinodendron heudelottii	-	-	-	-	-	-	17
Macaranga barteri	-	-	-	-	-	-	13
Sterculia oblonga	-	-	-	-	-	-	11
Total number of trees	**71**	**158**	**105**	**145**	**283**	**114**	**209**

Diversity indices determine species richness and evenness, which is a function of the Shannon-Wiener diversity index (H'). The results show higher species richness (91) and evenness (0.5962) in forest, followed by HAF with 75 for species richness and 0.34 for evenness, and the lowest for MAF with 59 and 0.34, respectively (Table 6.5). The forest had the highest diversity value (H' = 3.99), followed by HAF (H' = 3.24) and MAF (H' = 3).

Table 6.5: Shannon-Wiener diversity indices of trees species in the study area

Diversity index	**MAF**	**HAF**	**FR**
Taxa species*	59	75	91
Individuals	516	908	481
Dominance (D) **	0.1194	0.09391	0.0269
Simpson (1-D)#	0.8806	0.9061	0.9731
Shannon (H)##	3.003	3.246	3.994
Evenness (e^H/S)***	0.3414	0.3424	0.5962
Relative abundance timber species (%)	37.40	33.04	48.65
Relative abundance non-timber species (%)	62.60	66.96	51.35

Species richness, **Simpson's Index, # Simpson's Index of Diversity, ## Shannon Diversity, ***Shannon Evenness Index

The species identified in the three land-use types were grouped into timber and non-timber trees. The relative abundance of non-timber trees was about twice that of timber species for MAF and HAF, except for FR where the value for non-timber and timber was 51.4% and 48.6%, respectively (Table 6.8). In general, the number of non-timber tree species was higher than that of the timber trees. In both MAF and HAF, the number of timber trees was about half that of the non-timber trees.

Table 6.6. Shade tree characteristics in the different land-use types

Land-use types	Total individuals	% of total individuals	Number of species	Mean DBH (cm)	Mean BA (m^2)
MAF	**516**	**27.1**	**59**	**51.71 ± 4.85**	**0.31 ± 0.70**
Non-timber	323	62.5	32	39.22 ± 4.01	0.17 ± 0.59
Timber	193	37.4	27	59.54 ± 4.90	0.39 ± 0.70
HAF	**908**	**47.7**	**75**	**40.97 ± 4.52**	**0.20 ± 0.65**
Non-timber	608	66.9	45	32.46 ± 3.82	0.12 ± 0.51
Timber	300	33.1	30	48.81 ± 4.63	0.27 ± 0.68
Forest	**481**	**25.2**	**92**	**19.42 ± 4.36**	**0.06 ± 0.63**
Non-timber	247	51.4	53	15.99 ± 3.60	0.04 ± 0.46
Timber	234	48.6	39	22.41 ± 4.69	0.08 ± 0.67

The number of species of non-timber trees was higher than that of the timber trees in all land-use types. On the other hand, the mean DBH was higher for timber species compared to the non-timber species. This resulted in a higher basal area of timber species compared to the non-timber trees (Table 6.6). In general, the highest mean diameter and basal area in MAF of 51.71 cm and 0.31m^2, respectively, followed by HAF with 40.97 cm and 0.20m^2, and FR with 19.42 cm and 0.06m^2, respectively (Table 6.6).

6.3.3. Statistical relations between tree characteristics and biodiversity

6.3.3.1 Relationship between aboveground carbon stocks of cocoa and shade trees, and age

The age of cocoa establishment and the management practice on the farm can influence aboveground carbon stocks of cocoa and shade trees of agroforestry systems (Table 6.7). The total aboveground carbon stocks increased significantly with age in FS (F=29.11, df=2, P<0.0001). A statistically significant relationship was also observed between total aboveground carbon stocks and age of the cocoa farm for MAF (F=53.53, df=2, P<0.0001) unlike HAF, which where the relationship was not significant (F=4.848, df=2, P value=0.028). carbon stock in cocoa trees and shade trees in agroforest differed significantly with age except for the carbon stocks in shade trees in HAF. Though the carbon stocks increased with increasing age, there were no significant differences in the means of shade tree carbon stocks in HAF (f=0.4227, df=2, P =0.6579).

Table 6.7: Carbon stocks of cocoa and shade trees in cocoa agroforestry systems in three age classes

Land-use types	**Age**	**Aboveground carbons stocks of cocoa trees (Mg C/ha)**	**Aboveground carbon stocks of shade trees (Mg C/ha)**	**Total aboveground carbon stocks of cocoa and shade trees Mg C/ha)**
Fullsun cocoa	Young	2.40 ± 0.30	-	2.40 ± 0.30
	Mature	6.12 ± 1.09	-	6.12 ± 1.09
	Old	11.14 ± 1.48	-	11.14 ± 1.48
				F=29.11, df=2, P < 0.0001
Medium shade agroforest cocoa	Young	3.62 ± 0.50	3.00 ± 1.45	6.62 ± 0.91
	Mature	7.42 ± 0.77	11.31 ± 1.69	18.73 ± 1.38
	Old	10.57 ± 1.24	18.36 ± 3.28	28.93 ± 3.01
		F=27.43, df=2, P<0.0001	F=26.6, df=2, P<0.0001	F=53.53, df=2, P<0.0001
High shade agroforest cocoa	Young	1.56 ± 0.57	11.96 ± 2.54	13.51 ± 2.45
	Mature	5.09 ± 0.43	15.23 ± 3.65	20.32 ± 2.38
	Old	8.71 ± 1.14	18.79 ± 4.02	27.50 ± 3.55
P value at 5%		F=65.67, df=2, P<0.0001	f=0.4227,df=2, P=0.6579	F=4.848, df=2, P=0.02866

Fullsun cocoa (FS), High agroforestry cocoa (HAF), Medium agroforestry system (MAF)

6.3.3.2 Relationships between shade tree stem diameter, crown area, height, and Shannon index and carbon stocks

The strength of the relationships between shade tree carbon stocks and tree parameters (DBH, height, crown area and Shannon index) varied. Shade tree DBH and carbon stocks showed the strongest statistical relationship (R^2=0.95) compared to shade tree height and carbon stocks (R^2=0.65) (Figure 6.3). The relationship between crown area and carbon stocks was weak as depicted by R^2 value of 0.33. The results reveal weak statistical relationships between shade tree carbon stock per plot and the corresponding Shannon Index (H’). This is indicated by the low R^2 value of 0.12 of the line of best fit.

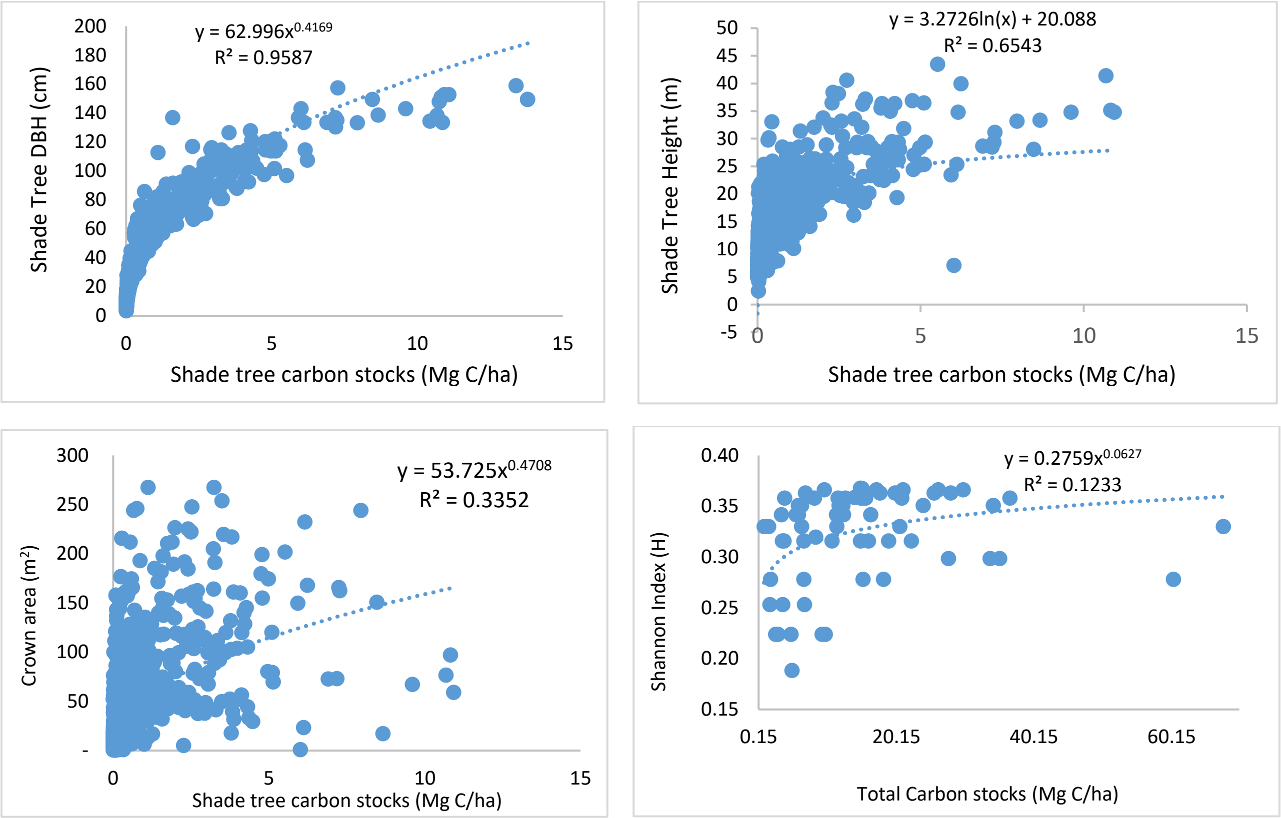


Figure 6.3. Statistical relationship between selected shade tree variables and carbon stocks and Shannon Index of tree diversity

6.4 Discussions

6.4.1 Carbon storage in natural forest and cocoa plantations

The ecological conditions of natural forest enable it to store more carbon than other land-use types including cocoa plantations. The mean total carbon stocks (in aboveground and soil) of 136.84 ± 3.97 Mg ha^{-1} obtained for forest is substantially higher than that in the cocoa plantations, which showed a mean of 85.56 ± 8.82 Mg ha$^{-1.}$ The differences in carbon stocks among FR, HAF, MAF, and FS were statistically different ($p < 0.0001$). The values in this study are within the range reported for both forest and cocoa plantations (Kessler et al. 2012). Here, carbon storage in soils made up more than 80% of the total carbon stocks, which is in agreement with the notion that soils are the largest terrestrial carbon sinks (Elbasiouny et al. 2014; Mohammed et al. 2016). Therefore, clearing natural forest could mean a potential source of carbon emissions and reduction in tree diversity richness.

Within the cocoa plantations, as reported by Kessler et al. (2012) and Rajab et al. (2016), HAF had higher aboveground carbon storage than MAF and FS. With aboveground carbon stocks of 23.77 Mg ha^{-1}, 20.81 Mg ha^{-1}, and 7.65 Mg ha^{-1}, the results compare well with the range of values published for cocoa agroforest plantations in Ghana (Dawoe et al. 2016; Mohammed et al. 2016) and other regions (Montagnini & Nair 2012; Somarriba et al. 2013).

Shade trees made up 73% (17.34 Mg ha^{-1}) and 61% (12.72 Mg ha^{-1}) in HAF and MAF, respectively, but the differences were not significant. The average carbon stocks of 14.93 ± 3.18 Mg ha^{-1} of non-cocoa trees was about 25% lower than that in FR (23.57 ± 2.13 Mg ha^{-1}). Although Rajab et al. (2016) and Kessler et al. (2012) reported similar trends of higher contributions of shade trees to the aboveground carbon stocks in cocoa plantations, the differences were slightly higher than the results we obtained in this study. In general, the high percentage of shade tree carbon stocks further supports the often reported notion of the important role of shade trees in carbon stock dynamics in cocoa plantations (Dawoe et al. 2016; Rajab et al. 2016; Asare & Ræbild 2016; Jim Gockowski & Sonwa 2011). While the carbon stocks measured in this study for shade trees were slightly lower than those of the forest, other studies (Kessler et al. 2012; Rajab et al. 2016; Dawoe et al. 2016) reported comparatively higher differences. The influences of forest conditions and the management regime of shade trees (stem density, crown cover, age) are assumed to be the reasons why we observed some differences in the aboveground carbon stocks in the other land-use types.

The cocoa trees contributed nearly 25% to the aboveground carbon stocks in the cocoa plantations. The mean carbon stocks of 6.44 ± 1.48, 7.81 ± 1.37 and 7.65 ± 1.79 Mg ha^{-1} are lower than the 10.3 and 11.8 Mg ha^{-1} published by Isaac et al. (2007) and Mohammed et al. (2016), respectively, in Ghana. A variety of reasons contributed to the lower values in this study. The main reason is the relatively young age of the cocoa plantations and the possible elimination of shade trees because of the notion that excessive shade is the cause of pests, diseases and low yields (Dawoe et al. 2016). We also found no significant difference in the carbon stored in cocoa trees among the three cocoa plantation systems HAF, MAF, and FS.

Although soil carbon makes up more than 80% of the total carbon stocks, the results do not show any significant variability among the forest, cocoa agroforest, and the fullsun systems especially in the upper soil layer (0-15 cm). This is consistent with the findings by Kessler et al. (2012), which suggest that the shift in land-use from forest to cocoa plantations does not end up in substantial losses in soil carbon stocks in the long term. The soil carbon stocks in forest and agroforest cocoa were slightly different (average of 3%) as compared to the 9% of FS cocoa. We believe that reason for the small differences in this study is similar to that reported by Kessler et al. (2012) suggesting that during the establishment of cocoa plantations, tree elimination does not lead to major erosion and decomposition. It is also important to recognize the difference in carbon stocks that arises because of the type of allometric equation used in the estimation of carbon stocks. As assumed by Dawoe et al. (2016), applying location-specific allometry or even using specific tree densities in the allometric equation can lead to some differences in the values. Therefore, the interpretations of the results from this study must consider the subtleties in the method applied as well as the kind of intensification practices in the study area.

6.4.2 Trends in shade tree parameters, carbon stocks and age

Shade trees are important contributors to aboveground carbon stocks of cocoa plantations of different ages. Tree height, diameter at breast height and carbon stocks tended to increase with increasing age of the cocoa plantation unlike crown cover and stem density, which did not follow any clear pattern. The age of the cocoa farm corresponded well with its aboveground carbon stocks and basal areas. In the cocoa plantations, the carbon stocks differed significantly among farm ages (old, matured and young). Typically, old cocoa plantations tended to have higher carbon stocks compared to matured and young farms, which also corresponded to the basal area of the shade trees. The highest mean height of 17.62 m of shade trees in old plantations in both HAF and MAF farms is in agreement with the results documented by Dawoe et al. (2016). Similarly, the mean DBH values of 50.03 cm (old), 40.27 cm (matured) and 26.49 cm (young) are comparable with the range of values (33.1-51.6 cm) published by Dawoe et al. (2016) for different sites.

In effect, the high above-ground carbon stocks in old cocoa plantations may be due to the combined influence of the presence of shade trees of relatively tall height, large stem diameter and high crown cover percentage. This also means that older cocoa plantations store higher amounts of carbon, and these are reflected in not just the cocoa trees, but also in the larger non-cocoa trees that are mostly left on the cocoa farms for agroforestry services over the maturity phases of the cocoa system.

6.4.3 Tree diversity in the cocoa-forest landscape

The cocoa-forest landscape continues to experience changes as a result of expansive cocoa cultivation and shade trees removal. Even though some remnants of trees remain in the cocoa plantation after forest clearing, the conversion contributes to a decline in carbon stocks and biodiversity in the landscape (Tondoh et al. 2015). Besides the ecological importance of forest, trees that are incorporated in cocoa agroforestry systems provide direct financial benefits and ecosystem service to farmers (Dawoe et al. 2016; Kessler, Jungkunst, et al. 2012; Asare & Ræbild 2016). In this study, 134 species belonging to 38 families (DBH ≥ 24.57 cm) were recorded in an area of 72 ha, with a Shannon diversity index (H') of 3.25 in HAF to 3.00 in MAF.

These results are within the range of values published for similar cocoa systems in different locations. However, the Shannon diversity index (H') values in this study were higher when compared to the results published by Dawoe et al. (2016) of 109 species (DBH ≥ 15 cm) with H' from 0.99 to 1.54 in 90 ha of shaded cocoa systems in Ghana. This could be because this study sampled cocoa farms located around the Krokorsua Hills Forest Reserve where farmers possibly left more remnant forest trees during land clearance for cocoa establishment. But there are also chances that the relative differences in plot areas in the two studies could have contributed to the difference in diversity indices. The results of this study are consistent with those of Sonwa et al. (2007), who reported DBH >2.5 cm and 206 hard and soft tree species in 60 cocoa farms and Shannon diversity indices between 3.1 and 4.2 in each of the studied agroforestry systems. Even though more individual trees were encountered in this study in HAF (908) and MAF (516) than in forest (481), the latter showed higher diversity (H' = 3.99) compared to agroforest cocoa plantations (H' = 3.12).

This contradicts the notion posited by Kessler et al. (2012) that having more individual trees leads to high biodiversity when contrasting shade trees in cocoa with forest trees. We also observed that replacing forest with agroforest not only prevents biodiversity loss but also facilitates the introduction of mostly exotic tree species to serve the production objective set by the farmers (Asare 2006). Farmers in the study area were clearly incorporating trees to meet specific needs and also to avoid possible tree tenure challenges (Acheampong et al., 2014), hence the dominance of *N. laevis*, for instance, in the cocoa agroforestry systems. In effect, the context of tree diversification in cocoa systems needs to be explored further to understand options available to help farmers overcome challenges in tree incorporation in cocoa systems for diversified and biodiversity-rich landscapes.

The modification of the cocoa landscape not only led to a decline in tree diversity, but also marked an era where farmer tree preferences promoted the occurrence of the dominance tree species *N. laevis* (Dawoe et al. 2016). The emergence of this tree as the most dominant shade tree species across three age classes (old, matured and young farm), as also reported by several authors (Dawoe et al. 2016; Mohammed et al. 2016; Asare & Ræbild 2016; Isaac et al. 2007), confirms its importance to the farmers. For instance, most farmers indicated that during the established of cocoa plots, they planted food crops such as yam. *Newbouldia laevis* is used to stake the yam because it has high growth. Additionally, the tree has a small crown, so when the cocoa plants grow, it can provide optimal shade. Therefore, the introduction of exotic and fruit tree species in the cocoa plantations explains the high relative abundance of non-timber species in both HAF and MAF but not in forest. The results agree with the findings by Dawoe et al. (2016) on the high abundance of non-timber species in the cocoa landscape. The different tree management practices we observed in this study provide a fresh perspective to the need to strengthen the tree tenure regime in the country (Forestry Commission 2015).

6.4.4 Relationships among shade tree parameters, carbon stocks and tree species diversity

Shade tree parameters (crown area, stem diameter and height) have different levels of influence on aboveground carbon stocks in cocoa plantations. The results obtained in this study depict different levels of relationships among selected shade tree parameters and carbon stocks, and corroborate the findings reported in literature (Dawoe et al. 2016; Isaac et al. 2007; Asare & Ræbild 2016). The predicative power of the equation between carbon stocks and stem diameter, tree height and crown area were strong (R^2=0.95), moderately strong (R^2 = 0.65) and low (R^2 = 0.33), respectively. However, Dawoe et al. (2016) found a similar trend but the R^2 = 0.36 was low, which illustrates the weak relationship between carbon stocks and shade tree stem diameter. Overall, the results suggest that aboveground carbon stocks increased with increasing tree stem diameter, height and crown area. These findings reinforce the conclusions by Dawoe et al. (2016) that larger shade tree stem diameter corresponds to high carbon storage in cocoa plantations. Our results also reveal the weak statistical relationship between tree biodiversity (H’) and total carbon stocks, and again are consistent with findings reported by Kessler et al. (2012) and Dawoe et al. (2016). Thus, our results contrast the common assumption that agroforest cocoa plantations with more shade trees tend to be rich in diversity. As indicated by Kessler et al. (2012), we found no such evidence to support the existence of a statistical relationship between carbon stocks and tree diversity.

6.5 Conclusions

This research provides sound insights into carbon stocks and tree diversity dynamics in the cocoa landscape. The results corroborate the widely documented findings that the high carbon storage capacity and rich tree biodiversity of natural forest declines when it is replaced with agroforest or monoculture cocoa plantations. Nevertheless, in both forest and cocoa plantations, soil carbon stocks constitute more than 80% of the total carbon stocks. We demonstrated that whereas age and the adopted shade tree management practices somewhat influence the level of aboveground carbon, soil carbon stocks levels do not vary greatly as a result of the forest conversion to these agroforestry systems.

Carbon stocks are higher in older plantations irrespective of the agroforestry system, and this is probably because old plantations are usually well stocked with high trees with large crowns and tend to have higher carbon storage capacity and tree diversity than other systems. Shade trees contribute more to the carbon stocks in cocoa farms than the cocoa tree itself. Therefore, the dendrometric characteristics of shade trees largely determine the extent to which they can influence the carbon stocks levels. This explains the strong statistical relationship between tree parameters (stem diameter, tree height and crown area) and carbon stocks. Our results further corroborate the important role of shade trees in cocoa plantations. Apart from being a major source of carbon storage, they are a resource for biodiversity preservation in cocoa plantations. These dynamics have implications for REDD+ interventions in the cocoa landscape. Not only would the conversion of forest and removal of shade trees lead to a decline in carbon stocks and to biodiversity loss, it would also contribute to deforestation levels in the country.

7 EFFECTS OF SOCIO-ECONOMIC FACTORS ON COCOA FARMERS' LAND-USE PREFERENCES

7.1 Introduction

The influence of socio-economic factors on the adoption of farming technologies such as agroforestry practices (Obeng and Weber 2014), fertilizer application (Denkyirah et al. 2016), cocoa spraying (Baffoe-Asare et al. 2013), and climate change adaptation options (Asante et al. 2017; Yegbemey et al. 2013; Deressa et al. 2009) have been widely researched. But, as far as we know, there are few studies on the effects of socio-economic factors on land-use choices in the cocoa landscapes. Some studies focused on different dimensions of tree management in polyculture cocoa systems. For instance, Anglaaere et al. (2011) and Asare et al. (2014) came up with insightful findings on farmer knowledge of shade trees, while the study by Dumont and Ohouo (2014) explored the reasons why the majority of cocoa farmers in Cote D'Ivoire prefer to have trees on their farms.

Farmer decisions to adopt or reject a particular farming practice can be interpreted as the result of a rationale iterative consideration of options to maximize stated or inferred income security objectives (Denkyirah et al. 2016). Such decisions are not made in vacuum, and farmers typically weigh the risk involved by drawing from their past experiences and the influences of socio-economic circumstances (Baffoe-Asare et al. 2013; Obeng & Weber 2014). Studies have established the strong influence of key socio-economic factors such as household age (Souza et al. 1990), gender (Villamor et al. 2014), and ethnicity (Ruf 2011; Knudsen & Agergaard 2016; Gockowski et al. 2011) on the adoption of new agronomic technologies as well as land-use choices. However, details of options, risks, perceptions and household-level variations cannot be independently measured, and can only be inferred from the choices made.

Although farmers' choices are largely yield-driven, their ability to achieve production targets is influenced by the socio-economic factors such as ethnicity (Knudsen & Agergaard 2016; Ruf 2011; Gockowski & Sonwa 2007), gender (Villamor et al. 2017) and land tenure (Damnyag et al. 2012). For instance, Knudsen & Agergaard (2016), Ruf & Zadi (1998) and Ruf (2011) provided valuable insights into how migrant farmers' preference for no-shade cocoa led to deforestation in the cocoa-forest frontier. Such findings on socio-economic drivers of landscape changes are essential to support efforts to find policy and practical options to achieve sustainable landscape configurations in the cocoa belt of Ghana. In this study, we aim at exploring the relationships between socio-economic status of farmers and their land-use preference. Specifically, we investigated into how agronomic and socio-economic factors influence farmer's decision to expand into forests or incorporate trees into cocoa systems. The objective was thus to answer the following questions: (a) what are the main socio-economic factors affecting local cocoa farmers' land-use decisions? and (b) how do these factors influence farmers' leaning towards expansion or intensification?

7.2 Conceptual framework

The land-use decision a farmer opts for can be determined using discrete choice models. These are the logistic regression or logit and probabilistic regression or probit models (Denkyirah et al. 2016). Logistic regression determines the probability of "ones or zeroes" of a dependent variable given the values of explanatory variables (Baffoe-Asare et al. 2013). In this context, we emphasized the need to explain the key factors that determine the socio-economic status of smallholder cocoa farmers and the effects they have on farmers' land-use choices (Figure 7.1). The socio-economic factors were further divided into demographic and agronomic factors. The key demographic factors of the cocoa farmers we included in the model were age, gender, income, ethnicity, household size, and education, and for the agronomic factors, farm size, land ownership, years of farming and participation in a cocoa certification program. In the modeling, we hypothesized that individual socio-economic factors have positive or negative effects on land-use choices and tested the empirical basis using binary logistic regression.

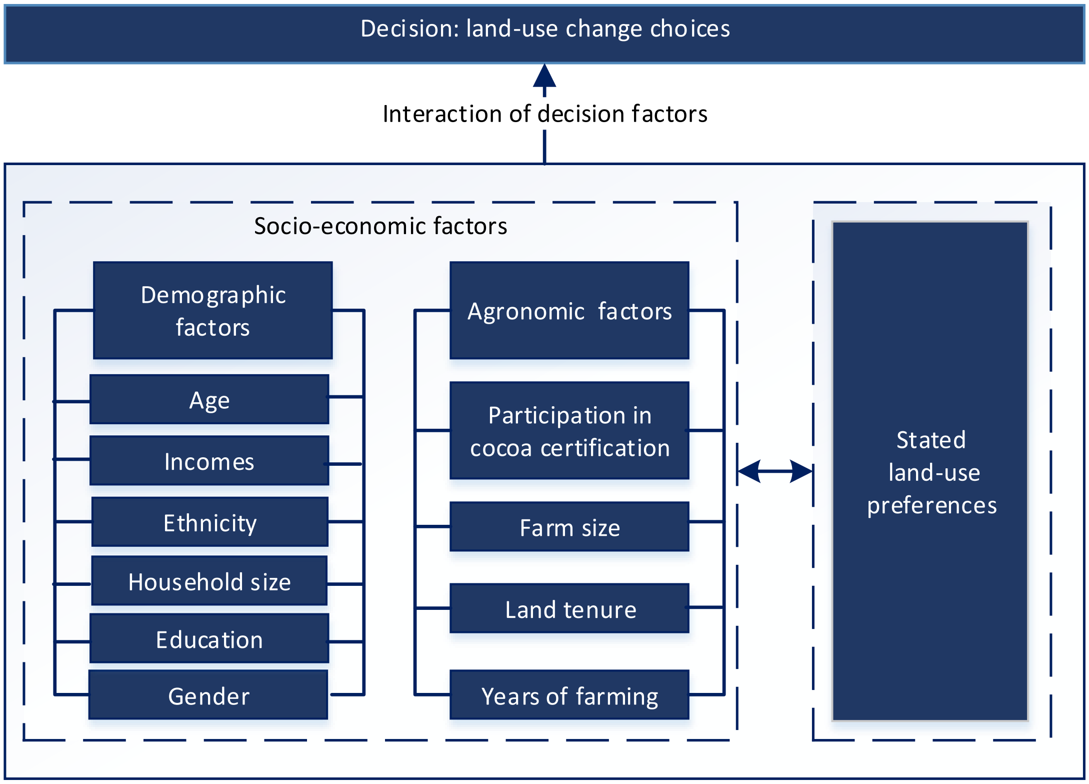


Figure 7.1. Modified conceptual model depicting the relationships between factors that can influence land-use choices (based on Obeng & Weber 2014).

7.2.1 Explanatory variables

Variables used, measurement scale and the expected effects on land-use choice of the selected explanatory variable are shown in Table 7.1. We expected that male farmers would be more likely to convert forest to cocoa or to eliminate shaded trees, which would have negative effects on land-use choices. Male farmers dominate the cocoa farming business (Taiwo et al. 2015; Tetteh & Asase 2017), are well-informed, endowed and often willing to take the risk of expanding their farms (Asfaw & Admassie 2004). Farmer age is likely to affect land-use choice. Generally, younger farmers are more willing to accept new ways of farming than older farmers, who are usually risk averse and reluctant to adopt a new technique such as shade tree variation (Denkyirah et al. 2017). This scenario could lead to an overall positive effect on forest to cocoa conversion (no land conversion). Young farmers are energetic and in most cases more prepared than their parents to undertake long-term investments to secure the future productivity of their farm (Adejumo et al. 2014). Thus, the net effects of age on land-use choice were expected to be negative, i.e. productivity oriented at the risk of loss of forest/tree cover. The effect of household income was expected to be positive, as high-income households are able to afford the cost of intensification by introducing new farming technologies instead of engaging in shifting cultivation (Adam et al. 2014). Farmers with large households tend to have access to cheap labor to support farm expansion activities (Mignouna et al. 2011). This means that this is more likely to have a negative influence on land-use preference. In the same vein, Knudsen & Agergaard (2016) and Ruf (2011) established that the style of farming of migrant cocoa farmers leads to deforestation and shade tree removal. Hence, we assume that an ethnicity would have negative effects on land-use choices linked to intensification. Denkyirah et al. (2017) pointed out that farmers with large farms have a wider range of adaptation options to choose from than those owning smaller farms. Having said that, we reckoned that in the cocoa landscape, farmers with large farms are less likely to expand into forestland or eliminate shade trees. Thus, we expect farm size to have a positive net effect on land-use choices. The relationship between educational level and land-use choice is positive. As explained by Clough et al. (2016), educated farmers have obtained information to enable them to better understand and appreciate the importance of the ecological functionality of a landscape.

Table 7.1. Explanatory variables, measurement scale and their expected effect on land-use choices

Variable	**Measurement scale**	**Expected effects on land-use choices**
Gender	1= male, 0 = female	–
Age	Years	+/–
Av. household income	Ghana cedi	+
Ethnicity	1= migrant, 0 = native	–
Household size	1=1-3, 2=4-6, 3=7-9, 4=>9	–
Schooling years	1= No school, 2=1-6 years, 3=7-11 years, 4=12-16, 5 = >16 years	+
Farm ownership	1=Individual, 2=Family farm, 3=Sharecropping, 4=Community farm, 5=Corporate farm	+/–
Farm size	Ha	+
Year of farming	Years	+
Membership of cocoa certification program	1= Yes, 0=No	+

More farming years have a positive influence on land-use choices. As farmers gain more farming experience over the years, they are more likely to have a positive attitude toward maintaining the integrity of the landscape (Clough et al. 2016). We anticipated that the migrant status of a farmer and farm ownership (sharecropping) would have negative effects on land-use choices. This is because in most cases cocoa farmers with insecure tenure (mostly migrant farmers) perceive that trees or keeping forest is a long-term investment that is unlikely to be achieved within the tenure period. Therefore, they resort to the “rapid planting quick return model” in the farming business. The net effects contribute to deforestation and shade elimination (Ruf 2011). Finally, farmers who are members of a cocoa certification program would tend to have a positive view of the landscape due to certification standard conditionality on the environment, farmer training programs and incentives for adhering to such standards.

7.3 Materials and methods

7.3.1 Data collection

The data used for this study was obtained via a household survey (using semi-structured questionnaires), key informant interviews and focus group discussions between December 2015 and February 2016. The questionnaires were used to generate a representative understanding of farmers’ land-use preferences and decision making, while the focus group discussions and key informant interviews were used to validate the responses from the questionnaires. Before the household survey was executed, a multi-stage random sampling technique (Bryman A. 2016; Saunders et al., 2012; Baffoe-Asare et al. 2012) was followed to select cocoa farming households for the survey. In the first stage, we selected Bia East, Juabeso and Sefwi Wiawso districts from the several cocoa-growing districts in the Western Region of Ghana. These districts were selected because they represent a classical cocoa mosaic landscape, as well as forest reserves including Krokorsua Hills Forest Reserve. In the second stage, the study area was defined as a rectangle with latitudes from 6.631420° to 6.425712° and longitudes from 2.634741° and 2.953857°, an area of 80,507 ha, 12.3 km of streams, and a road network of 3.2 km.

Communities in the defined area were counted as well as 'admitted farms' within the Krokorsua Hills Forest reserve. A total of 21 communities were identified with a large population of migrant farmers. There were 38 "admitted farms" with footpaths between farms and homesteads (Solidaridad, 2013). These farms were validated from the District Forest office in Juabeso. Out of the 21 communities, 5 communities were located in the Juabeso District, 8 in the Sefwi Wiawso Municipal Area, and 8 in the Bia East District. A total of 497 cocoa farmers were randomly selected among a list of 726 who had registered with the chiefs in each of the communities (Table 7.2).

Table 7.2: Selected communities for the study

Juabeso District	**Sefwi Wiawso District**	**Bia District**
Kojina	Asempanaye	Benkyema
Esakrom	Breman	Nkatieso
Domi	Dominibo	Kantankurobu
Sayeraso	Elluokrom	Sayerano
Nsennua	Eteso	Madina
	Old papase	Tettehkrom
	New papase	Aboagyekrom
	Asenteman	Brekuline

The unit of analysis was the household defined as comprising a person or group of persons living together in the same homestead but not necessarily with common housekeeping arrangements and answering to the same head of the household. (Madulu 1998) further described the household as a unit. For each farm household, we targeted household heads as respondents and conducted household interviews using semi-structured questionnaires. The questionnaire contained seven sets of questions about demographic and topographic information, landholdings, tree typification, productivity, past and future land-use choices, farmer knowledge on sustainable farming, and farm decision making. Transact walks were also conducted with 97 selected farmers across their farms to validate collected geographic data of their farms. During these walks, on-farm trees were identified and their uses determined. Data analysis was done using SPSS version 20.

7.3.2 Modeling land-use and tree incorporation choices

We modeled the effects of socio-economic factors on land use based on farmers' previous choices. These were selected based on their broad influence on farmer adoption of various cocoa technologies (Baffoe-Asare et al. 2012).

The land-use choices we modeled included decision on forest-cocoa conversion and shade tree elimination from existing farms using the explanatory variables (Table 7.1). We assigned the decision to covert forest to cocoa and tree removal from farms as NEGATIVE because of their negative influence on the ecological integrity/vitality at both plot and landscape levels. Conversely, we assigned the decision not to covert forest to cocoa and to maintain trees on-farm as POSITIVE because of the potential this will have to maintain or enhance ecological integrity at both plot and landscape levels. A binary logistic regression analysis was conducted using SPSS. If the probability to expand cocoa farm into forest or to eliminate shade trees is denoted by Y, then the alternative of not clearing forest or not eliminating shade trees is given by 1-Y. The ratio of the two variables expressed as $\left(\frac{Y}{1-Y}\right)$ is referred to as the odd ratio. In logistic regression, the logarithm of the odd ratio is a linear function of the explanatory variables (Equation 7.1):

$$\text{Ln}\left(\frac{Y}{1-Y}\right) = \alpha + \beta_0 + \beta_1 X_1 \dots\dots \beta_n X_n \qquad \text{Equation 7.1}$$

where ß = coefficient to be estimated, X_1……X_n = explanatory variables, α = error term

Using Equation 7.2 the farmer’s land-use choice (i.e. expand cocoa farm to forest or eliminate shade trees in cocoa systems) is determined as a function of three terms, namely socio-economic factors, agronomic factors and the stated land-use preference. Mathematically, the expression is represented as the “decision to expand cocoa farm into forest (Y) denoted by 1; the choice not to do this by 0; expressed as functions of (demographic factors, agronomic factors and stated land-use preference)”. In the model, the dependent function (i.e. land-use choices) is expressed as:

$$Y_i \, {}^{1}_{0} = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \dots\dots \beta_n x_n \qquad \text{Equation 7.2}$$

where Y_i lies between 0 and 1, which is probability of farmer deciding to covert forest to cocoa.

The Ln odd of converting forest to cocoa is given as $ß_1$, $ß_1$…………. $ß_n$ for any increase in the independent variables. X ($_{1, 2, 3 \dots\dots n}$) are explanatory demographic and agronomic variables.

α …….. error term in the estimated equation model. Eq. 2 was applied to model farmer's decision to convert forest to cocoa using SPSS with the following variables:

Y_i – dependent variable (decision to convert forest to cocoa)
X_1 – gender of respondent
X_2 – average household income
X_3 – age of respondent
X_4 – ethnicity
X_5 – household size
X_6 – Schooling years
X_7 – Land ownership
X_8 – Farm size
X_9 – Years of farming
X_{10} – Membership in cocoa certification program.

7.4 Results

7.4.1 Analysis of farmer responses

7.4.1.1 Household characteristics

Of the 497 farmers surveyed, 62% were male and 38% female. The age of the farmers was between 17 and 82 years (average 47 years). The majority of the farmers (41%) were within the 37-50 years age class, followed by those of 17-36 years (24%), older than 60 (19%) and 51-60 (16%) based on 25th percentile groups. The age of both the native and migrant male farmers was within the 37-50 and >60 age class (Table 7.3). Males (84%) headed most of the farming households (average size 6 persons).

Table 7.3 Socio-economic profile of farmers interviewed

		Socio-economic variables				**Pearson Chi-Square Tests**			
		Native Gender		**Migrant Gender**					
		F	M	F	M	Test Variables		Native	Migrant
Survey Parameters N=497		%	%	%	%			Gender	Gender
Age	17-36	35.5	64.5	53.8	46.2				
	37-50	39.5	60.5	18.4	81.6	Age	X^2	1.523	12.477
	51-60	45.5	54.5	53.8	46.2		df	3	3
	>60	38.9	61.1	21.1	78.9		Sig	0.677	0.006*
Schooling years	No school	51.8	48.2	41.9	58.1				
	1-6	23.5	76.5	26.4	73.6				
	7-11	0	100	0	0	Schooling years	X^2	36.788	2.548
	12-16	0	0	0	0		df	2	1
	>16	0	0	0	0		Sig	0.000^{*,b}	0.110^{b}
Household Head	Male	32.7	67.3	28.2	71.8	Household Head	X^2	46.815	13.094
	Female	87.8	12.2	100	0		df	2	2
	Single	44.4	55.6	40	60		Sig	0.000*	0.001^{*,b}
Household Size	1-3	50	50	26.7	73.3				
	4-6	36.8	63.2	42.9	57.1	Household Size	X^2	2.861	2.861
	7-9	45.5	54.5	24.1	75.9		df	3	3
	>9	23.6	76.4	35.3	64.7		Sig	0.413	0.413

** Chi-square statistic is significant at .05 level.*

Generally, most of the respondents had little education. A sizeable percentage either had no formal education (55%) or terminated their education after 1-6 years of schooling (44%). Only 1.4% of the respondents spent 7-11 years at school. The results also show that males, especially natives, spent more years at school than female cocoa farmers. Most of the interviewed farmers (80%) were natives (mainly Akan ethnicity) from the study region. The remaining 20% were migrants from districts within the Western Region, and from adjoining cocoa and non-cocoa regions mainly in northern Ghana. Apart from the responses by the household heads where chi square test indicated statistically significant difference among natives and migrants, for the remaining socio-economic variables the null-hypothesis of homogeneity could not be rejected.

7.4.1.2 Landholding arrangements

The survey shows that cocoa farm sizes ranged from 0.4 ha to 17.8 ha with an average of size 3.4 ha. The farms <2 ha (34%) and 2-4 ha (38%) were in the majority. Although both the native and migrant farm sizes were largely <2 ha and 2-4 ha, there were many more migrant cocoa farmers who had 2-4 ha and 6-8 ha cocoa farms compared to the natives. Most males claimed to have relatively large farm sizes (2-4 ha, 4-6 ha, 6-8 ha and >8 ha), while female farmers had more farms <2 ha (Table 7.4). Farmers owned 1-4 plots per household (average 2 plots). Overall, 32% of the farmers interviewed indicated that they owned one cocoa plot followed by 30% who had two plots. The majority of migrant farmers owned two plots as against the native farmers who owned more than two plots.

In terms of gender, the results show that females either had one (40%) or two plots (32%) compared to their male counterparts, who indicated having more than three cocoa plots. Similarly, 45% of the farmers in the age class 17-36 years had one plot, whereas the majority of those of >60 years had more plots. The surveys further reveal that 92% of the farmers owned their cocoa farms relative to those whose cocoa farms were either family owned (4.8%) or under a sharecropping arrangement (3.4%). The disaggregated results among ethnicity and gender show similar trends except that a slightly higher percentage of migrants (10%) was sharecropping. Typically, cocoa plots were 1.8 km away from the settlements. A majority of the farmers (90.3%) trekked 1-3 km to get to their farming plots regardless of gender, ethnicity and age. Most of the farmers (69%) indicated using walking as the commonest mode of transport. Some of the farmers (22.3%) adopted mixed transport modes (walking, bike, motor, river crossing).

Table 7.4: Landholding characteristics of surveyed cocoa farmers

	Frequency (%)									**Variables**
	Overall	Ethnic Origin		Gender		Age				
No. of plots		Native	Migrant	F	M	17-36	37-50	51-60	>60	Total number of cocoa farms owned by farming households. Non-cocoa farms are excluded
1	33.2	34.4	28.1	39.7	29.2	45.0	33.7	23.5	25.3	
2	30.8	28.7	39.6	31.7	30.2	25.8	32.2	37.0	28.6	
3	19.3	20.0	16.7	15.3	21.8	19.2	20.0	14.8	22.0	
4	16.7	17.0	15.6	13.2	18.8	10.0	14.1	24.7	24.2	
Farm size (ha)										
<2	34.2	36.7	24.0	48.7	25.3	48.3	35.1	21.0	25.3	Average sizes of cocoa farms elicited from respondents
2-4	37.6	35.9	44.8	36.5	38.3	32.5	43.9	42.0	26.4	
4-6	12.3	12.2	12.5	5.3	16.6	8.3	10.2	14.8	19.8	
6-8	8.0	7.2	11.5	7.4	8.4	7.5	5.4	11.1	12.1	
>8	7.8	8.0	7.3	2.1	11.4	3.3	5.4	11.1	16.5	
Mode of transport to farm										
Walking	69.4	71.8	59.4	88.4	57.8	67.5	66.8	77.8	70.3	Preferred means of transport farmer uses to get to the farm on daily basis
Walking and river crossing	0.6	0.5	0.0	0.0	0.6	1.7	0.0	0.0	0.0	
Motor cycle	4.4	4.2	5.2	2.1	5.8	8.3	2.9	0.0	6.6	
Bicycle	3.2	3.4	3.1	0.0	5.5	5.8	2.5	1.2	4.4	
Mixed modes	22.3	20.0	32.3	9.5	30.2	16.7	27.8	21.0	18.7	
Land ownership arrangement										
Individual farm	91.8	93.3	85.4	93.1	90.9	86.7	94.1	95.1	90.1	Description of cocoa farm ownership arrangement from the point of view of the respondents
Family farm	4.8	4.5	4.2	5.3	3.9	7.4	2.9	3.7	5.5	
Share cropping	3.4	2.2	10.4	1.6	5.2	5.9	2.9	1.2	4.4	
Distance to plots (km)										
1-3	90.3	91.3	86.5	90.5	90.3	92.5	91.7	82.7	91.2	Apparent distance travelled by farmers to cocoa farm and back to home
4-6	9.1	8.0	13.5	9.0%	9.1	7.5	7.3	17.3	7.7	
7-9	0.2	0.2	0.0	0.0%	0.3	0.0	0.5	0.0	0.0	
10-12	0.4	0.5	0.0	0.5	0.3	0.0	0.5	0.0	1.1	

7.4.1.3 Preference for tree retention/elimination on cocoa farms

The kind of tree management on the cocoa plots has an effect on yields. Although the traditional way of planting cocoa requires some tree shade, the emergence and adoption of fullsun cocoa varieties in recent times has led to shade tree reduction. The results show that 80.9% of the farmers interviewed had trees on their cocoa farm. Most native and migrant farmers responded positively to having trees on their farm, although migrants had slightly lower percentages (78.1%) than natives (81.5%) (Table 7.5). Similarly, slightly more female farmers (83.1%) claimed to have trees on their farm than their male counterparts (79.5%). The results show four main possible reasons why farmers retain or incorporate trees on their cocoa farm. These include (a) future sales of the trees as timber or wood fuel, (b) the trees serve as sources of fuelwood, (c) the trees serve as timber for domestic use, and (d) for ecosystem services such as shade. Overall, 79.7% of the farmers preferred to keep or incorporate trees on their cocoa farm for ecosystem services, e.g. for shade provision that is suitable for cocoa cultivation. The other reasons are for future sale of trees (for multiple use) (11.3%), sale of timber wood (7.4%), while the least important was energy use (2.6%). The results are not different when disaggregated by ethnic origin, gender or age.

Table 7.5: Shade trees retention/incorporation preference in cocoa plantations

			Frequency (%)							
		Overall	Ethnic origin		Gender		Age			
Survey Questions			Native	Migrant	F	M	17-36	37-50	51-60	>60
Trees on cocoa farm	Yes	80.9	81.5	78.1	83.1	79.5	86.7	82.0	77.8	73.6
	No	19.1	18.5	21.9	16.9	20.5	13.3	18.0	22.2	26.4
Reasons to keep or introduce trees on a plot										
For future sale	Yes	11.3	10.5	14.6	5.3	14.9	11.7	11.7	13.6	7.7
	No	88.7	89.5	85.4	94.7	85.1	88.3	88.3	86.4	92.3
Used for energy (firewood)	Yes	2.6	2.0	5.2	2.6	2.6	0.8	3.9	2.5	2.2
	No	97.4	98.0	94.8	97.4	97.4	99.2	96.1	97.5	97.8
Timber	Yes	7.4	6.0	13.5	2.6	10.4	2.5	11.2	3.7	8.8
	No	92.6	94.0	86.5	97.4	89.6	97.5	88.8	96.3	91.2
Provides ecosystem services	Yes	79.7	81.0	74.0	82.5	77.9	85.0	80.0	76.5	74.7
	No	20.3	19.0	26.0	17.5	22.1	15.0	20.0	23.5	25.3
Stage at which trees were introduced or retain in the farm										
	Yes	49.9	47.9	58.3	57.1	45.5	47.5	47.3	51.9	57.1

Retained during land clearing	No	50.1	52.1	41.7	42.9	54.5	52.5	52.7	48.1	42.9
Planted during establishment of cocoa farm	Yes	38.4	36.9	44.8	22.2	48.4	35.8	44.4	37.0	29.7
	No	61.6	63.1	55.2	77.8	51.6	64.2	55.6	63.0	70.3
Spontaneous growth after cocoa farm establishment	Yes	20.3	20.0	21.9	15.9	23.1	19.2	23.4	16.0	18.7
	No	79.7	80.0	78.1	84.1	76.9	80.8	76.6	84.0	81.3

When farmers who indicated having trees on their cocoa farms were asked about the stage in the cultivation cycle where they incorporated or kept the trees, 50% indicated that trees were mostly retained on the plot during land preparation. A lower percentage either planted the trees during plot establishment (38.4%) or later (20.3%). Even though most farmers had stated that they had incorporated shade trees either at the time of farm establishment or at a later stage in the cycle (Table 7.5), a pattern of shade trees removal is apparent (Table 7.6). Farmers were asked to indicate if they had eliminated shade trees, and if so, at what stage, what motivated them, and what method did they use to remove these trees. The shade tree elimination pattern follows a similar trend for all farmers regardless of ethnicity, gender and age, although there are marginal differences. In general, 70.4% of the cocoa farmers had once eliminated shade trees. The practice of tree removal is slightly more popular among migrant farmers (78.1%) than among those native to the area (68.6%).

Table 7.6: Preferences for shade tree elimination from cocoa plantations

		Frequency (%)								
		Overall	**Ethnic origin**		**Gender**		**Age**			
Survey Questions			Native	Migrant	F	M	17-36	37-50	51-60	>60
Tree elimination	Yes	70.4	68.6	78.1	77.2	66.2	68.3	65.4	76.5	79.1
	No	29.6	31.4	21.9	22.8	33.8	31.7	34.6	23.5	20.9
Stage of tree elimination										
Land preparation	Yes	35.6	35.4	36.5	44.4	30.2	37.5	33.2	40.7	34.1
	No	64.4	64.6	63.5	55.6	69.8	62.5	66.8	59.3	65.9
Matured plot	Yes	30.4	26.9	44.8	25.4	33.4	25.8	26.8	37.0	38.5
	No	69.6	73.1	55.2	74.6	66.6	74.2	73.2	63.0	61.5
Growing stage	Yes	7.6	7.7	7.3	6.9	8.1	5.8	8.8	6.2	8.8
	No	92.4	92.3	92.7	93.1	91.9	94.2	91.2	93.8	91.2
Method of shade tree elimination										
Chainsaw	Yes	32.0	29.2	39.6	33.3	29.9	32.5	28.8	30.9	35.2
	No	68.0	70.3	58.3	66.7	70.1	67.5	71.2	69.1	64.8
Poison	Yes	2.4	2.2	3.1	1.1	3.2	5.0	2.0	0.0	2.2
	No	97.6	97.8	96.9	98.9	96.8	95.0	98.0	100.0	97.8

Ring bark	Yes	26.8	24.7	34.4	27.0	26.3	18.3	26.3	32.1	33.0
	No	73.2	75.3	65.6	73.0	73.7	81.7	73.7	67.9	67.0
Fire underneath tree	Yes	19.1	16.7	29.2	24.9	15.6	10.8	17.6	30.9	23.1
	No	80.9	83.3	70.8	75.1	84.4	89.2	82.4	69.1	76.9

When asked about at what farming stage (land preparation, growing stage and maturity stage) the shade trees elimination took place, the responses are inconclusive (Table 7.6). A good number of the farmers were uncertain when they had removed the trees. However, 35.6% and 30.4% suggested that tree removal occurred during land preparation and maturity stage, respectively. The main methods of tree elimination applied were use of chainsaws (32%), removal of the bark by creating a circular ring around the stem (26.8%), use of fire to burn the lower stem and roots (19.1%), and the use of arboricide (2.4%). The farmers mentioned a variety of reasons for shade tree removal. Most farmers (83.9%) indicated that they believed the trees acted as hosts for pests and diseases. Only 13.9% of the farmers said they removed shade trees as a result of explicit adoption of fullsun cocoa systems.

7.4.1.4 Previous, current and future land-use choices

The results also show that cocoa plot age ranged from 2-70 years with an average age of 22 years. According to the farmers, the majority of the cocoa plots (39.2%) were within the 10-20 years age class followed by 20-30 years (24.9%) and >30 years (22.9%) (Table 6). The responses based on ethnic origin and gender were similar to the earlier observations. Farmers were asked about the previous land use before cocoa plot was established. The majority indicated bush-fallow (71.8%), overage cocoa plot (25.8%), open forest (11.3%) and intact forest (2.4%). Disaggregated by ethnicity, the results show that a high percentage (11.2%) of migrants preferred replacing intact forest with cocoa as against 0.2% of the native farmers (Table 7.7).

Table 7.7. Farmer land-use preferences elicited during the survey

			Frequency (%)							
Land-use preferences		**Overall**	**Ethnic origin**		**Gender**		**Age**			
Farming experience			Native	Migrant	F	M	17-36	37-50	51-60	>60
Years of farming on present land	<5 years	12.9	13.0	12.5	17.5	10.1	25.0	11.2	6.2	6.6
	10-20 years	39.2	40.1	35.4	34.4	42.2	39.2	50.7	30.9	20.9
	20-30 years	24.9	23.2	32.3	24.9	25.0	15.8	22.0	43.2	27.5
	>30 years	22.9	23.7	19.8	23.3	22.7	20.0	16.1	19.8	45.1
Previous land-use										
Intact forest	Yes	2.4	0.2	11.5	3.7	1.6	1.7	1.0	4.9	4.4
	No	97.6	99.8	88.5	96.3	98.4	98.3	99.0	95.1	95.6
Open forest	Yes	11.3	10.2	15.6	10.1	12.0	7.5	9.8	9.9	20.9
	No	88.7	89.8	84.4	89.9	88.0	92.5	90.2	90.1	79.1
Bush-fallow	Yes	71.8	71.8	71.9	69.8	73.1	71.7	70.7	71.6	74.7
	No	28.2	28.2	28.1	30.2	26.9	28.3	29.3	28.4	25.3
Old cocoa plot	Yes	25.8	26.4	22.9	22.2	27.9	21.7	34.1	24.7	13.2
	No	74.2	73.6	77.1	77.8	72.1	78.3	65.9	75.3	86.8
Reasons for converting previous land-use to cocoa										
Family asset	Yes	45.1	41.9	58.3	36.0	50.6	29.2	48.8	51.9	51.6
	No	54.9	58.1	41.7	64.0	49.4	70.8	51.2	48.1	48.4
Profitable than other crops	Yes	70.2	69.3	74.0	68.8	71.1	66.7	72.2	74.1	67.0
	No	29.4	30.6	26.0	31.3	28.9	33.3	27.3	25.9	33.0
Guarantee buyer	Yes	31.4	30.2	36.5	21.2	37.7	14.2	40.5	34.6	30.8
	No	68.6	69.8	63.5	78.8	62.3	85.8	59.5	65.4	69.2
Owning cocoa plot raises social status	Yes	7.8	8.0	7.3	2.6	11.0	7.5	8.3	12.3	3.3
	No	92.2	92.0	92.7	97.4	89.0	92.5	91.7	87.7	96.7
Land was affordable and accessible	Yes	8.0	7.2	11.5	4.70	5.20	5.0	9.8	14.8	2.2
	No	92.0	92.8	88.5	95.3	94.8	95.0	90.2	85.2	97.8
Previous lands were fertile and suitable for cocoa	Yes	7.4	6.0	13.5	5.8	8.4	5.0	8.8	6.2	8.8
	No	92.6	94.0	86.5	94.2	91.6	95.0	91.2	93.8	91.2

When asked about the factors that motivated them to convert the previous land use to cocoa plots, the farmers offered the following three key reasons: (a) cocoa plot is a family asset that can be bequeathed to the future generation (45.1%), (b) cocoa plot is more profitable than keeping the previous land use (70.2%), and (c) government is a guaranteed buyer of cocoa.

Other factors such as availability and access to suitable and affordable lands and availability of buyers of cocoa did not feature prominently in the farmers' responses. The results reveal that migrant farmers considered the motives profit (74%), access to land (11.5%) and soil fertility (13.5%) in establishing cocoa plots more frequently than the native farmers did, though the differences were not significant.

The next set of responses focused on understanding the plot-level decision-making process using input sourcing and decisions on permanent changes in the plots. Generally, the farmers' responses were unanimous on the dominant role of the plot owner, especially in instances where sharecropping arrangements were involved, or where the plots were managed by caretakers. Particularly on input purchase, the results show that in most cases (65.4%) plot owners undertake these purchases before informing the farmers. There were some cases (30.6%) where both the plot owner and the sharecropper or caretaker jointly took the decision on input supply (Table 7.8). With respect to making a permanent decision such as tree incorporation or removal, the results do not differ from the previous observations. Farmers emphasized the major role of the plot owner in determining whether a tree needed to be removed or otherwise, which also included trees incorporated after establishment of the cocoa plot.

Table 7.8. Factors affecting plot-level land-use decision-making

		Frequency (%)								
		Overall	**Ethnic origin**		**Gender**		**Age**			
Farm decision-making			Native	Migrant	F	M	17-36	37-50	51-60	>60
Who takes decisions on what inputs are introduced in each farming season	Sharecropper only	3.4	3.0	5.2	3.7	3.2	2.5	3.4	4.9	3.3
	Land owner only	65.4	67.6	56.3	59.3	69.2	78.3	71.7	50.6	47.3
	Joint land owner and farmer	30.6	29.2	36.5	36.0	27.3	19.2	24.4	42.0	49.5
	Agents of the land owner	0.6	0.2	2.1	1.1	0.3	0.0	0.5	2.5	0.0
Who takes decision on permanent changes in the plot	Sharecropper only	3.0	2.2	6.3	3.2	2.9	1.7	2.4	6.2	3.3
	Land owner only	64.4	66.1	57.3	58.7	67.9	77.5	70.2	50.6	46.2
	Joint land owner and farmer	31.8	30.9	35.4	38.1	27.9	20.0	26.3	43.2	49.5
	Agents of the land owner	0.8	0.7	1.0	0.0	1.3	0.8	1.0	0.0	1.1
	Not Consulted	52.1	55.6	37.5	47.6	54.9	60.8	59.0	33.3	41.8

If decisions are taken by land owner or his agent, how do you describe the consultation	Little consultation (sometimes involved)	19.7	18.7	24.0	23.8	17.2	16.7	20.0	25.9	17.6
	High consultation (involved)	18.5	19.0	16.7	21.2	16.9	16.7	12.2	25.9	28.6
	Very high consultation (always involved)	9.7	6.7	21.9	7.4	11.0	5.8	8.8	14.8	12.1

A high percentage of the farmers (55.3%) planned to expand their cocoa plot once they could access suitable land (Table 7.9). Both native and migrant farmers expressed intentions to expand, and a higher proportion were migrant and male farmers. Generally, in making decisions on where to expand to, farmers considered potential lands in off-reserve and on-reserve forest and other viable lands.

Table 7.9: Farmer preferences for future land-use

			Frequency (%)							
		Overall	Ethnic origin		Gender		Age			
Future land-use preference			Native	Migrant	F	M	17-36	37-50	51-60	>60
I plan to expand my cocoa farm	Yes	55.3	52.4	67.7	47.1	60.4	55.0	57.1	66.7	41.8
	No	44.7	47.6	32.3	52.9	39.6	45.0	42.9	33.3	58.2
I don't intend to expand my cocoa farm because there is no available land	Yes	40.4	42.9	30.2	48.1	35.7	43.3	39.0	32.1	47.3
	No	59.6	57.1	69.8	51.9	64.3	56.7	61.0	67.9	52.7
Will expand cocoa farm to available land outside forest	Yes	39.6	37.7	47.9	38.6	40.3	40.8	36.6	45.7	39.6
	No	60.4	62.3	52.1	61.4	59.7	59.2	63.4	54.3	60.4
Will expand cocoa farm into forest reserve if I get the chance	Yes	21.3	19.7	28.1	10.6	27.9	20.0	23.9	23.5	15.4
	No	78.7	80.3	71.9	89.4	72.1	80.0	76.1	76.5	84.6
I might consider other tree crops if they are more profitable than cocoa in my future expansion	Yes	1.6	2.0	0.0	3.2	0.6	2.5	1.5	2.5	0.0
	No	98.4	98.0	100	96.8	99.4	97.5	98.5	97.5	100
Will you consider eliminating trees to plant fullsun cocoa in expectation of more yield?	Yes	27.4	26.9	28.1	30.7	25.0	33.3	24.4	24.7	27.5
	No	72.6	73.1	71.9	69.3	75.0	66.7	75.6	75.3	72.5

The results show that 60.4% and 78.7% of the farmers do not intend to expand their cocoa farms to off-reserve and on-reserve forest, respectively. However, especially migrants (47.9%) and male (40.3%) farmers were willing to clear forest to cultivate cocoa in the future, notwithstanding the risk of expanding into forest in view of the fact that these forest are state-protected areas (Table 7.9). The farmers also considered other plot management options such as shade tree removal and crop diversification in their future expansion plans. The results also reveal that shade tree elimination as a way of boosting productivity is a more plausible option than replacing cocoa with other tree crops.

7.4.2 Underlying socio-economic factors and their effects on land-use preferences

A logistic regression analysis was performed of factors affecting farmers' decisions to convert forest to cocoa (Table 7.10) or eliminate shade trees (Table 7.10). For the farmers' choices on forest-to-cocoa conversions, ethnic origin and farming years were the significant factors. The model had a log likelihood value of -63.92 and χ2 value of 43.71. With regard to shade tree elimination, the log likelihood figure was 53.38 and χ2 was 44.01.

Table 7.10. Logistic regression of socio-economic factors affecting farmers' decision to convert forest to cocoa

Explanatory Variable	**Odd ratio**	**Standard Error**	**P-value**	**95% CI of Odd Ratio**	
				Lower	**Upper**
Gender	0.523	0.845	-0.443	0.100	2.741
Household size	1.550	0.359	0.222	0.767	3.132
Age	0.873	0.385	0.724	0.411	1.855
Education	2.755	0.737	0.169	0.650	11.674
Ethnic origin	9.385	1.149	-0.000**	9.868	892.68
Farms size	0.981	0.066	0.773	0.862	1.117
Household income	179.050	21.953	0.999	0.000	0.000
Plot ownership	1.500	0.672	0.547	0.402	5.601
Farming years	0.245	0.558	0.012*	0.082	0.732
Membership in certification program	0.905	0.734	0.892	0.215	3.816
Constant	0.000	21.95	1.000	0.100	2.741

Summary: Log Likelihood = -63.92, Chi^2 = 43.71, Pseudo R^2 =0.143 ** Significant level at 1% *Significant level at 5%

The ethnic origin of a farmer had a statistically significant (at 1%) negative effect in influencing the farmer's decision to convert forest to a cocoa farm. For instance, migrant farmers were more likely to convert forest to cocoa should they be confronted with the choice of expanding their farm. Farming experience had a positive influence and was statistically significant at 5%. This indicates that as the farmer accumulates farming experience, the farmer is less likely to undertake forest-to-cocoa conversion (Table 7.11).

Table 7.11. Logistic regression of socio-economic factors influencing shade tree elimination in cocoa plots

Explanatory Variable	**Odd ratio**	**Standard Error**	**P-value**	**95% CI of Odd Ratio**	
				Lower	**Upper**
Gender	0.660	0.237	-0.079	0.415	1.049
Household size	0.970	0.119	0.798	0.768	1.225
Age	0.692	0.120	-0.002*	0.547	.877
Education	1.510	0.284	0.147	0.865	2.636
Ethnic origin	1.823	0.206	-0.003*	1.219	2.728
Plots Sizes	1.002	0.017	0.915	0.970	1.035
Household income	0.973	1.275	0.983	0.080	11.854
Plot ownership	0.695	0.268	0.174	0.411	1.174
Farming years	1.752	0.117	0.000**	1.392	2.204
Membership in certification program	0.907	0.212	0.647	0.598	1.376
Constant	0.123	1.479	0.156		

Summary: Log Likelihood = -53.39, Chi^2 = 44.01, Pseudo R^2 =0.19 ** Significant level at 1% *Significant level at 5%

The age and ethnic origin of the farmer negatively influenced the decision to eliminate shade trees from the cocoa plot, and was statistically significant at 5%. In contrast, farming experience had a positive effect on shade tree elimination at 1% significance level (Table 7.11). In effect, both younger and migrant farmers had the predisposition to eliminate shade trees as against well-experienced farmers who were less likely to remove trees.

7.5 Discussion

7.5.1 Structure of cocoa farming households

The findings from this study are consistent with the generally held notion from previous studies suggesting that the majority of cocoa communities typically have large, male-headed families (Table 3) who dominate cocoa farming (Tetteh & Asase 2017; Taiwo et al. 2015). The recorded average household size between 5 and 10 persons illustrates the preference to employ family members to lower farm labor costs (Mango & Hebinck 2016; Wiredu et al. 2011) to boost productivity. The social background of the farmers informs on the way they relate to the landscape and on-farm decisions. With the large households, farmers are able to mobilize cheap family labor to help in key farm operations like regular weeding, chemical spraying, tree tending, etc. In making decisions that introduce permanent changes on the farm, such as tree removal or incorporation and farm expansion, farmers rely on the readily available labor at their disposal. The results further reveal that migrant males tend to have larger households than the native farmers. The motivation for migrant farming families to have large families may not only be the supply of labor to the family, but also that they can sell labor to the market to earn an extra income for the family. Most of the cocoa farmers surveyed had poor education and low incomes, were middle-aged and of diverse ethnic origin. Tetteh & Asase (2017) reported similar findings of a dominating middle-age group in cocoa farming, which means a positive outlook for industry in future once the issue is properly harnessed. However, the low incomes and poor education background put the farmers weakened their situation especially when dealing with government structures and adopting plot management technologies.

Cocoa farming is a labor-intensive venture, and the capital outlay to maintain optimal productivity can be prohibitive for poor farmers (Baah et al. 2012). Thus, with their low incomes, farmers are not able to meet the cost of innovations or the inputs associated with the adoption of new farming practices such as fullsun cocoa. The low level of education, particularly among females and migrant farmers, has negative implications for the way they manage their plots and their interactions with cocoa market actors. We found that about 70% of the sampled cocoa farmers had little or no education and as a result were not able to keep simple farm records. There were virtually no records of productivity, farming inputs (labor, seedlings, chemicals, etc.) and more importantly, documentation of landholding arrangements was poor (Asamoah & Owusu-Ansah 2017). Additionally, the low educational level of farmers disabled them from contesting the various market abuses from cocoa purchasing clerks who buy cocoa directly from the farmers (Baah et al. 2012).

Migrants made up 20% of the farmers we interviewed (Table 4), which is in line with the results of several studies in Ghana, Nigeria and Cote D'Ivôire on the influence of settler farmers in cocoa farming who contribute to the on-going landscape changes (Asamoah & Owusu-Ansah 2017; Bitty et al. 2015; Knudsen & Agergaard 2016; Obikili 2015; Aneani et al. 2012; Kolavalli & Vigneri 2011; Ruf 2011; Ruf 2007; Gockowski & Sonwa 2007). Generally, the cocoa farming practices among native and migrant farmers differ significantly as a result of their unique socio-cultural circumstances.

Typically, farmers who migrate to a cocoa farming community adopt strategies that allow them to establish and own cocoa farms in the shortest possible time. They achieve this by entering into sharecropping arrangements with native landowners. Once they get access to cocoa farmland, they adopt the “rapid return” method by clearing vegetation or removing shade trees with a view to maximizing yields within the timeframe of the sharecropping arrangement. This strategy is similar to what Knudsen & Agergaard (2016) and Ruf (2011) described as the role of migrant farmers in cocoa frontier formation and spillover effects on deforestation.

7.5.2 Landholding arrangements

In this study, we recorded cocoa farm sizes of a wide range between 0.4 ha and 18 ha with an average of 3.4 ha, which is characteristic of smallholder farmers. These figures are in the range of farm sizes reported by Acheampong et al. (2014), Abbott (2013), Tetteh & Asase (2017) and Asare et al. (2014). Perhaps the idea to keep relatively small farms is because of the low absorptive capacity of the farmers. One of the ways to diversify their income sources was to have additional parcels of cocoa land, and this practice is consistent with the findings of Acheampong et al. (2014). Most of the cocoa farms are not too far from major settlement areas. With an average distance of 1.8 km from the community, most farmers, especially migrants, prefer to live in hamlets close to the farm to reduce the cost of traveling to the farm. Those who live in the main community have to walk or go by motorcycle or bicycle. Three main land tenure arrangements existed in the study area, which included individually owned land, family land, and sharecropping land. Individually owned land mostly acquired through inheritance or purchase dominated. Farmers in other cocoa districts in Ghana who revealed a land tenure arrangement backed on the dominance of individually owned land and sharecropping (Acheampong et al. 2014; Tetteh & Asase 2017; Asamoah & Owusu-Ansah 2017). The prevalence of this tenure system could explain why it is far easier for a farmer to adopt new farming practices or expand the cocoa farm with no major hindrance. This is because such decisions are usually made at the individual level and are purely based on profit considerations.

7.5.3 Shade tree incorporation and elimination

Traditionally, cocoa is planted under shade trees, which provide the necessary microclimate for cocoa growth, and this could explain why the majority of the farmers interviewed had trees on their cocoa farms. The results show that not many migrants positively responded to having trees on their farms compared to the native farmers, and the same difference was found between male and female farmers. This suggests that both migrant and male cocoa farmers are less likely to have more trees on their farms than their native and female counterparts. The motivation behind these findings could be drawn from the fact that both migrant and male farmers are energetic and willing to take the risk of adopting new farming technologies, which may require removing shade trees (Knudsen & Agergaard 2016; Gockowski & Sonwa 2007; Ruf & Zadi 1998). Those who had shade trees revealed a couple of reasons why they left the shade trees during land preparation. The majority selected trees species that served their purpose of providing shade and would allow them to stake their food crop (e.g. yam) at the younger stage.

On the other hand, when the famers were asked what factors motivated them to eliminate shade trees and at what stage in the farming, the 70.4% who indicated to have eliminated shade trees made contradictory claims to the widely held belief that tree removal is instigated by unclear tree tenure arrangement in the country (Hoogendjik 2012). However, most of farmers (83.9%) made the uncontested assertion that they would remove trees if they acted as a host to pests and diseases (Ruf 2011), which would be a threat to their farm. Shade tree removal followed the same pattern, irrespective of ethnicity or gender of the farmer. Most used chainsaw and ringbark methods to remove shade trees because they felt they were cheap, easy to use and readily available.

7.5.4 Past and future land-use preferences

The age of the cocoa farms spanned over seven decades with the majority of them within the matured age class (10-20 years). Although this is in contrast to the notion that most of the cocoa farms in Ghana are overage and need rehabilitation (Bosompem et al. 2011), this finding is consistent with the findings of Acheampong et al. (2014). The authors posited that farmers may have rehabilitated or established new cocoa plots, which is why most of the farms were of relatively younger age.

The result of this study also shows that nearly 72% of the farmers converted bush-fallow areas (typically off-reserve forest) to establish their cocoa. More migrant farmers in the past had cleared intact forest to cultivate cocoa than the native farmers. This indeed compares positively with the widely published assertion of cocoa expansion being a driver of deforestation (Asare et al. 2014; Ruf & Zadi 1998; Wessel & Quist-Wessel 2015; Addo-Fordjour & Ankomah 2017) and that migrant farmers are major participants (Ruf & Schroth 2004; Knudsen & Agergaard 2016; Gockowski et al. 2013). This pattern of cocoa expansion is highly plausible since the study area is located on the new cocoa frontier in the Western Region of Ghana (Knudsen 2007). Major decisions in cocoa farm management such as shade tree elimination, expansion of farm to adjoining land use, and inputs acquisition are made at the discretion of the farm owner though on rare occasions they do consult the sharecropper (Asamoah & Owusu-Ansah 2017). The type of sharecropping model that governs the plot management determines the extent of involvement of the sharecropper in such major decisions. In this respect, the majority of the farmers interviewed expressed strong willingness to expand their cocoa farm to suitable lands in future into both off-reserve and on-reserve forest. Particularly migrant farmers showed a high level of desperation in search of fertile lands. This phenomenon of striving to make a living from the ecological resources is a typical characteristic of the underlying factors that drive modification of landscapes in the cocoa frontier.

7.5.5 Influences of socio-economic factors on land-use choice

The results of this study illustrate the influence of socio-economic factors on farmers' land-use choices at farm level and the broad implications at the landscape scale. We tested the effects of socio-economic factors on farmers' decisions to convert forest to cocoa as well as on shade tree elimination. Both preferences together contribute to shaping the vitality of the cocoa-forest landscapes of Ghana. Generally, the results indicate that while most socio-economic factors may influence the land-use preference of farmers, it was only a selected few that had strong negative statistically significant relationships. We found that ethnic origin, farming years and age strongly influenced farmers' land-use preferences albeit at different significant levels. With respect to forest-cocoa conversion, both ethnicity and years of farming significantly influenced farmers' choice.

Whereas ethnicity, in this case migrants, had a negative relationship, that of years of farming was positive. This implies that migrant farmers are more likely to convert forest to cocoa, unlike native farmers. Similar conclusions are reported in several studies (Knudsen & Agergaard 2016; Ruf & Schroth 2004; Gockowski & Sonwa 2007; Rudel 2013; Aide et al. 2012). Years of farming proved to have a statistically significant positive influence on forest-cocoa preference. This suggests that more experienced cocoa farmers are less likely to eliminate shade trees. A number of reasons could explain this, however it relates more to the level of experience farmers have gathered over the years that may have shaped their positive view of preserving landscape vitality (Obeng & Weber 2014). When it comes to shade tree elimination, the statistically significant negative trend of ethnicity and gender sufficiently reveal the high propensity young and migrant farmers have towards removing on-farm trees. It has been suggested in a number of studies (Deressa et al. 2009; Denkyirah et al. 2017; Obeng & Weber 2014; Aneani et al. 2012) that young and migrant farmers are quick to adopt new farming practices that promise to improve yield even in the short term, but this could have unsustainable impacts on the ecological system in the long term.

7.5.6 Shade trees preferences

We demonstrated that in cocoa-agroforestry, farmers sufficiently take into account the direct benefits they seek to derive from trees before establishing them in their cocoa plots. The positive influence of keeping shade trees on the wider landscape is hardly taken into account at the farm level. Thus, once national policies such as REDD+ straightened-up tree tenure arrangements, especially in the off-reserve areas to gain farmers' interest (i.e. guarantee full ownership of planted trees), positive incentives would be provided for reducing deforestation (UNDP, 2016). Farmers' decisions to incorporate shade trees usually occur at the time of cocoa plot establishment during land clearing. The farmers' preference for *N. laevis* (Figures 3 and 4) is certainly because of the ecosystem services provision they obtained from these trees for supporting their farming activities. The reason given by the farmers for keeping *N. laevis* on their agroforest cocoa farm is that when during the establishment of the cocoa farm, they grow food crops such as yam, etc., and *N. laevis* is used to stake the plants because of its tall growth.

Additionally, the species has a small crown, so when the cocoa grows, it can provide optimal shade. The tree species we identified in the forest areas were mainly timber species that occurred naturally and were managed under the state law.

7.6 Conclusions

This study sought to examine how socio-economic factors influence the land-use preferences of cocoa farmers. Firstly, we empirically established that poorly educated males with large families dominate the cocoa farming industry. Additionally, we show that the majority of the cocoa farms are less than 4 ha in size because they are primarily established to support subsistent livelihoods. The responses from the farmers through the interviews did not show great differences in ethnic or gender influence on land-use choice. The results show a slightly negative effect of the choices of young, male, migrant farmers. Statistically, socio-economic factors and stated farmer land-use preference influenced the decision to convert forest to cocoa or eliminate shade trees. Although the logistic regression model was unsuccessful in showing a statistical significance for most of the explanatory variables in farmer forest-cocoa conversion and shade tree removal, the factors that had a significant influence on farmer land-use decisions were ethnic origin, farming years and age. In spite of the fact that the model failed to show high statistical significance for the remaining socio-economic factors, we believe that the insights we have gained can contribute to designing landscape interventions in the on-going REDD+ debate in the country.

8 GENERAL CONCLUSIONS

In this study, using the combination of image fusion and maximum likelihood classification improved the accuracy levels for segregating cocoa plantations from cocoa and other vegetation. With this, it was possible to obtain a high accuracy level when calculating deforestation rates attributed specifically to cocoa expansion even though differentiating cocoa plantations from the forest was a technological limitation. Additionally, the results also confirm that there is a greater possibility to spectrally isolate different agroforest cocoa plantations from the forest. The results of the post-classification changes detection for 1986 and 2015 further corroborated the notion of cocoa production as a major driver of land-use change in cocoa landscapes. In the land-use transition process, cocoa expansion usually more frequently targets open forest and land-in-transition areas.

The results provide the basis for assessing of implications cocoa-driven land-use change on soil fertility, tree diversity and carbon emissions while recognizing the role of farmers at the farm level. In terms of the implications of land-use change on the spatial pattern of soil properties, we found no evidence of the influence of topography on the spatial pattern of TN, SOC and P. However, the results confirm more SOC in forest soils than in cocoa plantations with strong association with clay, TN and pH distribution due to the combined effects of forest litter fall and root system turnover. The spatial pattern of TN was controlled neither by land use nor by topography though it had strong associated with pH. The high P values in the cocoa plantations demonstrate the potential effects of fertilizer application.

With respect to the contribution of shade trees in determining soil fertility of cocoa agroforest plantations, the results conclusively establish that at the farm level, irrespective of species composition and the number of non-cocoa trees, soil fertility benefits do not depend on whether the farming system under consideration is fullsun cocoa or a complex agroforest. Our findings further establish that while cocoa goes through the cultivation phases from establishment through maturity to the old phase, the farm level interactions do not provide soil fertility benefits. When it comes to the implications of land-use change on dendrometric parameters, carbon stocks and tree diversity, the results corroborate the widely documented findings that the high carbon storage capacity and rich tree biodiversity of natural forest declines when it is replaced with agroforest or monoculture cocoa plantations.

Furthermore, in both forest and cocoa plantations, soil carbon stocks constituted more than 80% of the total carbon stocks. We also demonstrated that whereas age and the adopted shade tree management practices somewhat influence the level of aboveground carbon storage, soil carbon stock levels do not vary greatly as a result of the forest conversion to these agroforestry systems. Shade trees contribute more to the carbon stocks on cocoa farms than the cocoa tree itself. Therefore, the dendrometric characteristics of shade trees largely determine the extent to which the trees can influence the carbon stock levels. This explains the strong statistical relationship between tree parameters (stem diameter, tree height, and crown area) and carbon stocks. Our results further corroborate the important role of shade trees in cocoa plantations.

Apart from being a major source of carbon storage, shade trees are a resource for biodiversity preservation in cocoa plantations. On the role of farmers in the observed land-use changes, the results empirically establish that poorly educated male with large families dominates the cocoa farming industry. The majority of the cocoa farms are less than 4 ha in size because they are primarily established to support subsistence livelihoods. The results do not show great differences in ethnic, or gender influence on land-use choice. Statistically, some socio-economic factors and the stated farmer land-use preferences influenced the decision to convert forest to cocoa or eliminate shade trees. For instance, ethnic origin, farming years and age had a significant influence on farmer land-use decisions.

9 RECOMMENDATIONS

The key findings of this study are valuable inputs into the policy discourse on sustainable landscapes particularly REDD+, smart cocoa production and land-based climate mitigation. Nonetheless, the study faced some challenges, i.e. limited finances and focus, that prevented exploring all perspectives of the research issue. The research limitations, gaps for future research and lessons for policy considerations are listed below:

9.2 Research limitations

- Due to inadequate funds and the short period of time, the research was conducted in only one specific cocoa growing region (Western Region, Ghana). We would have like to have collected additional data from another cocoa growing region to compare the results.
- In the land-use mapping study, the original plan was to deploy the drone technology together with high-resolution satellite images to spectrally detect and isolate different cocoa agroforest systems. However, due to limited funds Landsat data was used because it had the capability of detecting variabilities in cocoa plantations. Although the spatial resolution of Landsat was coarse, it had the advantage of being open source and having high temporal availability.

9.3 Areas to explore in future research

- Evaluation of the extent of improvement in the accuracy levels in the detection of different intensities of cocoa agroforest systems and natural forest vegetation in selected locations using the “multi-spatial data source”, including drones.
- Investigation of the potential effects of the adoption of fullsun cocoa on the trajectory of the “boom-bust” cocoa production pattern.
- Assessment of the influence of age and shade patterns on the spatial distribution of selected soil properties in cocoa agroforest.

9.4 Lessons for policy considerations

- The ability to spectrally delineate different cocoa agroforest systems and national forest is a major contribution to reducing uncertainty in land representations in the national forest reference level under the REDD+ especially in the cocoa landscape.

- Management of cocoa landscapes must give special management attention to lands in transition (bush/shrubs, annual crops) and open forest. The results of this research show that, historically, the rapid cocoa expansion target lands in transition and open forest. In the design of landscape fallow programs, bush/shrubs are usually considered as unproductive marginal lands and are left to undergo natural regeneration. Introduction of management-assisted regeneration of lands in transition can create land banks fertile enough to support cocoa expansion.

- Tree tenure regimes that give farmers the right to their own on-farm trees and to enjoy direct benefits would provide incentives to reducing tree elimination. Tree rights that favor farmers must feature prominently in any landscape governance program.

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APPENDIX

Appendix 1. Forest and shade tree distribution in forest and agroforest

Scientific name	Family	Species	Use	Individuals (number)			
				All Land -use	Forest	Cocoa	
						High-shade AFS	Medium-shade AFS
Chrysophylum subnudum	Sapotaceae	adasama	Timber	9	8	1	
Dacryodes klaineana	Burseraceae	adwea	Non-Timber	3	3		
Strombosia glaucescens	Olacaceae	afena	Non-Timber	9	8	1	
Chrysophylum albidum	Sapotaceae	akasaa	Non-Timber	1		1	
Bombax buonoposenze	Bombacaceae	akata	Timber	37	2	11	24
Dracaena manii	Dracaenaceae	akeseakese	Non-Timber	5		3	2
Spathodia campanulata	Bignoniaceae	Akuokuoninsuo	Non-Timber	27		23	4
Blighia sapida	Sapindaceae	Akye	Non-Timber	17	5	4	8
Cola caricifolia	Sterculiaceae	ananseaya	Non-Timber	14	5	9	
Turraeanthus africanus	Meliaceae	Apapaye	Timber	1	1		
Antrocaryon micraster	Anacardiaceae	aprokuma	Timber	3		3	
Pouteria altissima	Sapotaceae	asamfena	Timber	6	5	1	
Parkia bicolor	Mimosaceae	asoma	Timber	3	3		
Chrysophylum purpulcrom	Sapotaceae	atabene	Non-Timber	7	6	1	
Spondias mombin	Anacardiaceae	atoa	Non-Timber	1		1	
Calpocalyx brevibracteatus	Mimosaceae	atrotere	Non-Timber	4	1		3
Albizia ferruginea	Mimosaceae	Awiemfosamina	Timber	20	1	11	8
Vernonia amygdalina	Asteraceae	Awonwono	Non-Timber	1			1
Canarium schweinfurthii	Burseraceae	Bediwonua	Non-Timber	1	1		
Berlinia tomentella	Caesalpiniaceae	belinia towentila	Non-Timber	1	1		
Cola nitida	Sterculiaceae	bese	Non-Timber	6	2	2	2
Irvingia gabonensis	Irvingiaceae	abesebuo	Non-Timber	1			1
Distermonanthus benthamianus	Caesalpiniaceae	bonsam dua	Non-Timber	6	1	1	4
Anthocleista nobilis	Gentianaceae	bontodie	Non-Timber	4		1	3

Entandrophragma candolei	Meliaceae	Candolii	Timber	1	1		
Cecropia peltata	Cecropiaceae	cecropia	Non-Timber	13	2	11	
Ceiba pentandra	Bombacaceae	ceiba	Timber	40		30	10
Citrus senensis	Rutaceae	citrus	Fruit	30		15	15
Pipterdeniastrum africanum	Mimosaceae	dahoma	Timber	5	1	4	
Nesogordonia papaverifera	Sterculiaceae	danta	Timber	23	7	11	5
Okoubaka aubrevillei	Santalaceae	diiball	Non-Timber	3			3
Diospyros monbunttensis	Ebenaceae	diospyrous	Non-Timber	4	4		
Ficus capensis	Moraceae	doma	Non-Timber	35	2	20	13
Chrysophylum beguei	Sapotaceae	dua tadwe	Non-Timber	1	1		
Hexalobus crispiflorus	Annonaceae	duabaha	Non-Timber	3	3		
Dialium aubrevillei	Caesalpiniaceae	duabankye	Non-Timber	1	1		
Greenwayodendron oliveri	Annonaceae	duabre	Non-Timber	4	4		
Enantia polycarpa	Annonaceae	duasika	Non-Timber	3	3		
Khaya ivorensis	Meliaceae	dubin	Timber	15	1	10	4
Mareya micrantha	Euphorbiaceae	dubrafoo	Non-Timber	2		1	1
Dialium dinklagei	Caesalpiniaceae	dwedwedwedwe	Non-Timber	1	1		
Lecaniodiscus cupanioides	Sapindaceae	dwendweraa	Non-Timber	2	2		
Baphia pubescens	Papilioniaceae	dwenekobre	Non-Timber	1		1	
Entandrophragma angolense	Meliaceae	edinam	Timber	37	2	15	20
Baphia nitida	Papilioniaceae	edwene	Non-Timber	1		1	
Terminalia ivorensis	Combretaceae	emire	Timber	37		28	9
Entandrophragma utile	Meliaceae	ent.utile	Timber	2		1	1
Aulacocalyx jasminiflora	Rubiaceae	entwesono	Non-Timber	1	1		
Erythrina mildbraedii	Papilioniaceae	erithrina	Non-Timber	2		2	
Celtis mildbraedii	Ulmaceae	esa	Timber	38	26	11	1
Celtis zenkeri	Ulmaceae	esakokoo	Timber	2	1	1	
Celtis adolfifrederici	Ulmaceae	esakosua	Timber	5	5		
Petersianthus macrocarpus	Lecythidaceae	esia	Timber	4	2	1	1
Discoglypremna caloneura	Euphorbiaceae	fetefre	Non-Timber	17	10	4	3
Ficus Sur	Moraceae	ficus sur	Non-Timber	3		2	1
Hannoa klaineana	Simaroubaceae	footie	Non-Timber	5	1	2	2

Grewia mollis	Tiliaceae	fotonkuroma	Non-Timber	8	8		
Millettia zechiana	Papilioniaceae	frafraha	Non-Timber	1		1	
Funtumia elastica	Apocynaceae	funtum	Non-Timber	13	3	7	3
Gliricidia sepium		gliricedia	Non-Timber	2			2
Cidium guajava		guava	Fruit	2		2	
Pterocarpus santalinoides	Papilioniaceae	hote	Non-Timber	1		1	
Danielia ogea	Caesalpiniaceae	hyedua	Timber	1		1	
Rauvolfia vomitoria	Apocynaceae	kakapenpen	Non-Timber	29		28	1
Trichilia preureana	Meliaceae	kkdk	Non-Timber	18	18		
Panda oleosa	Pandaceae	kokroboba	Non-Timber	2	2		
Buchholzia coriacea	Capparaceae	konini	Non-Timber	1	1		
Morinda lucida	Rubiaceae	konkroma	Non-Timber	117	4	84	29
Harungana madagascariensis	Guttiferae	Kosoa	Non-Timber	3		3	
Pterygota macrocarpa	Sterculiaceae	koto	Timber	8		2	6
Lannea welwitschii	Anacardiaceae	kumnini	Non-Timber	21	2	10	9
Nauclea diderrichii	Rubiaceae	kusia	Timber	1	1		
Guarea cedrata	Meliaceae	Kwabohoro	Non-Timber	4	4		
Tricalysia discolor	Rubiaceae	kwae coffee	Non-Timber	2	2		
Antiaris toxicaria	Moraceae	kyenkyen	Timber	39	4	19	16
Pterygota macrocarpa	Sterculiaceae	kyereye	Timber	20	20		
Mangifera indica	Anacardiaceae	mango	Fruit	5		4	1
Myrianthus arboreus	Cecropiaceae	myrianthus alborios	Non-Timber	4		4	
Mansonia altissima	Sterculiaceae	mansonia	Timber	35	33	2	
Cleidion gabonicum	Euphorbiaceae	mpawuo	Non-Timber	25	25		
Myrianthus libericus	Cecropiaceae	Nyankoma	Non-Timber	4	4		
Cleistopholis patens	Annonaceae	nnwo ne nkyene	Non-Timber	1	1		
Copaifera salikounda	Caesalpiniaceae	ntedua	Timber	2		2	
Alstonia boonei	Apocynaceae	nyamedua	Timber	24	2	15	7
Ficus exasperata	Moraceae	nyankyerenee	Non-Timber	39	6	20	13
Milicia excelsa	Moraceae	odum	Timber	47		38	9
Baphia nitida	Papilioniaceae	Odwene	Non-Timber	12	10	1	1
Baphia pubescens	Papilioniaceae	Odwenekobri	Non-Timber	7	6	1	
Microdesmis keayana	Pandaceae	ofema	Non-Timber	8	8		

Terminalia superba	Combretaceae	ofram	Timber	101	7	48	46
Sterculia oblonga	Sterculiaceae	ohaa	Timber	14	11	3	
Albizia zygia	Mimosaceae	okoro	Timber	32	1	15	16
Albizia glaberima	Mimosaceae	Okoro-Akoa	Non-Timber	9		6	3
Zanthoxylum gillettii	Rutaceae	okuo	Non-Timber	12	5	4	3
Trilepisium madagascariense	Moraceae	okure	Timber	4	3		1
Diospyros mannii	Ebenaceae	omenewa	Non-Timber	1	1		
Ceiba pentandra	Bombacaceae	Onyina	Timber	7	7		
Bombax brevicuspe	Bombacaceae	onyina koben	Timber	3	3		
Macaranga barteri	Euphorbiaceae	opam	Non-Timber	22	13	9	
Homalium Letestui	Flacourtiaceae	osonankoma	Non-Timber	2		1	1
Erythrina mildbraedii	Papilioniaceae	osorowa	Non-Timber	1		1	
Pycnanthus angolensis	Myristicaceae	otie	Timber	28	6	14	8
Treculia africana	Moraceae	ototim	Non-Timber	3	1	1	1
Vitex grandifolia	Verbenaceae	otwentorowa	Non-Timber	1		1	
Zanthoxylum leprieurii	Rutaceae	oyaa	Non-Timber	1	1		
Albizia adianthifolia	Mimosaceae	pampena	Non-Timber	20	1	12	7
Corynanthe pachyceras	Rubiaceae	pamprama	Non-Timber	4	4		
Carapa procera	Meliaceae	kwakuo bese	Non-Timber	1	1		
Persea americana	Lauraceae	pear	Fruit	98		61	37
Entandrophragma cylindricum	Meliaceae	penkwa	Timber	1	1		
Margaritaria discoidea	Euphorbiaceae	pepia	Non-Timber	11	2	9	
Tetrapleura tetraptera	Moraceae	prekese	Non-Timber	1		1	
Rothmannia longiflora	Rubiaceae	samankube	Non-Timber	1	1		
Lonchocarpus sericeus	Papilioniaceae	sante	Non-Timber	13		13	
Holarrhaena floribunda	Apocynaceae	sese	Non-Timber	26		20	6
Trema orientalis	Ulmaceae	sesea	Non-Timber	4	2	2	
Newbouldia laevis	Bignoniaceae	sesemasa	Non-Timber	490	8	287	195
Sterculia tragacantha	Sterculiaceae	sofo	Non-Timber	32	11	13	8
Danielia thurifera	Caesalpiniaceae	sopi	Timber	6		2	4
sterculia spp	Sterculiaceae	sterculia spp	Non-Timber	1		1	
Hymenostegia afzelii	Caesalpiniaceae	takorowa	Non-Timber	6	6		

Trichilia monadelpha	Meliaceae	tanuro	Non-Timber	10	7	3	
Trichilia tessmannii	Meliaceae	tanuro nyini	Non-Timber	3	1	1	1
Tectona grandis	Verbenaceae	teak	Non-Timber	1			1
Scotellia klaineana	Achariaceae	tiabutuo	Non-Timber	4	3		1
Cordia millenii	Boraginaceae	tweneboa	Non-Timber	7		4	3
Ricinodendron heudelotti	Euphorbiaceae	wama	Non-Timber	24	17	2	5
Cola gigiantia	Sterculiaceae	watapuo	Timber	22	5	13	4
Triplochiton scleroxylon	Sterculiaceae	wawa	Timber	35	21	11	3
Sterculia rhinopetala	Sterculiaceae	wawabima	Timber	27	25	1	1
Monodora myristica	Annonaceae	wedeaba	Non-Timber	4	2	2	
Morus mesozygia	Moraceae	wonton	Non-Timber	7		4	3
Amphimas pterocarpoides	Papilioniaceae	yaya	Timber	39	1	17	21
				2173	476	1072	625